A Generic FEP Database for the Assessment of Long-Term Performance and Safety of the Geological Storage of CO_2

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Summary

Systems analysis has been successfully applied to assessments of the performance and safety of the geological disposal of radioactive wastes and this approach is now being applied to the long-term geological storage of carbon dioxide. The use of 'FEPs' to describe the storage concept to be evaluated has proved to be a powerful tool to ensure that assessments incorporate comprehensive consideration of all potentially significant factors. FEPs are the features, events, and processes that are relevant to describe the behaviour of carbon dioxide in the system being assessed.

A generic FEP database for the geological storage of carbon dioxide has been developed, with the chosen FEPs being included for their relevance to the long-term safety and performance of the storage system after injection of carbon dioxide has been completed and the injection boreholes have been sealed. Some FEPs associated with the injection phase are nevertheless considered where these can affect long-term performance. The OECD/Nuclear Energy Agency FEP database for radioactive waste provided the inspiration for this generic CO_2 database, although the aims and content of the database have been developed significantly from the original NEA model.

The database currently includes around 200 FEPs in a hierarchical structure, with individual FEPs grouped into eight categories. Each FEP has a text description and an associated discussion of its relevance to long-term performance and safety. Key references from the published literature are included to enable retrieval of more detailed information for each FEP. The database is internet-enabled incorporating hyperlinks to other relevant sources of information (reports, websites, maps, photographs, videos, etc.), and is searchable in a variety of ways; it has the potential to provide a 'knowledge base' for the geological storage of carbon dioxide.

Potentially important scenarios for the future evolution of a geological storage system have been considered. These scenarios need to be addressed in systems-level models for the assessment of performance and safety. The use of the FEP database as an audit tool to evaluate the completeness of such models has been demonstrated.

The studies described in this report have been carried out in close cooperation with safety assessment work carried out in North America for the IEA Weyburn CO_2 Monitoring and Storage Project. Staff from North American organisations involved with the Weyburn Project have participated in Workshops held in Europe to ensure a free flow of ideas and concepts.

Contents

1 Introduction

The geological storage of carbon dioxide could make a significant contribution to the mitigation of anthropogenic emissions of carbon dioxide (Holloway, 1996). The feasibility of the geological storage of CO_2 as a mitigation measure depends on a number of factors. Firstly, the volumes available for geological storage must be sufficient to enable a significant reduction to be made in discharges of CO_2 to the atmosphere, and hence to make a significant contribution to reducing anthropogenic climate change. Secondly, capture and storage technologies need to be cost-effective. Thirdly, the geological system to isolate the CO_2 from the atmosphere should be effective over a suitably long timescale. Lastly, potential impacts on human health and the environment from these technologies must be within acceptable limits (e.g. Saripalli et al., 2003).

Most of the potential safety impacts of the geological storage of CO_2 are related to the migration of CO_2 from the storage reservoir or aquifer back to the accessible near-surface environment. Direct release of CO_2 to atmosphere could occur due to the failure of decommissioned wells (e.g. Celia and Bachu, 2003), whereas more diffuse releases could result in accumulation in ground and surface water bodies and buildings.

Systems analysis has been successfully applied to assessments of the performance and safety of the geological disposal of radioactive wastes and this approach is now being applied to the long-term geological storage of carbon dioxide. In Section 2 a brief summary is given of some of the systems analysis concepts used in this report. The use of 'FEPs' to describe the storage concept to be evaluated has proved to be a powerful tool to ensure that the assessments incorporate comprehensive consideration of all potentially significant factors. FEPs are the features, events, and processes that are relevant to the behaviour of carbon dioxide in the system being assessed.

A generic FEP database for the geological storage of carbon dioxide has been developed with the chosen FEPs being included for their relevance to the long-term safety and performance of the storage system after injection of carbon dioxide has been completed and the injection boreholes have been sealed. Some FEPs associated with the injection phase are nevertheless considered where these can affect long-term performance. The OECD/Nuclear Energy Agency FEP database for radioactive waste (NEA/OECD, 2000) provided the inspiration for this generic CO_2 database, although the aims and content of the database have been developed significantly from the original NEA model.

The development of the FEP database is the main activity carried out in the present project. The content of the database, which currently includes around 200 FEPs organised in a hierarchical structure using eight main categories, is described in Section 3. Each FEP within the database is provided with a text description and an associated discussion of its relevance to long-term performance and safety. Key references from the published literature are also included to enable retrieval of more detailed information for each FEP. The database is internet-enabled incorporating hyperlinks to other relevant sources of information (reports, websites, maps, photographs, videos, etc.), and is searchable in a variety of ways; it has the potential to provide a 'knowledge base' for the geological storage of carbon dioxide.

Potentially important scenarios for the future evolution of a geological storage system have been considered, and these are described in Section 4. These scenarios need to be addressed in systems-level models for the assessment of performance and safety. Section 4 also includes an example of the use of interaction matrices to represent interactions between FEPs to demonstrate a comprehensive understanding of the behaviour of the system.

A discussion of systems-level modelling for safety and performance assessment is developed in Section 5, and the use of the FEP database as an audit tool to evaluate the completeness of such models is demonstrated.

Finally, the status of the application of systems analysis methods to the geological storage of carbon dioxide, and recommendations for future work are discussed in Section 6.

The studies described in this report have been carried out in close cooperation with safety assessment work carried out in North America for the IEA Weyburn CO_2 Monitoring and Storage Project. Staff from North American organisations involved with the Weyburn Project have participated in Workshops held in Europe to ensure a free flow of ideas and concepts. The FEP database described in this report has provided essential input to the definition of scenarios for potential CO_2 migration at Weyburn described by Stenhouse and co-workers (Stenhouse, 2001; Zhou, 2001a; Zhou, 2001b; Stenhouse, 2002; Zhou and Stenhouse, 2002).

2 The Use of Systems Analysis

Systems Analysis methods have been widely applied in the field of safety and performance assessment for radioactive waste disposal (e.g. SKI, 1996). Some of the techniques that have proved useful in that field have been applied in this project to the geological storage of carbon dioxide. It is not the intention to discuss the background to these techniques in any detail, since this has been discussed in detail elsewhere in the Weyburn Project (see Stenhouse, 2001). However, a brief description is given in this section of methods that are adopted in the remainder of the report.

The first activity in the systems analysis approach is to specify the boundaries of the system that is to be analysed (both in space and time) so that the System Domain is clearly identified. The system can then be described in terms of relevant Features, Events and Processes (FEPs). *Processes* influence the evolution of the system, while events can be viewed as processes that take place on comparatively short timescales. Simple examples of the three types of FEP relevant to carbon dioxide storage might be: a near-surface aquifer and its associated characteristics (a *feature* of the system); erosion of the land surface (a *process* that affects the evolution of the system); and a large earthquake (a short-term *event* that also affects how the system evolves with time). The FEP database described in Section 3 describes includes around 200 FEPs relevant to the description of the long-term performance and safety of the geological storage of CO_2.

Even for a well-characterised CO_2 storage site, there will be unavoidable uncertainty regarding the future state or evolution of the system. In assessments of the impacts of the geological disposal of radioactive wastes, uncertainty in long-term evolution of the system has traditionally been handled by carrying out assessment calculations for a number of stylised conceptual descriptions of future system states or evolution narratives, termed scenarios. Scenarios have become widely used in business and industry as planning and brainstorming tools; they were first applied to the disposal of radioactive waste in the early 1980s by Sandia National Laboratory for the US Nuclear Regulatory Commission (Cranwell et al., 1982). In relation to CO_2 storage, a scenario can be thought of as:

> *"a hypothetical sequence of processes and events, devised to illustrate a range of possible future behaviours and states of a carbon sequestration system, for the purposes of making or evaluating a safety case, or for considering the long-term fate of CO_2."*

Processes and Events that determine scenarios are referred to as *external* FEPs, or EFEPs, since they relate to phenomena that are treated as being extrinsic to the system being assessed. In Section 4 consideration is given to the most important scenarios that need to be considered for a geological storage system.

In developing mathematical models for the long-term fate of CO_2 it can be helpful to represent the interactions between FEPs that relate to the intrinsic evolution of the system. Two general methods have been widely used: 'Process Influence Diagrams' (PIDs) and 'Interaction Matrices'. An example of the use of PIDs is given in SKI (1996), but these will not be described here as they were not employed in the current project.

The use of the Interaction Matrix was developed in the context of rock engineering systems (Hudson, 1992) and has been applied in a number of studies relevant to radioactive waste disposal (see for example, Skagius et al., 1995; BIOMOVS, 1996). The approach starts with a top-down partitioning of the system into constituent components, which are then presented as the leading diagonal elements (LDEs) of a matrix. Processes corresponding to interactions between LDEs are then recorded in the off-diagonal elements (ODEs). The convention adopted for illustrating influences between components is that an off-diagonal element *ij* implies the influence of LDE_{ii} on LDE_{jj} if $i < j$ and vice versa if $i > j$. This can be done without direct reference to a FEP list, since, at later stages in the assessment, the matrix and the FEP list contents can be audited against each other. A specific FEP, or group of FEPs, may correspond to an LDE, an interaction, an alteration to an interaction, or a pathway through the matrix, depending upon the initial choice of LDEs.

The Interaction Matrix approach allows FEP interactions and pathways to be mapped, which is an important step in developing and defining a conceptual model and in the logical progression to a mathematical model. Moreover, the top-down focus provided by identifying the LDEs, and then examining how the system components relate to one another assists in assuring comprehensive coverage of all potentially relevant Process System FEPs and may help to identify new, previously unrecognised relevant characteristics of the system. Figure 1 gives an example Interaction Matrix. Interaction Matrices are used in Section 4 to investigate process interactions for CO_2 storage.

FEP databases and Interaction Matrices can be helpful in developing mathematical models to describe the evolution of the system as a whole; such models are described here as system-level models. Once developed, such models can be audited against a FEP list to ensure that all the important processes relevant to a given assessment have been included. An illustration of this procedure is given in Section 5.

Figure 1: An Example Interaction Matrix. From IAEA (2003).

River Aquifer	X	Discharge through sediment	X	X	X	To adjacent aquifers maintaining constant concentration
X	River Atmosphere	X	Gas, aerosol, dust and detritus, spray, dust, detritus deposition	Gas, aerosol, dust and detritus, spray, dust, detritus deposition and active uptake	Gas, aerosol, dust and detritus, spray, dust, detritus inhalation (ducks, otters etc)	Wind blown gas, aerosol, spray, dust, detritus
Recharge maintaining constant concentration in the aquifer	Suspension and volatilisation	Riverbed Sediments	Resuspension, diffusion, advection, gas evolution	Uptake of water, nutrients and gases adhesion	Ingestion (fish, ducks etc)	X
X	Evaporation, evolution of volatiles, spray, evolution of aerosols	Deposition of suspended sediment, diffusion	River Surface Water Bodies	Uptake of water, nutrients and gases adhesion of suspended sediment	Ingestion and surface absorption	Outflow
X	Transpiration and respiration	Detritus from death and decay, root exudates	Detritus from living plants and death and decay	River Plants	Ingestion (fish, ducks etc)	X
X	Respiration	Excreta, death and decay	Excreta, death and decay	X	River Animals	Export as food
X	X	X	X	X	X	River Sinks

3 The FEP Database

3.1 Introduction

As discussed in Section 2, the classification and description of the Features, Events and Processes (FEPs) relevant to the geological sequestration of carbon dioxide can provide the basis for developing a comprehensive understanding of the geological storage system and evaluating its performance and safety.

The production of databases of FEPs has proved to be valuable in the field of radioactive waste disposal assessment. For example, the OECD/Nuclear Energy Agency FEP database for radioactive waste (NEA/OECD, 2000) is widely used internationally. The database has been used as an audit tool to evaluate the completeness of a number of systems-level models for radioactive waste disposal.

The development of the generic FEP database for the geological storage of CO_2 proceeded as follows:

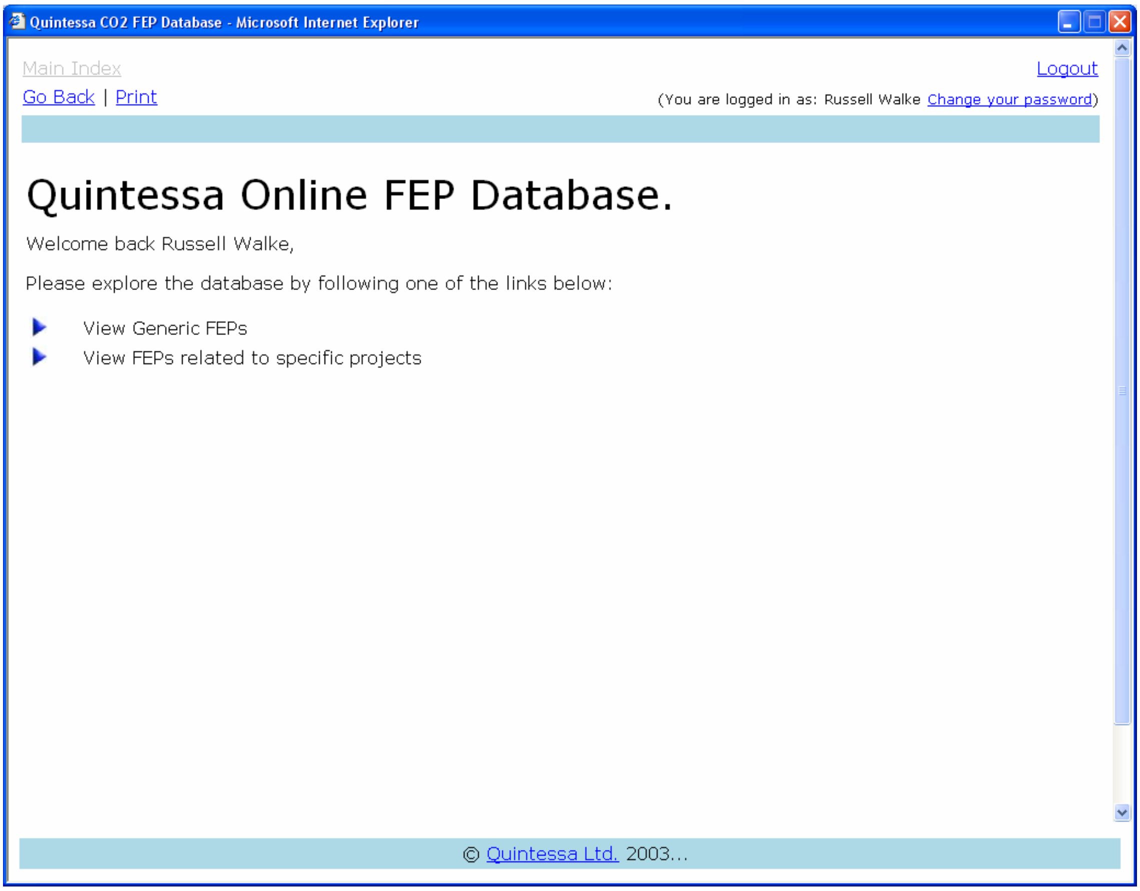
- ▲ An outline structure was initially produced, based on the approach used in the NEA radioactive waste database.
- ▲ A 'brainstorming' meeting was held jointly with members of the EC Nascent project team in Rome in January 2002 to identify key FEPs.
- ▲ A workshop was held in Orléans (again with the EC Nascent project team) in March 2003 to identify important scenarios for the long-term performance and safety of sequestration systems. The output from this workshop is summarised in Section 4.1.
- ▲ A workshop held in Copenhagen in November 2003 reviewed a draft version of the database, with EC Weyburn project participants providing additional material for inclusion.

In the following sections the structure of the database is described, and then further details are given on the individual database categories. Finally, a summary is given of the status of the database and its potential for future applications.

3.2 Accessing the FEP Database

The database can be accessed by using the following internet link: http://www.quintessa-online.com/co2/. Once access to this site has been achieved

Figure 2: The introductory window for the FEP database.



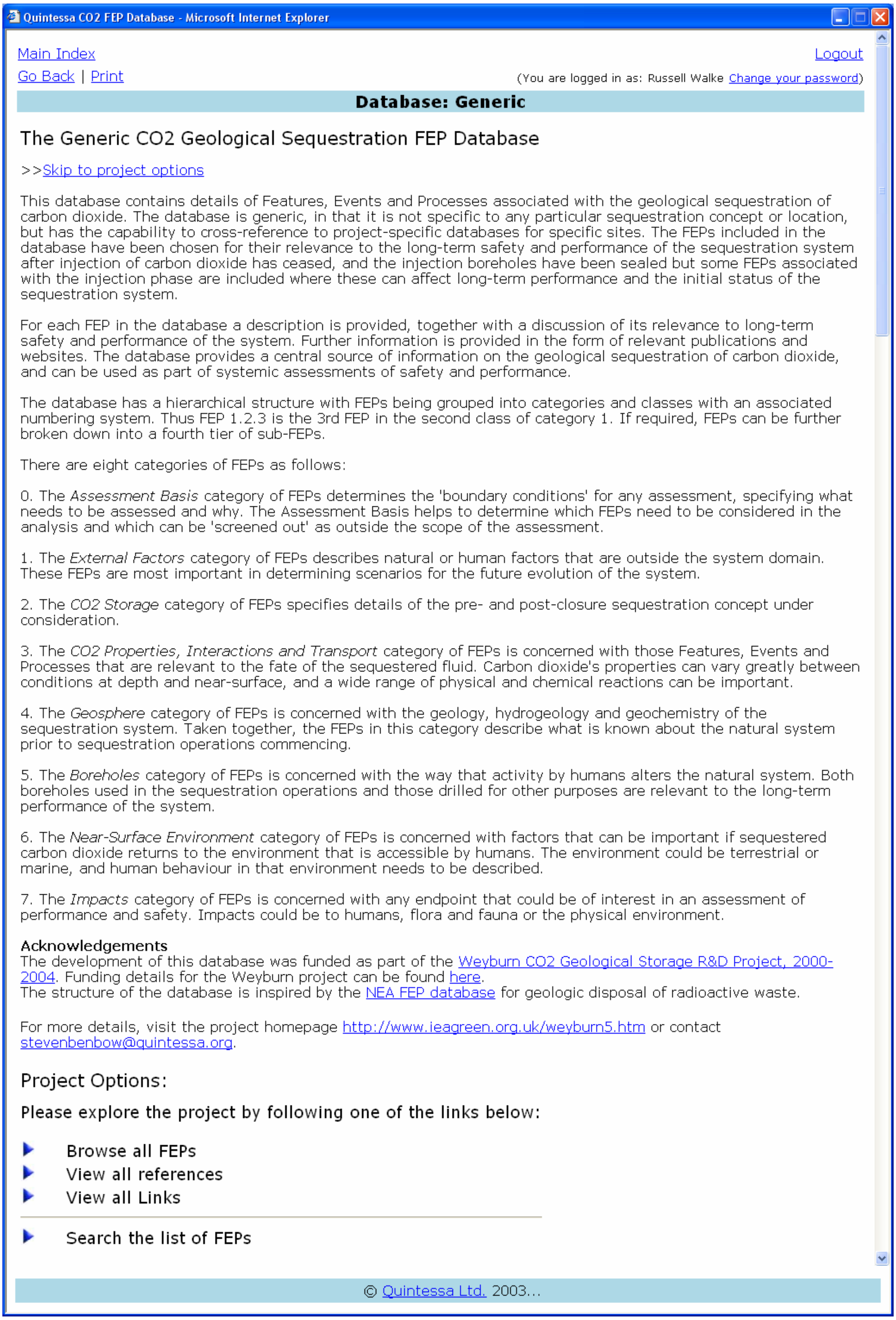
the user needs complete a registration process, following which a confirmatory e-mail is sent. Once logged onto the database the user will see the screen shown in Figure 2.

The user can choose to view the generic FEPs or project-specific FEPs. At the present time there are no links to project-specific FEP lists, and so it is only the generic FEP list that can be viewed.

When the generic FEP list is chosen, the window shown in Figure 3 is presented to the user. Introductory text is provided, explaining the structure of the database and the use of eight FEP categories (see Section 3.3). At the bottom of the page the user has the option to:

- browse all the FEPs in the generic database;
- look at the list of references in the database;
- look at the list of links used in the database; and
- search the database.

Figure 3 Introduction to the generic FEP database.



Quintessa CO2 FEP Database - Microsoft Internet Explorer

Main Index
Logout
Go Back | Print
(You are logged in as: Russell Walke Change your password)

Database: Generic

The Generic CO2 Geological Sequestration FEP Database

>>Skip to project options

This database contains details of Features, Events and Processes associated with the geological sequestration of carbon dioxide. The database is generic, in that it is not specific to any particular sequestration concept or location, but has the capability to cross-reference to project-specific databases for specific sites. The FEPs included in the database have been chosen for their relevance to the long-term safety and performance of the sequestration system after injection of carbon dioxide has ceased, and the injection boreholes have been sealed but some FEPs associated with the injection phase are included where these can affect long-term performance and the initial status of the sequestration system.

For each FEP in the database a description is provided, together with a discussion of its relevance to long-term safety and performance of the system. Further information is provided in the form of relevant publications and websites. The database provides a central source of information on the geological sequestration of carbon dioxide, and can be used as part of systemic assessments of safety and performance.

The database has a hierarchical structure with FEPs being grouped into categories and classes with an associated numbering system. Thus FEP 1.2.3 is the 3rd FEP in the second class of category 1. If required, FEPs can be further broken down into a fourth tier of sub-FEPs.

There are eight categories of FEPs as follows:

0. The *Assessment Basis* category of FEPs determines the 'boundary conditions' for any assessment, specifying what needs to be assessed and why. The Assessment Basis helps to determine which FEPs need to be considered in the analysis and which can be 'screened out' as outside the scope of the assessment.

1. The *External Factors* category of FEPs describes natural or human factors that are outside the system domain. These FEPs are most important in determining scenarios for the future evolution of the system.

2. The *CO2 Storage* category of FEPs specifies details of the pre- and post-closure sequestration concept under consideration.

3. The *CO2 Properties, Interactions and Transport* category of FEPs is concerned with those Features, Events and Processes that are relevant to the fate of the sequestered fluid. Carbon dioxide's properties can vary greatly between conditions at depth and near-surface, and a wide range of physical and chemical reactions can be important.

4. The *Geosphere* category of FEPs is concerned with the geology, hydrogeology and geochemistry of the sequestration system. Taken together, the FEPs in this category describe what is known about the natural system prior to sequestration operations commencing.

5. The *Boreholes* category of FEPs is concerned with the way that activity by humans alters the natural system. Both boreholes used in the sequestration operations and those drilled for other purposes are relevant to the long-term performance of the system.

6. The *Near-Surface Environment* category of FEPs is concerned with factors that can be important if sequestered carbon dioxide returns to the environment that is accessible by humans. The environment could be terrestrial or marine, and human behaviour in that environment needs to be described.

7. The *Impacts* category of FEPs is concerned with any endpoint that could be of interest in an assessment of performance and safety. Impacts could be to humans, flora and fauna or the physical environment.

Acknowledgements
The development of this database was funded as part of the Weyburn CO2 Geological Storage R&D Project, 2000-2004. Funding details for the Weyburn project can be found here.
The structure of the database is inspired by the NEA FEP database for geologic disposal of radioactive waste.

For more details, visit the project homepage http://www.ieagreen.org.uk/weyburn5.htm or contact stevenbenbow@quintessa.org.

Project Options:

Please explore the project by following one of the links below:

- Browse all FEPs
- View all references
- View all Links

- Search the list of FEPs

If the user chooses to browse the database, the structure of the database is presented as shown in Figure 4. The entry for any FEP is obtained by clicking on that FEP (see Section 3.3). The user can navigate around the database by using the 'Go Back' and 'Main Index' links, or can move through the list sequentially by using the 'up' and 'down' arrows alongside the FEP number, or can click on any entry in the hierarchy links shown.

If the search function is used, the initial window shown to the user is illustrated in Figure 5. It is possible to search for text in any of the fields of the database. In the example show here, a simple search is illustrated for the word 'earthquake' in the FEP description - the results are shown in Figure 6. Here, it can be seen that three relevant FEPs have been identified.

Figure 4: Browsing the generic FEP database.

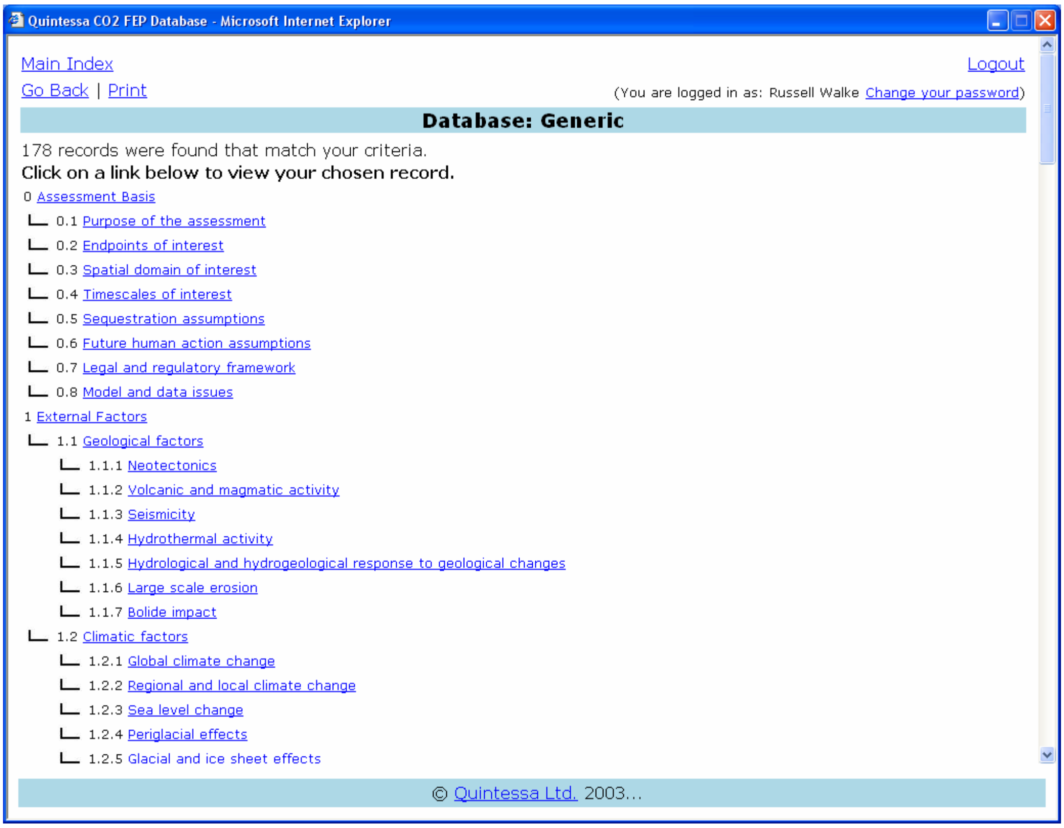


Figure 5: The database search facility.

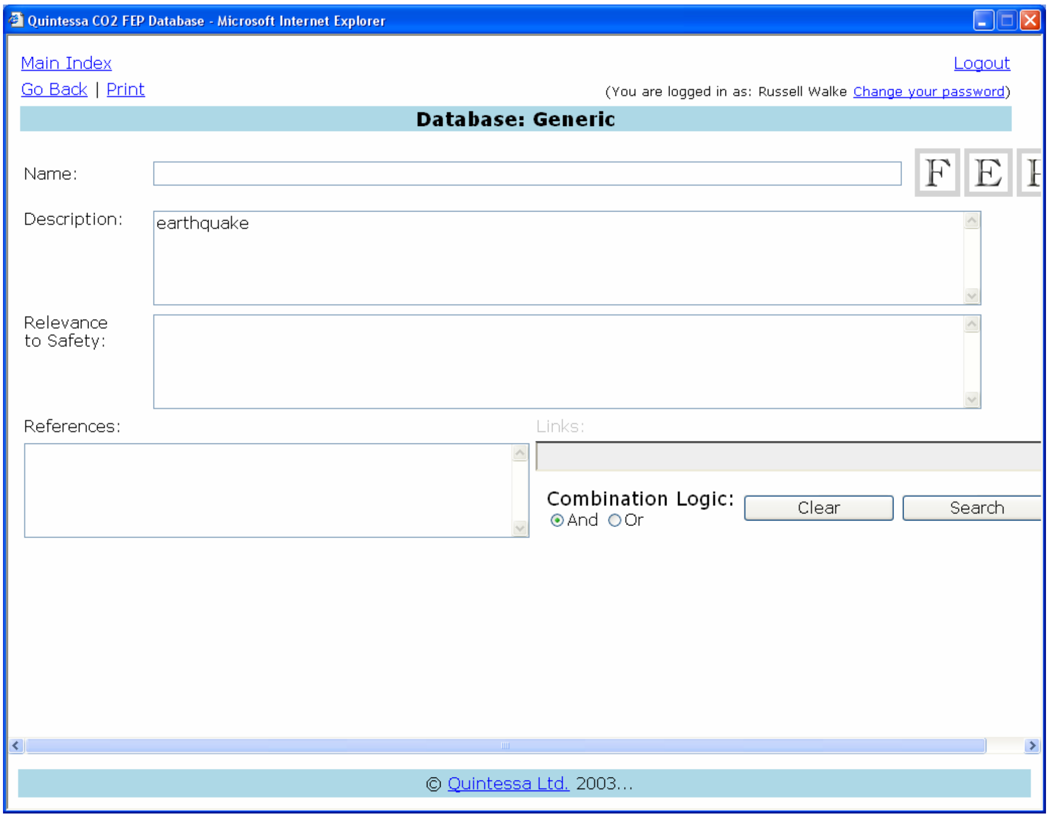


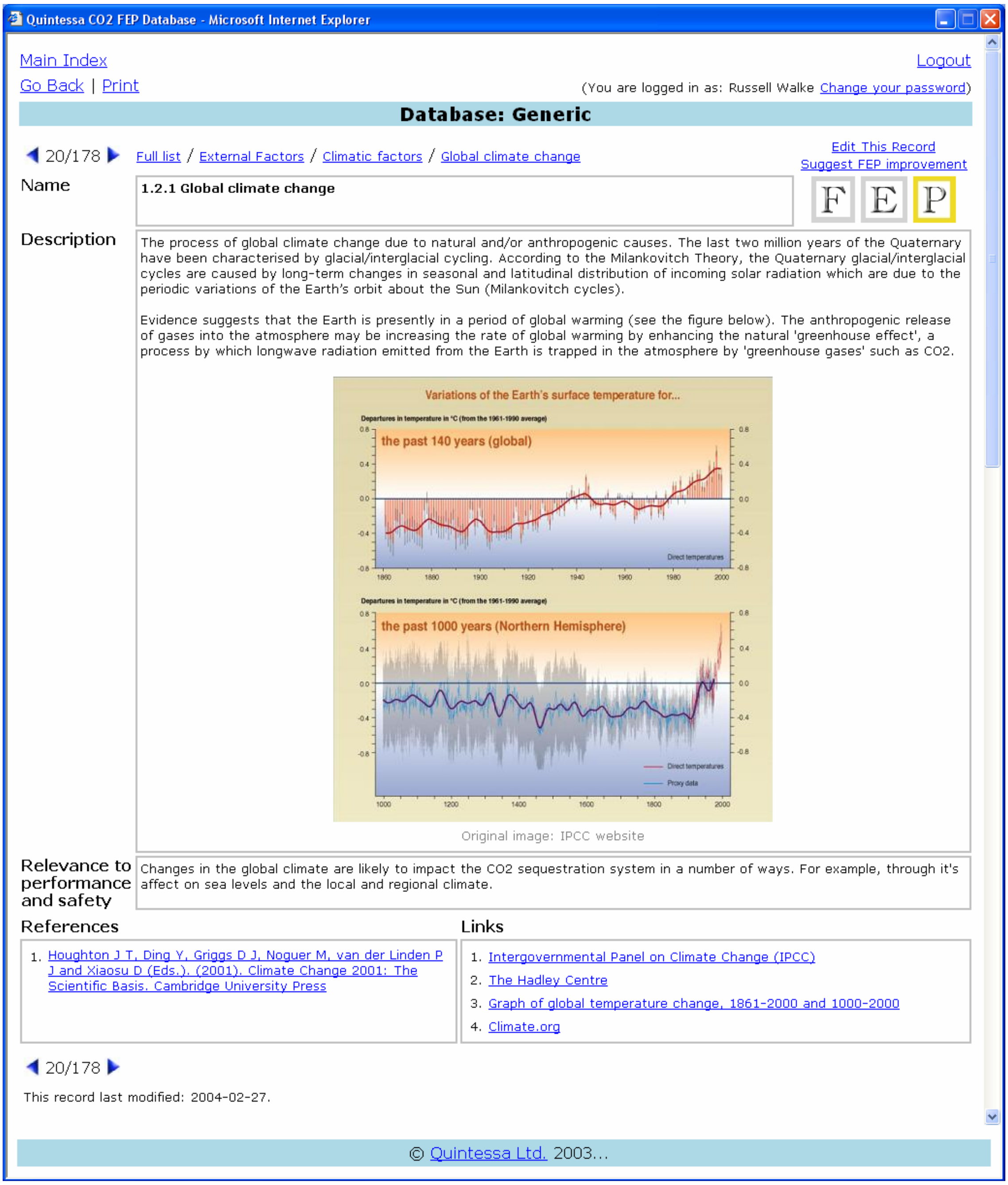
Figure 6: Results from a database search.

3.3 Database Structure and Content

For each FEP in the database a description is provided, together with a discussion of its relevance to the long-term safety and performance of the system. Further information is provided in the form of relevant publications and websites. Taken as whole, the database therefore provides a centralised source of information on relevant technical and scientific considerations relating to the long-term geological storage of carbon dioxide, and can be used as part of systemic assessments of safety and performance. Figure 7 gives an example FEP entry. For each FEP entry there are fields for the FEP name, its description, its relevance to performance and safety issues, and references and links. To the right of the FEP name its categorisation as a Feature (F), Event (E) or Process (P) is provided. The example FEP shown in Figure 7 is a Process (P), but some FEPs can be defined as more than one type of factor.

The database has a hierarchical structure with FEPs being grouped into categories and classes with an associated indexing system. Thus FEP 1.2.3 is the 3rd FEP in the second class of category 1. If required, FEPs can be further disaggregated into a fourth tier of sub-FEPs. The eight main categories of FEPs are described in the following sections.

Figure 7: An Example FEP Entry.



3.4 The Assessment Basis

The Assessment Basis category of FEPs corresponds to the factors involved in characterising the 'boundary conditions' for any assessment, specifying what needs to be assessed and why. Clear understanding and definition of the Assessment Basis helps to determine which FEPs need to be considered in the systems analysis and which can be 'screened out' as outside the scope of the assessment.

The FEP classes in this category are:

FEP class	Description
0.1	Purpose of the assessment
0.2	Endpoints of interest
0.3	Spatial domain of interest
0.4	Timescales of interest
0.5	Sequestration assumptions
0.6	Future human action assumptions
0.7	Legal and regulatory framework
0.8	Model and data issues

This category is not typical of the other FEP categories because it only contains classes of FEP, no actual FEPs. In effect, these FEP classes provide the context in which the FEPs described in other categories can be assessed for their relevance to the assessment being undertaken.

Most of the FEP class descriptions within this category are sufficient to define what information needs to be to be given in a specific assessment, but a few examples in what follows serve to illustrate the type of issue that needs to be addressed.

The overall storage concept needs to be specified under FEP class 0.5, 'Sequestration Assumptions'. Any concept will have at least three components: the environment in which sequestration takes place (terrestrial or marine); the reservoir into which the CO_2 is pumped; and the sealing formations that prevent the CO_2 from migrating rapidly back to the accessible environment.

Although the necessary timescales for containment in order to contribute effectively to the mitigation of climate change may be only a few hundred years, the 'Timescales of Interest' (FEP class 0.4) in relation to potential long-term safety considerations for humans or the environment may be up to tens of thousands of years. These very long timescales are one of the reasons why it is important to consider scenarios for the long-term evolution of the system. A wide variety of potential impacts may be relevant, and these are considered in detail in Category 7 of the database.

3.5 External Factors

The 'External Factors' category of FEPs describes phenomena relating to natural or human factors that may influence long-term safety and performance but are considered to lie outside the System Domain that is represented in the systems models. These external FEPs (or EFEPs) are important in determining scenarios for the future evolution of the system, as discussed in Section 4.

This category includes three classes of FEP:

- Geological Factors;
- Climatic Factors; and
- Future Human Actions.

3.5.1 Geological Factors

The 'Geological Factors' class includes natural geological processes and events in the environment outside the system domain that are relevant to the evolution of the sequestration system.

The current contents of this class are as follows:

FEP number	Description
1.1.1	Neotectonics
1.1.2	Volcanic and magmatic activity
1.1.3	Seismicity
1.1.4	Hydrothermal activity
1.1.5	Hydrological and hydrogeological response to geological changes
1.1.6	Large scale erosion
1.1.7	Bolide impact

Figure 8 provides an example of one of the FEPs in this class: 'Volcanic and Magmatic Activity'. As stated in the FEP entry, processes and events of this type are potentially relevant to safety and performance assessment because they can directly affect the evolution of the geology of the sequestration system in regions such as Japan.

Figure 8: The Volcanic and Magmatic Activity FEP.

In regions that are not subject to processes that can lead to major changes in the geology, seismicity is likely to be the most important EFEP in this class (see the discussion in Section 4.1.2).

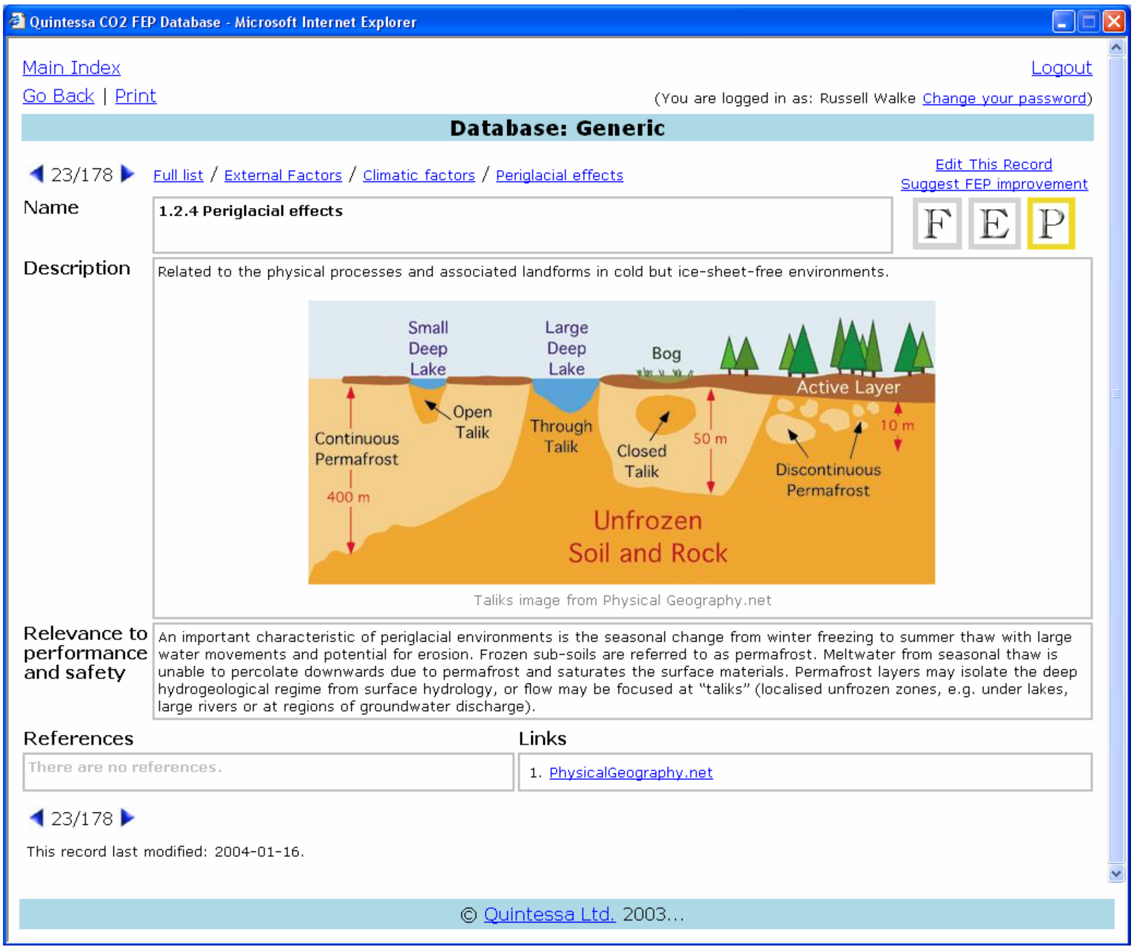
3.5.2 Climatic Factors

The 'Climatic Factors' class includes natural processes and events in the atmospheric environment that are relevant to the evolution of the sequestration system. The current contents of this class are as follows:

FEP number	Description
1.2.1	Global climate change
1.2.2	Regional and local climate change
1.2.3	Sea level change
1.2.4	Periglacial effects
1.2.5	Glacial and ice sheet effects
1.2.6	Warm climate effects
1.2.7	Hydrological and hydrogeological response to climate change
1.2.8	Responses to climate change

The global climate change FEP entry is shown in Figure 7. Climatic effects can result in significant modification to the accessible environment which, in turn, can affect both how CO_2 may be transported and the impacts that may be relevant. For example, Figure 9 shows the database entry for 'Periglacial Effects'. As shown in the illustration, taliks (unfrozen regions in the periglacial environment) may form that will affect patterns of groundwater discharge and hence, potential pathways for the return of CO_2 to the surface. The impacts that may be of concern in this type of environment may be very different from those of concern in a temperate climate.

Figure 9: The Periglacial Effects FEP.



3.5.3 Future Human Actions

The 'Future Human Actions' class of external factors includes human activities that are relevant to the evolution of the sequestration system. The current contents of this class are as follows:

FEP number	Description
1.3.1	Human influences on climate
1.3.2	Motivation and knowledge issues
1.3.3	Social and institutional developments
1.3.4	Technological developments
1.3.5	Drilling activities
1.3.6	Mining and other underground activities
1.3.7	Human activities in the surface environment
1.3.8	Water management
1.3.9	CO_2 presence influencing future operations
1.3.10	Explosions and crashes

As discussed in Section 4.1.1 participants in the Weyburn project considered that human activities are likely to be the most important factors in resulting in failure to contain CO_2 in the storage reservoir and its subsequent return to the accessible environment. A very wide range of such activities can be envisaged, and the current list of FEPs in this class is by no means comprehensive.

One aspect of FEP 1.3.2 ('Motivation and knowledge issues') concerns the assumptions that should be made in a safety and performance assessment about societal memory of CO_2 storage. In the field of radioactive waste disposal it is often assumed that institutional controls can be relied upon to prevent inadvertent intrusion into a radioactive waste disposal facility for periods up to a few hundred years. There is, however, plenty of experience with the location of abandoned wells of various types being 'forgotten' over much shorter periods. If knowledge of the CO_2 sequestration is lost, it is clearly possible that new boreholes might inadvertently be drilled into the CO_2 reservoir/aquifer. The probability that this will happen is difficult to determine, but will depend on understanding of the potential resources that may be present in the geological environment. Factors associated with boreholes are considered in Section 3.9.

3.6 Carbon Dioxide Storage

The CO_2 Storage category of FEPs specifies details of the pre- and post-closure sequestration concept under consideration.

There are just two classes of FEPs in this category:

2.1 Pre-closure; and

2.2 Post-closure.

The pre-closure class of FEPs currently contains the following FEPs:

FEP number	Description
2.1.1	Storage Concept
2.1.2	CO_2 quantities, injection rate
2.1.3	CO_2 composition
2.1.4	Microbiological contamination
2.1.5	Schedule and planning
2.1.6	Pre-closure administrative control
2.1.7	Pre-closure monitoring of storage
2.1.8	Quality control
2.1.9	Accidents and unplanned events
2.1.10	Overpressuring

There are different types of sequestration concept (FEP 2.1.1). In some concepts, a structural closure for the CO_2 is present, (for example an anticlinal or dome structure in oil and gas fields), but in others (such as saline aquifers), this may not be the case. The processes that are relevant to CO_2 transport, and therefore to the systems models used in an assessment, will depend upon the details of the storage concept.

One of the complicating factors for assessing the performance and safety of CO_2 sequestration is that impurities in the gas can have significant impacts on the subsequent evolution of the system and the potential impacts (FEP 2.1.3).

The post-closure class of FEPs currently contains the following FEPs:

FEP number	Description
2.2.1	Post-closure administrative control
2.2.2	Post-closure monitoring of storage
2.2.3	Records and markers
2.2.4	Reversibility
2.2.5	Remedial actions

The type of monitoring to be undertaken post-closure and the period over which this monitoring will be undertaken (FEP 2.2.2) will be an important part of any sequestration concept.

3.7 Carbon Dioxide Properties, Interactions and Transport

This category of FEPs is concerned with those that are relevant to the fate of the stored fluid. The physical and chemical properties of carbon dioxide can vary greatly between conditions at depth and near surface, and a wide range of physical and chemical reactions can be important.

There are three FEP classes in this category:

- CO_2 properties;
- CO_2 interactions; and
- CO_2 transport.

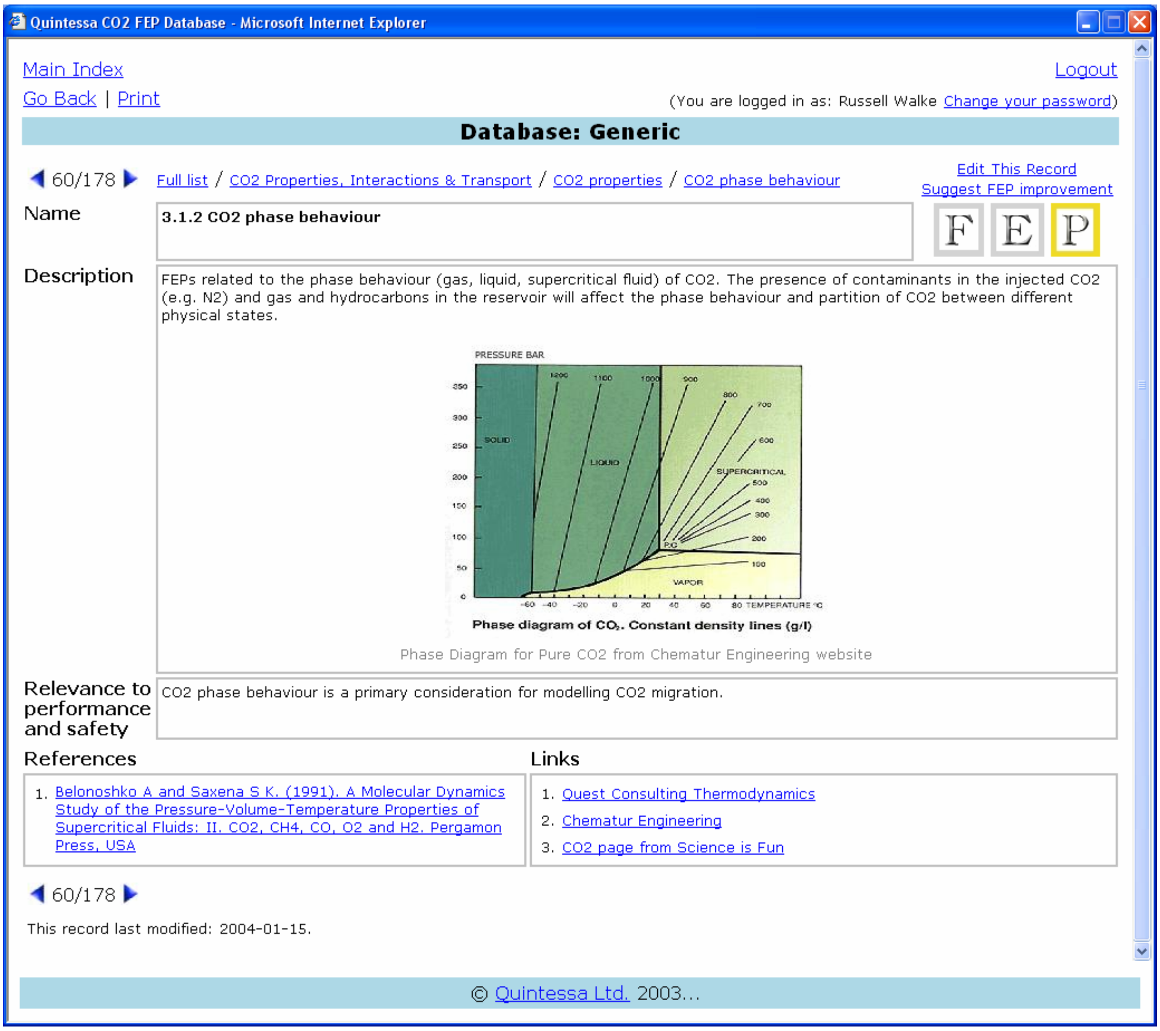
3.7.1 Carbon Dioxide Properties

The 'CO_2 properties' class currently contains the following FEPs:

FEP number	Description
3.1.1	Physical properties of CO_2
3.1.2	CO_2 phase behaviour
3.1.3	CO_2 solubility and aqueous speciation

Figure 10 shows the entry for FEP 3.1.2. The illustrated phase diagram shows the complexity of the variation of the phase and density with temperature and pressure.

Figure 10: CO_2 Phase Behaviour.



CO_2 is stored in its supercritical state, but if transport processes result in it moving towards the surface, its phase will change and this will in turn affect which transport processes are important.

3.7.2 Carbon Dioxide Interactions

The CO_2 interactions class currently contains the following FEPs:

FEP number	Description
3.2.1	Effects of pressurisation of reservoir on caprock
3.2.2	Effects of pressurisation on reservoir fluids
3.2.3	Interaction with hydrocarbons
3.2.4	Displacement of saline formation fluids
3.2.5	Mechanical processes and conditions
3.2.6	Induced seismicity
3.2.7	Subsidence or uplift
3.2.8	Thermal effects at the injection point
3.2.9	Water chemistry
3.2.10	Interaction of CO_2 with chemical barriers
3.2.11	Sorption and desorption of CO_2
3.2.12	Heavy metal release
3.2.13	Mineral phase
3.2.14	Gas chemistry
3.2.15	Gas stripping
3.2.16	Gas hydrates
3.2.17	Biogeochemistry
3.2.18	Microbial processes
3.2.19	Biomass uptake of CO_2

There is a large number of possible interactions between CO_2 and solid, liquid and gaseous materials in the geosphere, and it is not claimed that the list of FEPs in this class is comprehensive. The injection of CO_2 can lead to physical interactions in the geosphere, such as potential fracturing or stressing of the caprock/sealing formations (FEP 3.2.1) and creation of pressure gradients within the formation fluids in the reservoir/aquifer (FEP 3.2.2). Injection of CO_2 will also displace fluids within the reservoir (FEP 3.2.4), possibly inducing microseismic events (FEP 3.2.6). In extreme cases, injection of CO_2 could lead to uplift or subsidence of the local land surface (FEP 3.2.7).

Injection of CO_2 will lead to dissolution of free CO_2 into the aqueous phase (FEP 3.2.9), reducing the pH of the formation fluids and thus tending to cause mineral dissolution-precipitation reactions with reactive minerals such as carbonates or feldspars (FEPs 3.2.11, 3.2.13)

Some interaction processes can lead to the release of other substances that may be of concern in their own right. These include heavy metals (FEP 3.2.12), gas stripping of radon (FEP 3.2.15), and the displacement of saline formation fluids into potable water supplies (FEP 3.2.4). The potential impacts associated with these processes are considered in Section 3.11.

3.7.3 Carbon Dioxide Transport

The 'CO_2 transport' class currently contains the following FEPs:

FEP number	Description
3.3.1	Advection of free CO_2
3.3.2	Buoyancy-driven flow
3.3.3	Displacement of formation fluids
3.3.4	Dissolution in formation fluids
3.3.5	Water mediated transport
3.3.6	CO_2 release processes
3.3.7	Co-migration of other gases

There are a large number of FEPs that are relevant to the migration of CO_2 in the geosphere. Advection will occur through fractures as well as the bulk rock (FEP 3.3.1). Flow through fractures will depend on capillary pressures; high capillary pressures in caprocks/seals may completely prevent the vertical movement of CO_2. Flow can be initiated by buoyancy-driven forces (FEP 3.3.2).

CO_2 transport is a multi-phase problem that depends upon the properties of other fluids in the system (including groundwater and possibly other fluids such as hydrocarbons); properties such as compressibilities and wettability may be important. Dissolved CO_2 will be transported with flowing groundwater (FEP 3.3.5). Free gaseous CO_2 may be transported with other gases, particularly H_2S. This process of co-migration is covered in FEP 3.3.7.

Once CO_2 enters the near-surface environment, a number of release processes may be relevant (FEP 3.3.6); Figure 11 shows CO_2 erupting from a natural reservoir at Crystal Geyser in Utah, and Figure 12 shows gaseous discharge from a natural submarine hydrothermal vent.

Figure 11: Crystal Geyser, Utah. From Waltham (2001).

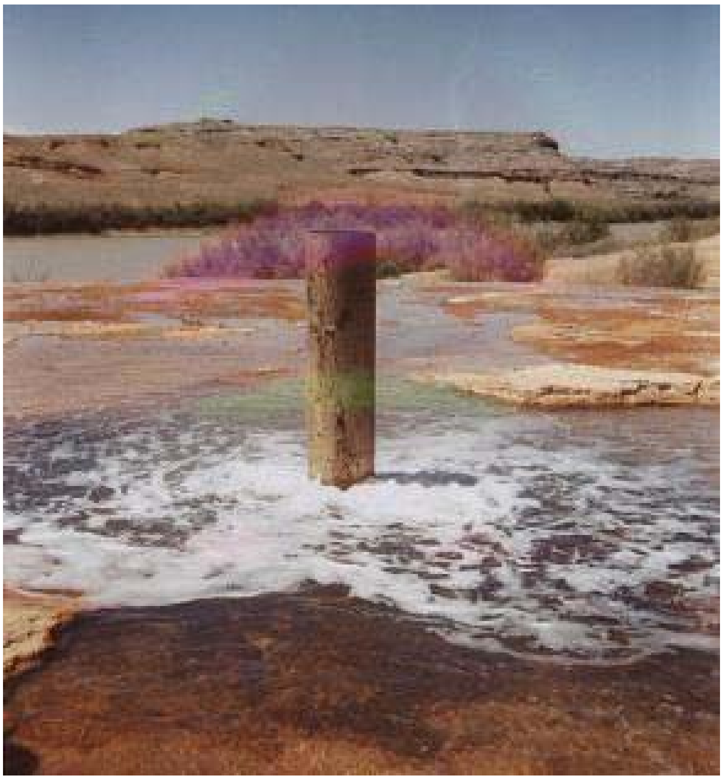
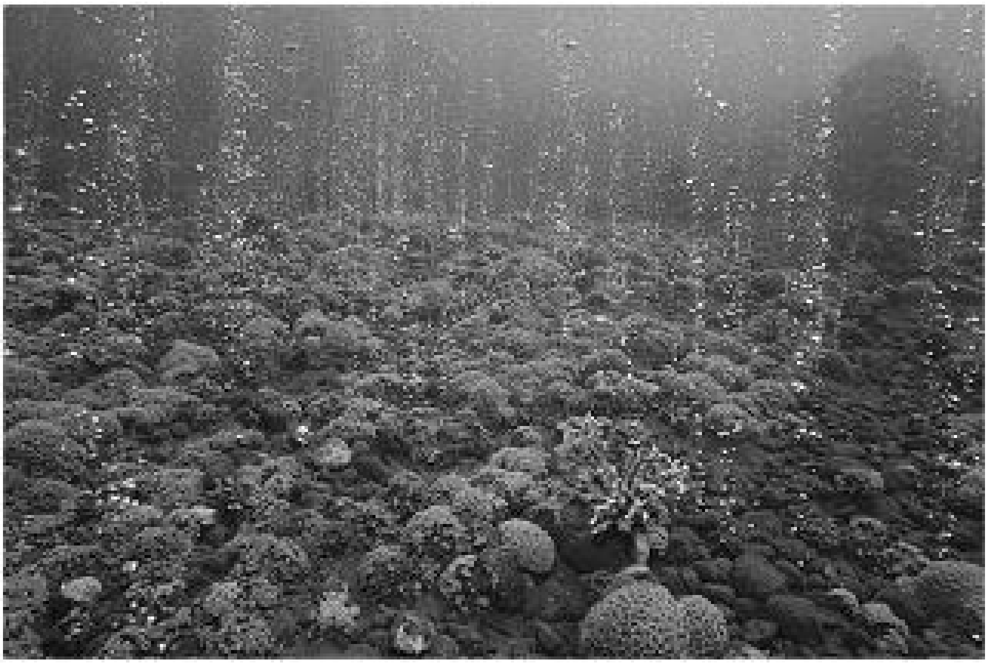


Figure 12: A submarine hydrothermal vent. From Pichler et al. (1999).



3.8 The Geosphere

The 'Geosphere' category of FEPs is concerned with the geology, hydrogeology and geochemistry of the storage system. Taken together, the FEPs in this category describe what is known about the natural system prior to injection of CO_2 commencing.

The category is divided into four classes:

4.1 Geology;

4.2 Fluids;

4.3 Geochemistry; and

4.4 Resources.

3.8.1 Geology

This class of FEPs gives details of the understanding of the geology before it is affected by storage operations. It currently contains the following FEPs:

FEP number	Description
4.1.1	Geographical location
4.1.2	Natural resources
4.1.3	Reservoir type
4.1.4	Reservoir geometry
4.1.5	Reservoir exploitation
4.1.6	Cap rock or sealing formation
4.1.7	Additional seals
4.1.8	Lithology
4.1.9	Unconformities
4.1.10	Heterogeneities
4.1.11	Faults and fractures
4.1.12	Undetected features
4.1.13	Vertical geothermal gradient
4.1.14	Formation pressure
4.1.15	Stress and mechanical properties

4.1.16	Petrophysical properties

A large number of FEPs are relevant to the description of the geology of the sequestration system. The geographical location (FEP 4.1.1) needs to be specified, and lithological and petrophysical properties of the system (porosity, permeability etc. - FEPs 4.1.8 and 4.1.16), including the reservoir into which the CO_2 is injected (FEPs 4.1.3, 4.1.4 and 4.1.5) as well as the caprock and other potential seals (FEPs 4.1.6, 4.1.7) will be central to system performance.

The injection of CO_2 may lead to the sterilisation of some natural resources (FEP 4.1.2) or the presence of resources may encourage future human intrusion (Section 3.5.3) into the storage site.

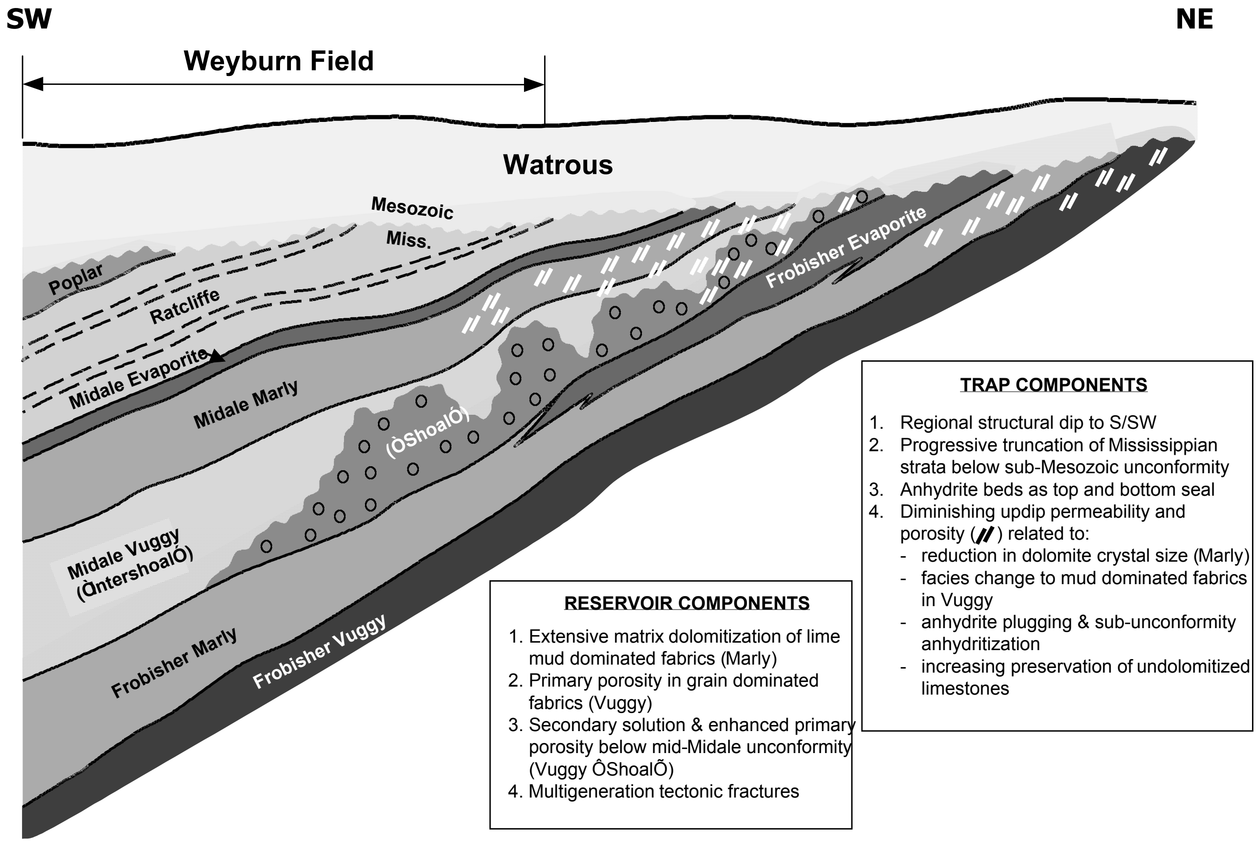
Unconformities (FEP 4.1.9), heterogeneities (FEP 4.1.10) and faults and fractures (FEP 4.1.11) may all be important in determining the potential for CO_2 transport back to the accessible environment. For example, at Weyburn (Figure 13) there is an impermeable barrier resulting from the widespread development of diagenetic anhydritized carbonate associated with the unconformity between the Mississipian beds and overlying Triassic Watrous Formation in the vicinity of the Weyburn reservoir. In any characterisation of a sequestration site, however, it is inevitable that there may be some undetected features (FEP 4.1.12) that could be relevant to CO_2 transport. This possibility needs to be considered in any assessment of performance and safety.

Although some sort of 'caprock' will generally be considered to be the primary seal for retaining CO_2 in the reservoir, additional seals (FEP 4.1.7) may be part of the sequestration concept, and these can be important for keeping CO_2 away from the accessible environment over long timescales.

The vertical geothermal gradient and formation pressure (FEP 4.1.13 and 4.1.14) can vary significantly from place-to-place. For example, the geothermal gradient is typically 0.025 °C m^{-1} (e.g. Holloway, 1996), although significant local variations are possible. These quantities are important because of the variation of fluid properties with temperature and pressure.

The initial stress field (FEP 4.1.15) is relevant to determining how the system will respond to changes in pressure arising from the injection of CO_2 (see Section 3.7.2).

Figure 13: Stratigraphic Section at Weyburn. From Whittaker and Rostron (2001).



3.8.2 Fluids

This class of FEPs is concerned with details of fluids present within the natural system. Water will be present, but other fluids, particularly hydrocarbons (FEP 4.2.3), may be important, dependent on the storage concept.

This class currently contains the following FEPs:

FEP number	Description
4.2.1	Fluid properties
4.2.2	Hydrogeology
4.2.3	Hydrocarbons

The fluid properties FEP (FEP 4.2.1) would include density, viscosity etc. which are essential to the understanding of fluid behaviour and migration.

The hydrogeology of the geosphere (FEP 4.2.2) affects the flowpaths of all fluids in the system.

3.9 Boreholes

The 'Boreholes' category of FEPs is concerned with the way that activities carried out by humans can alter the natural system. Both the boreholes used in the sequestration operations and those drilled for other purposes (in the past and in the future) are relevant to the long-term performance of the system.

There are just two classes of FEP in this category:

5.1 Drilling and completion; and

5.2 Borehole seals and abandonment.

3.9.1 Drilling and completion

FEP number	Description
5.1.1	Formation damage
5.1.2	Well lining and completion
5.1.3	Workover
5.1.4	Monitoring wells
5.1.5	Well records

The drilling of CO_2 monitoring and injection wells may directly modify the geology through formation damage (FEP 5.1.1). Records of wells provide an important input to society's knowledge of the injection system, but in general records will be incomplete or totally absent, particularly for old wells (FEP 5.1.5). Monitoring wells (FEP 5.1.4) can provide useful information before, during, and after sequestration operations, but may also provide an accidental leakage route for the stored CO_2.

The way in which a well has been lined or completed (FEP 5.1.2) may affect its potential as a leakage pathway. The workover of wells (FEP 5.1.3) may also affect the nature of well completions and the potential for wells to act as fast pathways.

3.9.2 Borehole Seals and Abandonment

Once operations have been completed on a borehole (whether for injection or any other purpose), it will be sealed and completed (FEP 5.2.1). Such boreholes provide the potential for 'short circuits' for CO_2 back to the accessible environment. The FEPs identified with this class are as follows:

FEP number	Description
5.2.1	Closure and sealing of boreholes
5.2.2	Seal failure
5.2.3	Blowouts
5.2.4	Orphan wells
5.2.5	Soil creep around boreholes

The way that the borehole is closed to prevent human access (FEP 5.2.1) affects the period for which the borehole can be considered to be effectively 'sealed'. Eventually, however, seal failure may occur (FEP 5.2.2). A surface blow-out (FEP 5.2.3) is an uncontrolled flow from depth leading to gas and/or fluid erupting from a well or borehole.

3.10 The Near-Surface Environment

The 'Near-Surface Environment' category of FEPs is concerned with factors that can be important if sequestered carbon dioxide returns to the accessible environment. The environment could be terrestrial or marine, and assumptions about human behaviour in that environment need to be described.

There are three classes of FEP in this category:

6.1 Terrestrial environment;

6.2 Marine environment; and

6.3 Human behaviour.

3.10.1 Terrestrial Environment

The FEPs below are relevant to the description of the near-surface environment if CO_2 returns to a terrestrial environment:

FEP number	Description
6.1.1	Topography and morphology
6.1.2	Soils and sediments
6.1.3	Erosion and deposition
6.1.4	Atmosphere and meteorology
6.1.5	Hydrological regime and water balance
6.1.6	Near-surface aquifers and surface water bodies
6.1.7	Terrestrial flora and fauna
6.1.8	Terrestrial ecological systems

Near-surface aquifers and surface water bodies (FEP 6.1.6) and the near-surface hydrological regime and water balance (FEP 6.1.5) will affect the transport and dispersion of CO_2 in the near-surface environment as well as the potentially important impacts of any release.

The main features of the near-surface environment (FEPs 6.1.1, 6.1.2, 6.1.4, 6.1.5, 6.1.6, 6.1.7 and 6.1.8) need to be known when potential impacts are to be investigated. The influence of ongoing surface erosion and/or deposition on the present day environment (FEP 6.1.3) can affect these impacts.

If CO_2 is released to the atmosphere, the atmospheric concentrations (and hence potential impacts) will depend upon the atmospheric conditions and meteorology (FEP 6.1.4) and the surface topography (FEP 6.1.1). CO_2 gas is denser than air and can therefore 'pond' in surface depressions.

3.10.2 Marine Environment

The FEPs below are relevant to the description of the near-surface environment if CO_2 returns to a marine environment:

FEP number	Description
6.2.1	Coastal features
6.2.2	Local oceanography
6.2.3	Marine sediments
6.2.4	Marine flora and fauna
6.2.5	Marine ecological systems

For each of these FEPs, which are relevant to the description of the migration, dispersion and impacts of released CO_2, there is an analogous FEP for the terrestrial environment.

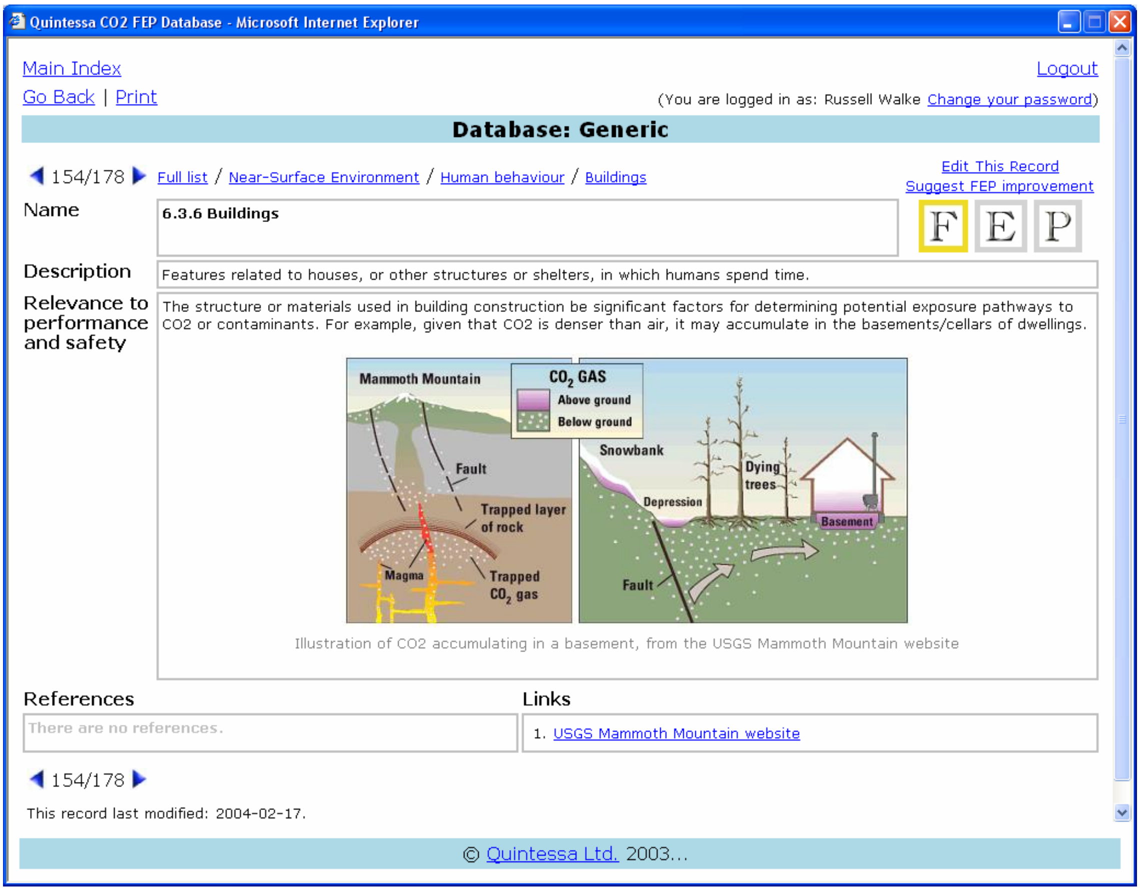
3.10.3 Human Behaviour

This class of FEPs is concerned with the behaviour of humans in the near-surface environment:

FEP number	Description
6.3.1	Human characteristics
6.3.2	Diet and food processing
6.3.3	Lifestyles
6.3.4	Land and water use
6.3.5	Community characteristics
6.3.6	Buildings

The characteristics of human population groups in the region where impacts may be incurred (FEPs 6.3.1 and 6.3.5) will affect the magnitude of those impacts. Factors that need to be considered include land and water use (FEP 6.3.4), buildings (FEP 6.3.6), diet and food processing (FEP 6.3.2), and general lifestyles (FEP 6.3.3). As shown in the database entry for FEP 6.3.6 (Figure 14), the way that buildings are constructed can be important for determining the type of impacts that may be incurred. Radon may be transported with CO_2 gas, and both may accumulate in basements.

Figure 14: Database Entry for the Buildings FEP.



3.11 Impacts

The Impacts category of FEPs is concerned with any endpoint that could be of interest in an assessment of performance and safety. Impacts could be to humans, flora and fauna, or the physical environment.

There are four FEP classes in this category:

7.1 System performance;

7.2 Impacts on the physical environment;

7.3 Impacts on flora and fauna; and

7.4 Impacts on humans.

3.11.1 System performance

There is currently only one potential impact on system performance included in the FEP database:

FEP number	Description
7.1.1	Loss of containment

The potential for loss of containment could be relevant to the establishment and confirmation of carbon credits resulting from the geological storage of carbon dioxide and would thus impact upon system performance (as opposed to safety).

3.11.2 Impacts on the Physical Environment

The current list of potential impacts on the physical environment is:

FEP number	Description
7.2.1	Contamination of groundwater
7.2.2	Impacts on soils and sediments
7.2.3	Release to the atmosphere
7.2.4	Impacts on exploitation of natural resources
7.2.5	Modified hydrology and hydrogeology
7.2.6	Modified geochemistry
7.2.7	Modified seismicity
7.2.8	Modified surface topography

Modification or contamination of different parts of the environment, both within the accessible environment and at depth (FEPs 7.2.1 to 7.2.8), may be viewed as impacts in their own right, even if they do not lead to significant impacts for flora, fauna or humans.

CO_2 injection can lead to microseismic events (FEP 7.2.7). Interaction of the CO_2 with sub-surface strata can lead to either subsidence or uplift (FEP 7.2.8).

The injection of CO_2 may affect the ease with which sub-surface resources can be exploited (FEP 7.2.4), and so this must also be regarded as a potential impact (see also FEP 4.1.2).

3.11.3 Impacts on Flora and Fauna

The current list of potential impacts on the flora and fauna is:

FEP number	Description
7.3.1	Asphyxiation effects
7.3.2	Effect of CO_2 on plants and algae
7.3.3	Ecotoxicology of contaminants
7.3.4	Ecological effects
7.3.5	Modification of microbiological systems

Released CO_2 can affect individual plants and animals directly (FEPs 7.3.2 and 7.3.1), and can modify microbiological systems at depth (FEP 7.3.5) as well as the near-surface ecology (FEP 7.3.4). In addition, other contaminants that become mobilised by CO_2 interactions (see FEP class 3.2) can themselves have ecological impacts (FEP 7.3.3).

3.11.4 Impacts on Humans

The current list of potential impacts on humans is:

FEP number	Description
7.4.1	Health effects of CO_2
7.4.2	Toxicity of contaminants
7.4.3	Impacts from physical disruption
7.4.4	Impacts from ecological modification

Humans can be asphyxiated if the concentration of CO_2 in air is as little as 5 % (FEP 7.4.1). Less direct impacts can occur as a result of contaminant mobilisation, for example leading to contamination of drinking water supplies (FEP 7.4.2), physical disruption, for example from induced seismic events (FEP 7.4.3), or to changes in the ecology (FEP 7.4.4).

3.12 Database Status and Future Applications

Like the NEA database (NEA/OECD, 2000), the CO_2 FEP database can be used as an audit tool to evaluate the completeness of performance assessment models. An example is given in Section 5.3 to illustrate this process.

The database has potentially wider applicability beyond specialised application in support of assessment modelling, for example as a 'knowledge base' for the geological storage of CO_2. Information can be retrieved using the database's search facilities. The database may also be linked to project-specific databases, providing a capability to demonstrate how generically-important FEPs identified here are represented in a specific assessment: this is termed 'FEP mapping'.

The FEP database produced in the present project must be seen as a preliminary version. In order for the full potential of this tool to be realised it needs to be further extended and maintained.

4 Scenarios and Interaction Matrices

4.1 EFEPs and Scenarios

Scenarios for long-term assessment were considered at a Workshop held jointly with the EC Nascent project team in Orléans in March 2003. Important external events and processes (EFEPs) were identified, which fed into the selection of EFEPs for the database (Section 3.5). The identified scenarios can be considered to be of two types: human interventions; and natural events.

4.1.1 Human Actions

During the Orléans workshop, it was generally considered that human actions (rather than natural events and processes) would be the most likely cause of rapid return of stored CO_2 to the accessible environment. A wide range of possibly relevant human activities was identified, including:

- future onshore drilling for resources such as potable water supplies;
- poor record keeping of geologically stored CO_2, leading to leakage via inadvertent drilling into pressured reservoirs;
- mining of evaporite resources by dissolution - this may cause subsurface geological conditions to change, which may lead to the rupturing of caprock seals;
- injection of additional CO_2 (leading to overpressurisation and caprock failure);
- large scale construction projects, such as a dam, could lead to fault movements; and
- future exploitation of carbon/CO_2 resources.

4.1.2 Natural EFEPs

The most important natural event is considered to be seismicity. This could cause the reactivation of old faults or produce new ones, which could in turn give rise to preferential pathways for CO_2 release. Other potentially important natural EFEPs include:

- geological uplift, resulting in a change in sea level;

- erosion of the overlying geological formations;
- glaciation leading to compression/rebound and changes in aquifer flow directions; and
- micro-fracturing from subsidence.

A number of low probability events such as meteorite impact were also identified.

4.1.3 Conclusions

A large number of EFEPs are potentially important over the timescales of relevance to safety and performance assessments for geological storage of CO_2. The EFEPs considered at the Orléans workshop have been included in the FEP database (Section 3), but it is likely that additional EFEPs could be added based on future evaluations. The EFEPs that actually need to be considered in defining assessment scenarios for any particular sequestration system will be determined by site-specific considerations; a different set of EFEPs will be relevant, for example, for a marine environment compared with a terrestrial environment.

Perhaps the most important outcome of the Orléans discussions was the identification of a wide range of human activities that could adversely affect the performance of the storage system. The significance of these potential actions will depend on the context of the assessment, and particularly the timescales of interest. Some sites could be chosen where the likelihood of disturbance resulting from such actions is very low for many years. However, on very long timescales it may be difficult to rule these out.

4.2 Interaction Matrices and Conceptual Models for CO_2 Transport

At the Orléans workshop, illustrative interaction matrices were produced to demonstrate how these could be used to describe conceptual models for CO_2 transport for a specified scenario. An example is shown here for an over-pressuring scenario, caused by additional CO_2 being injected into the reservoir.

In this example, CO_2 storage takes place in an offshore aquifer. Wells are plugged and sealed according to design specifications. Because of the over-pressurisation, leakage occurs beyond structural spill-points and CO_2 migrates laterally to an onshore aquifer, resulting in acidification of this aquifer and contamination of water in water supply boreholes.

A transition zone is considered between the offshore and onshore aquifers, this is designated the 'transfer aquifer' in Figure 15.

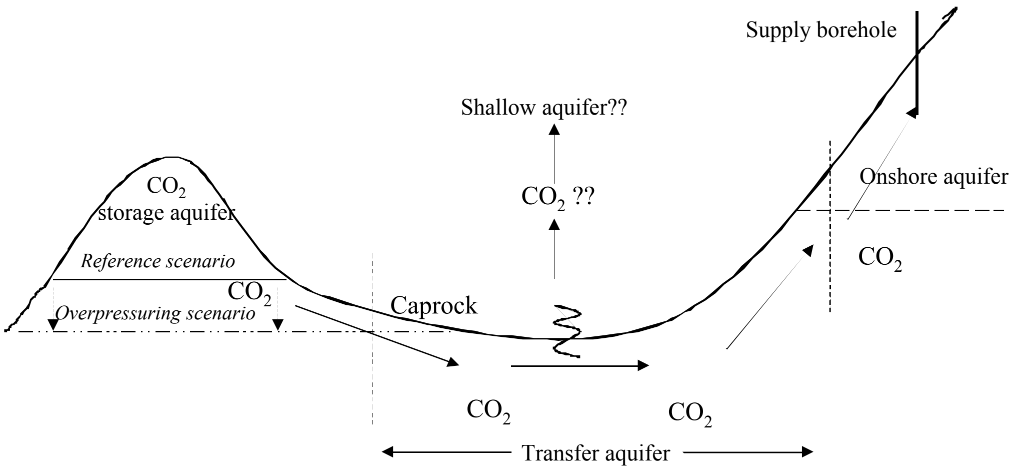


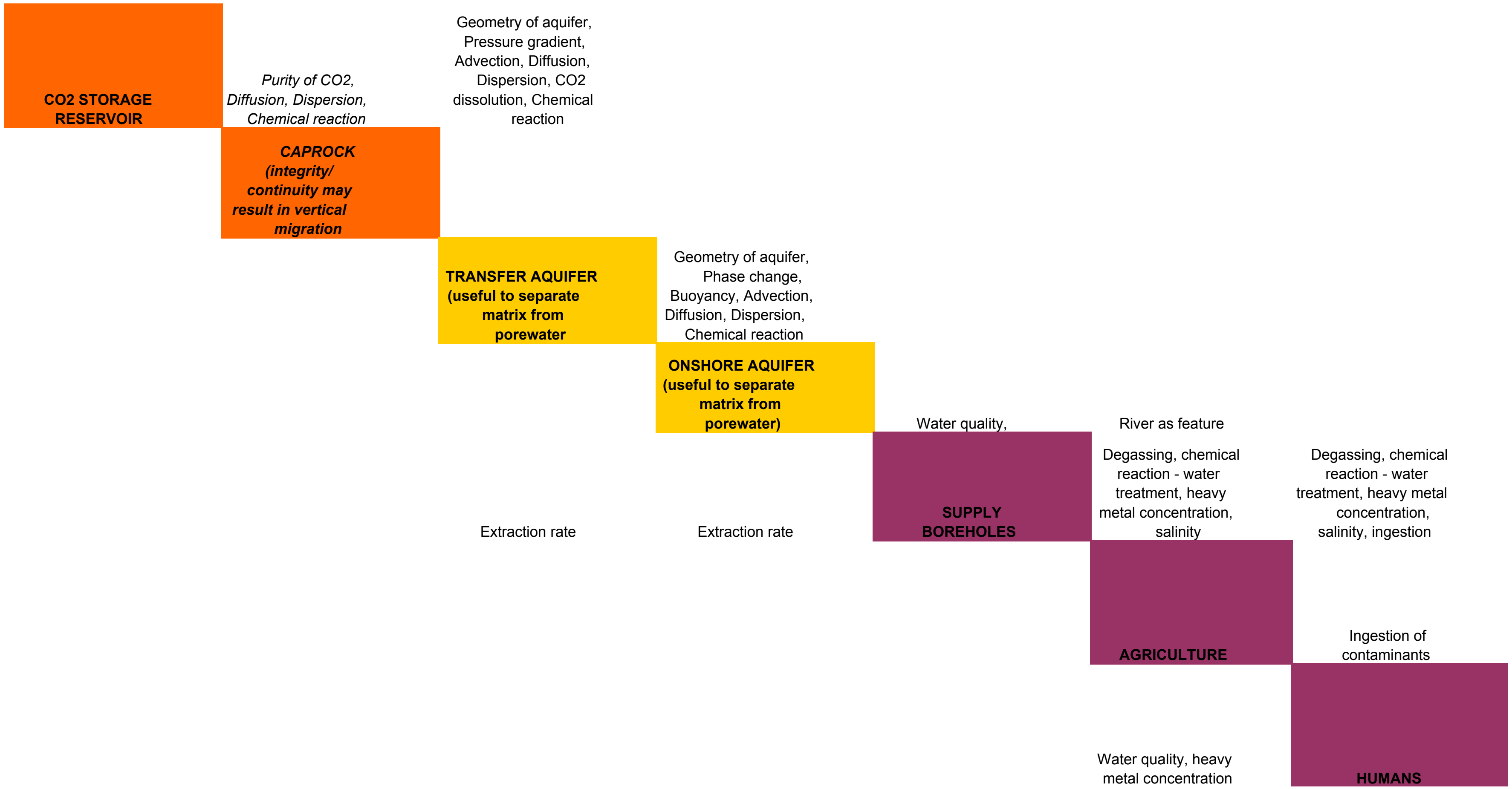
Figure 15: The over-pressurising scenario.

The interaction matrix that was developed for this conceptual model is shown in Figure 16. The caprock is included as a leading diagonal element (LDE) in the matrix, although the dominant migration path is assumed to be from the storage resevoir via the transfer aquifer to the onshore aquifer. Agriculture was included as an LDE to allow for the possibility that boreholes might be used as the source of irrigation water for crops.

In terms of interactions displayed on Figure 16, 'heavy metal concentration' reflects the possibility of heavy metal release from mineral surfaces by desorption or by mineral dissolution, under modified water chemistry conditions (modified by CO_2). This, in turn, could result in the ingestion of contaminants via the agricultural-food pathway. 'Chemical reaction – water treatment' was included to cover the possible existence of a water treatment plant as an intermediate component between water supply boreholes and agriculture and/or human consumption (strictly a main-diagonal component). Similarly, the existence of a river as a feature and subsequent water extraction for agriculture was acknowledged.

Note that the interactions shown in Figure 16 include system FEPs that describe influences other than those that occur along the CO_2 migration pathway. These include an 'extraction rate' from the water supply boreholes, which will affect the rate of flow of groundwater and, hence, CO_2 migration from the offshore aquifer. Also, humans have the capability of improving water quality (water treatment) prior to water use for agriculture; hence ‘Water quality, heavy metal concentration’.

Figure 16: Interaction Matrix for the over-pressurising scenario.



5 Systems-Level Modelling

5.1 Introduction

Having identified potential impacts on the environment and human health associated with releases of CO_2 from the storage reservoir (see Section 3.11), it is necessary to quantify the potential consequences of these impacts and the likelihood that they may be incurred. Because of the extensive experience in reservoir modelling within the oil and gas industry, many groups involved with assessment of the long-term fate of CO_2 have used detailed reservoir simulation models to investigate the transport of CO_2 both in the short-term injection phase and the longer-term 'post closure' phase. A good example of such work is Ennis-King and Paterson (2003). Such studies attempt to represent in detail the multiphase transport nature of the problem, but do not address the consequences of potential releases from the system. In the field of radioactive waste disposal these studies are analogous to the detailed flow and transport models that support so-called 'performance assessment' (PA) systems models.

There have been a number of studies that attempt to address the consequences of release of CO_2 from the disposal system. A good example of such a study is Saripalli et al. (2003). These studies consider the various end points of interest, but make simplifying assumptions about the 'source term' (i.e. the location, localisation, magnitude, and timing of the release within the accessible environment). Such studies can be compared with some biosphere models developed in the field of radioactive waste disposal.

The development of models for the whole system for the geological storage of CO_2 is at an early stage. Many of the advances made in the last twenty years in the field of safety assessments for the geological disposal of radioactive wastes can be applied to CO_2 storage. As is the case for CO_2 storage, a comprehensive appraisal of safety performance for the disposal of radioactive wastes requires an understanding of complex coupled physical-chemical-mechanical processes occurring over thousands to tens of thousands of years.

'Scenarios' or 'representative futures' have been discussed in Section 4.1. It is not necessary, or indeed possible, to describe all possible scenarios in order to develop a comprehensive safety case. However, the consideration of a set of assessment scenarios should provide an adequately robust test of performance and safety by addressing the most likely possible evolutions of the system together with less likely futures that exhibit features of possible concern.

Modelling the transport of CO_2 and the resulting impacts for a given scenario, as part of a systems-level assessment, requires consideration to be given to all the important FEPs, but it is not generally possible (or necessary) to include a detailed representation of all of them. For example, fluid flow may be treated in a fairly simple manner within the systems analysis (possibly in just one dimension), but this will use information derived from more detailed (three-dimensional) models. The representation of CO_2 transport in the deep geosphere part of the system can use information from reservoir simulation models.

However, there are some important technical challenges for CO_2 systems-level modelling. Firstly, the properties of CO_2 are very different in different parts of the system and its density and viscosity are complex functions of temperature and pressure (see Section 3.7). Secondly, unlike radionuclides in assessment models for radioactive waste disposal, CO_2 is not a 'trace' contaminant, so that the storage of large volumes of CO_2 at elevated pressure can directly affect the evolution of the system into which it is injected. Examples of possible CO_2-induced processes are micro-seismicity and subsidence due to dissolution (for example in carbonate aquifers). Lastly, the potential impacts resulting from CO_2 transport to the accessible environment may depend critically on the location of the release and the area within which that release occurs; impacts for a given total flux to the surface may vary from insignificant to immediate loss of life depending upon the detailed characteristics of the release.

The treatment of uncertainty

A key question for any systems-level model is the treatment of uncertainty. One of the main reasons for developing such a model is to provide a better understanding of the main features of the system that determine overall safety as well as the level of uncertainty in the calculated impacts resulting from uncertainties in model parameters. The use of probabilistic methods is widespread in environmental assessment. Here, uncertainties in model input parameters are represented by probability density functions (PDFs), and these enable a PDF for the estimated impacts to be produced. Probabilistic techniques can be very powerful in identifying the key sensitivities in the model, but can lead to misleading conclusions about overall risks if they are not used carefully.

One of the most difficult and controversial issues is the treatment of future human actions (see Sections 3.5.3 and 4.1.1). How likely is it that at some time in the future humans may drill inadvertently into the CO_2 storage reservoir? If drilling takes place within the region where CO_2 has been stored, will those involved know about the presence of the CO_2 beforehand? If not, what could the consequences be? Systems-level models can help to assess the possible consequences of future human actions, but cannot resolve some of the fundamental difficulties associated with making assumptions about human behaviour far into the future.

Timescales of relevance

The timescales over which a systems-level assessment should be performed will depend upon the context of the assessments and the impacts that are of concern. The assessment timescales influence the processes that must be considered in the assessment; different processes may be important over different timescales.

In general terms, there are two timescales of interest for geological storage of carbon dioxide. Firstly, there is that over which isolation of carbon dioxide from the atmosphere is necessary to mitigate climate change. Current views, taking into account various carbon dioxide emission scenarios, is that this timescale is of the order of a few hundred years at most (e.g. Lindeberg, 2003). The second timescale of interest is potentially much longer and is that pertaining to the assessment of potential impacts on human health and the environment. This timescale could be in the order of thousands to tens of thousands of years.

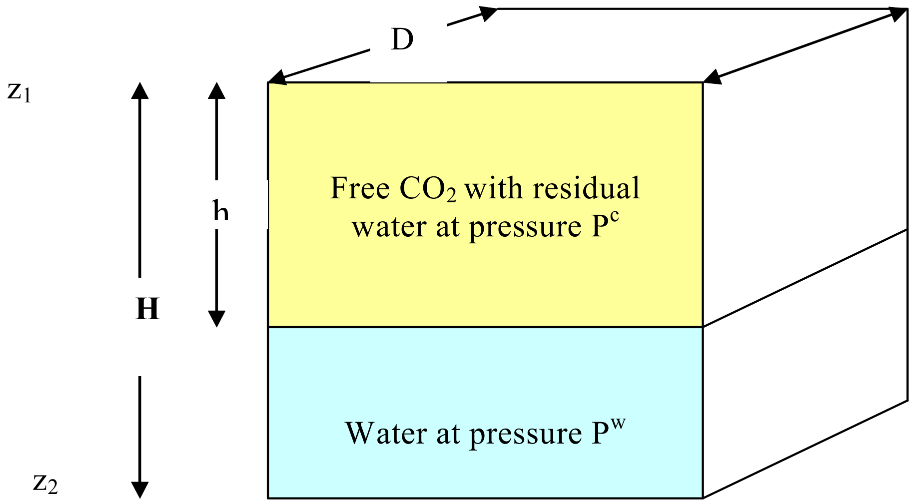
Performance and safety studies for the geological storage of CO_2 are unusual in that they need to consider the evolution of natural systems over timescales considerably in excess of those considered in typical engineering projects. Most environmental assessments address periods of tens, or occasionally hundreds, of years. For radioactive waste disposal, the long half-lives of some radionuclides play a part in defining the assessment timescales, but a recent review by the NEA/OECD (2002) emphasised that long assessment timescales (up to a million years) need to be considered because: (a) well-sited and well-designed geological disposal facilities imply that radionuclide releases to the biosphere are likely to take place only very far into the future; and (b) ethical considerations mean that the same level of environmental protection should be applied in the future as today. The NEA/OECD (2002) also indicated that that the importance attached to quantitative calculations of impacts and risk as part of an overall appraisal of the safety performance of a disposal system should decrease with time as a consequence of the uncertainty associated with the evolution of the natural system. These arguments may also be relevant to assessments for the geological storage of CO_2.

5.2 A Representative Conceptual Model

In order to make the discussion of how the FEP database can be used with systems-level models more concrete, a simple representative systems-level conceptual model is considered here.

The system to be modelled is conceptualised as a number of compartments with the following characteristics:

Figure 17: A model compartment.



1. Each compartment is related to an associated environmental medium (e.g. host rock, cap rock, soil etc.) so that processes can be linked to phenomena occurring within a given compartment type or between specified compartment types.

2. Wells are represented either directly (as one or more compartments) or indirectly (through their effects on other compartment properties).

3. The 'internal' processes within compartments include: porosity variations with pressure; dissolution of CO_2 into water; variation of CO_2 properties with pressure and temperature; and dissolution and precipitation reactions (and resulting variations in porosity).

4. Transfer processes between neighbouring compartments include the transport of water and CO_2 in both the 'free' and dissolved phases.

The pressures in a compartment are calculated from the porosity, amount of water, and amount of CO_2 in the 'free' and dissolved phases.

A single compartment is illustrated in Figure 17. Algorithms for the movement of CO_2 between the dissolved and free phases within a compartment are defined, dependent on the equilibrium saturation of CO_2 in water at any given temperature and pressure. Other algorithms are required to specify the ('vertical' and 'horizontal') fluxes of water (and associated dissolved CO_2) and free CO_2 between compartments depending upon factors that include pressure gradients, capillary pressures and interface areas.

In the near-surface environment 'free' CO_2 can enter the atmosphere or other receptor. The subsequent dispersion of the gas will depend upon its initial concentration and density as well as meteorological and topographic conditions.

5.3 An Illustrative FEP Audit

With the conceptual model described in Section 5.2, an illustrative FEP audit has been undertaken with the following key assumptions for the assessment context:

1. only CO_2 is considered - there are no other injected gases;
2. groundwater is the only geo-fluid of interest;
3. the key end point of interest is the timing and magnitude of fluxes to, and concentrations in, the accessible environment;
4. the system domain is terrestrial;
5. no controls of any sort are exercised post-closure, and no credit is taken for societal memory of the sequestration activity; and
6. no major environmental changes are considered either at the surface or at depth.

The results of the audit are shown in the following Tables. FEPs marked by ** are screened out and are not considered to be relevant to the assessment model. FEPs marked by * are not included directly in the model, but their effects could be simulated through an appropriate choice of model parameters.

This procedure illustrates how a systematic comparison of a model with the FEP database can provide a clear audit trail to what is represented in the model and what has been omitted and why.

Table 1: Illustrative FEP Audit for FEP Category 0, Assessment Basis.

FEP number	Description	Audit
0.1	Purpose of the assessment	To provide a system-level assessment of the post-closure performance of CO_2 geological storage systems. Initially the assessment will not consider other gases injected with the CO_2.
0.2	Endpoints of interest	The magnitude and timing of fluxes of CO_2 to the accessible environment. Possible impacts on humans can be considered in a very simplified way, assuming that people are present where the CO_2 flux occurs.
0.3	Spatial domain of interest	The region over which any fluxes to the accessible environment may occur. The assessment is for a 'terrestrial' system.
0.4	Timescale of interest	The timescales relevant to the flux of CO_2 back to the accessible environment. This may be up to several tens of thousands of years.
0.5	Sequestration assumptions	The rate of injection of CO_2 and the total amount injected are model inputs.
0.6	Future human action assumptions	Current human technology is assumed. No societal memory of the storage is assumed.
0.7	Legal and regulatory framework	Not considered explicitly.
0.8	Model and data issues	Simplified algorithms are used in order to represent complex processes at the systems level.

Table 2: Illustrative FEP Audit for FEP Class 1.1, Geological Factors.

FEP number	Description	Audit
1.1.1	Neotectonics	See 1.1.3.
1.1.2**	Volcanic and magmatic activity	Assumed not to be important in the region of interest.
1.1.3	Seismicity	The possible impact of earthquakes on the apertures of cap rock fractures and hence permeability can be simulated.
1.1.4* *	Hydrothermal activity	Assumed not to be important in the region of interest.
1.1.5*	Hydrological and hydrogeological response to geological changes	Major changes in the geology are not considered, but any variation with time of the hydrogeological regime could be simulated by varying model parameters.
1.1.6**	Large scale erosion	See 1.1.5.
1.1.7 **	Bolide impact	Screened out on the basis that the impact of the bolide will greatly exceed that of the disruption caused to the sequestration system.

Table 3: Illustrative FEP Audit for FEP Class 1.2, Climatic Factors.

FEP number	Description	Audit
1.2.1*	Global climate change	Climate Change may affect the characteristics of the accessible environment (e.g. water table depths). The effects of such changes can be investigated by varying model parameter values.
1.2.2*	Regional and local climate change	See 1.2.1.
1.2.3*	Sea level change	The site is assumed not to be affected directly by changing sea levels, but any changes in the hydrogeological regime could be represented by varying hydrogeological parameters with time.
1.2.4*	Periglacial effects	See 1.2.1.
1.2.5*	Glacial and ice sheet effects	Not explicitly represented, but any changes in the hydrogeological regime could be represented by varying hydrogeological parameters with time.
1.2.6*	Warm climate effects	See 1.2.1.
1.2.7 *	Hydrological and hydrogeological response to climate changes	This can be investigated by varying model parameter values.
1.2.8**	Responses to climate changes	Not considered.

Table 4: Illustrative FEP Audit for FEP Class 1.3, Future Human Actions.

FEP number	Description	Audit
1.3.1*	Human influences on climate	Not considered explicitly- see 1.2.1
1.3.2	Motivation and knowledge issues	No societal memory of the storage is assumed, and only inadvertent human intrusions are considered.
1.3.3**	Social and institutional developments	Screened out on basis of assessment context.
1.3.4**	Technological developments	Screened out on basis of assessment context.
1.3.5	Drilling activities	Assumed to be the most likely relevant human intrusion activity.
1.3.6*	Mining and other underground activities	Not explicitly considered. Impacts assumed to be covered by consideration of drilling activities (1.3.5).
1.3.7 **	Human activities in the surface environment	Not considered.
1.3.8 *	Water management	Human impacts on near-surface hydrology could be included implicitly in the description of near-surface hydrology.
1.3.9**	CO_2 presence influencing future operations	Only inadvertent intrusions are considered.
1.3.10*	Explosions and crashes	These are low probability events that are assumed to have possible consequences similar to seismic events (FEP 1.1.3).

Table 5: Illustrative FEP Audit for FEP Class 2.1, CO_2 Storage Pre-Closure.

FEP number	Description	Audit
2.1.1	Storage Concept	The model is applicable to a range of different storage concepts, although no hydrocarbons are present.
2.1.2	CO_2 quantities, injection rate	The total amount of CO_2 injected is a model input.
2.1.3**	CO_2 composition	Pure CO_2 is assumed.
2.1.4**	Microbiological contamination	Pure CO_2 is assumed.
2.1.5*	Schedule and planning	Any effects are included in the description of the system at closure.
2.1.6*	Pre-closure administrative control	Any effects are included in the description of the system at closure.
2.1.7	Pre-closure monitoring of storage	Any monitoring wells will need to be represented in the system description.
2.1.8*	Quality control	Any effects are included in the description of the system at closure.
2.1.9*	Accidents and unplanned events	Any effects are included in the description of the system at closure.
2.1.10	Over-pressuring	Over-pressures due to the amounts of CO_2 injected (FEP 2.1.2) will be calculated by the model. Over-pressuring may also occur due to CO_2 phase changes.

Table 6: Illustrative FEP Audit for FEP Class 2.2, CO_2 Storage Post-Closure.

FEP number	Description	Comment
2.2.1**	Post-closure administrative control	No administrative controls are assumed post-closure.
2.2.2**	Post-closure monitoring of storage	No post-closure monitoring is assumed.
2.2.3**	Records and markers	No records and markers are assumed.
2.2.4**	Reversibility	Outside the assessment context.
2.2.5**	Remedial actions	Outside the assessment context.

Table 7: Illustrative FEP Audit for FEP Class 3.1, CO_2 Properties.

FEP number	Description	Audit
3.1.1	Physical properties of CO_2	Simplified algorithms are used to represent the variation of CO_2 viscosity with pressure and temperature.
3.1.2	CO_2 phase behaviour	Simplified algorithms are used to represent the variation of CO_2 density with pressure and temperature.
3.1.3	CO_2 solubility and aqueous speciation	Dissolution in water is represented explicitly. Dissolution in oil is not considered.

Table 8: Illustrative FEP Audit for FEP Class 3.2, CO_2 Interactions.

FEP number	Description	Audit
3.2.1*	Effects of pressurisation of reservoir on caprock	Not included, but simple algorithms for pressure-dependent caprock changes could be considered.
3.2.2	Effects of pressurisation on reservoir fluids	Induced groundwater flows will be calculated.
3.2.3**	Interaction with hydrocarbons	Outside assessment context.
3.2.4*	Displacement of saline formation fluids	Not considered.
3.2.5*	Mechanical processes & conditions	Included implicitly in some process algorithms.
3.2.6*	Induced seismicity	Not considered directly. Effects are assumed to be similar to natural earthquakes (FEP 1.1.3).
3.2.7**	Subsidence or uplift	Not an endpoint of interest.
3.2.8*	Thermal effects on injection point	Any effects are included in the system description at the start of the post-closure period (e.g. through changes to permeability).
3.2.9	Water chemistry	Will affect CO_2 solubility and thus included implicitly in some process algorithms.
3.2.10*	Interaction of CO_2 with chemical barriers	Chemical reactions that remove CO_2 are not included. This is a conservative assumption as the flux of CO_2 back to the accessible environment is the main endpoint of interest.
3.2.11*	Sorption and desorption of CO_2	This process could be included in the model, but is not represented in the present version.
3.2.12**	Heavy metal release	Outside assessment context.
3.2.13	Mineral phase	Mineral trapping of CO_2 is ignored in the interests of conservatism.
3.2.14	Gas chemistry	Will affect CO_2 solubility and thus included implicitly in some process algorithms.
3.2.15**	Gas stripping	Outside the assessment context. See 3.1.2.
3.2.16**	Gas hydrates	Any formation of gas hydrates is assumed to be unimportant on the timescales of interest.

FEP number	Description	Audit
3.2.17*	Biogeochemistry	Not represented explicitly.

Table 8 Continued.

FEP number	Description	Audit
3.2.18*	Microbial processes	Not represented explicitly. Methanogenesis is conservatively assumed not to occur (thereby maximising the amount of stored CO_2).
3.2.19*	Biomass uptake of CO_2	Not represented explicitly.

Table 9: Illustrative FEP Audit for FEP Class 3.3, CO_2 Transport.

FEP number	Description	Audit
3.3.1	Advection of free CO_2	Included.
3.3.2	Buoyancy-driven flow	Vertical transport of free CO_2 due to buoyancy forces is directly represented.
3.3.3	Displacement of formation fluids	Could result from injection of CO_2.
3.3.4	Dissolution in formation fluids	Dissolution of CO_2 in groundwater is represented explicitly.
3.3.5	Water mediated transport	Advection of dissolved CO_2 in groundwater is represented explicitly.
3.3.6	CO_2 release processes	Included.
3.3.7**	Co-migration of other gases	See 3.2.15.

Table 10: Illustrative FEP Audit for FEP Class 4.1, Geology.

FEP number	Description	Audit
4.1.1	Geographical location	The model can be applied to any 'terrestrial' location.
4.1.2	Natural resources	May need to be considered in defining human intrusion scenarios and probabilities.
4.1.3	Reservoir type	Represented explicitly.
4.1.4	Reservoir geometry	Represented explicitly.
4.1.5*	Reservoir exploitation	Represented implicitly in the system description.
4.1.6	Cap rock or sealing formation	Represented explicitly.
4.1.7	Additional seals	Represented explicitly.
4.1.8*	Lithology	Properties of all rocks in the system domain are represented explicitly or implicitly.
4.1.9*	Unconformities	Represented implicitly in rock properties.
4.1.10	Heterogeneities	Represented by varying properties of model compartments.
4.1.11*	Faults and fractures	Represented implicitly in rock permeabilities.
4.1.12*	Undetected features	The importance of undetected features can be assessed by varying the representation of the system geology.
4.1.13	Vertical geothermal gradient	Represented explicitly.
4.1.14	Formation pressure	Represented explicitly.
4.1.15	Stress and mechanical properties	Included implicitly in some process algorithms.
4.1.16	Petrophysical properties	Represented explicitly.

Table 11: Illustrative FEP Audit for FEP Class 4.2, Fluids.

FEP number	Description	Comment
4.2.1	Fluid properties	Represented explicitly.
4.2.2	Hydrogeology	Represented explicitly, but approximately.
4.2.3**	Hydrocarbons	Outside assessment context.

Table 12: Illustrative FEP Audit for FEP Class 5.1, Drilling and completion.

FEP number	Description	Audit
5.1.1*	Formation damage	Included in the initial conditions if relevant.
5.1.2	Well lining and completion	Not represented explicitly, but relevant to seal failure.
5.1.3*	Workover	Any effects relevant to the initial conditions will be included implicitly.
5.1.4	Monitoring wells	May need to be represented in the system description.
5.1.5**	Well records	Screened out. No memory of the sequestration is assumed.

Table 13: Illustrative FEP Audit for FEP Class 5.2, Borehole Seals and Abandonment.

FEP number	Description	Audit
5.2.1*	Closure and sealing of boreholes	Not represented explicitly, but relevant to seal failure.
5.2.2	Seal failure	Simple algorithms used for the time to seal failure.
5.2.3	Blowouts	Can be represented.
5.2.4	Orphan wells	May need to be represented in the system description.
5.2.5	Soil creep around boreholes	May be included implicitly in system design.

Table 14: Illustrative FEP Audit for FEP Class 6.1, Terrestrial Environment.

FEP number	Description	Audit
6.1.1	Topography and morphology	Represented in a simplified way.
6.1.2	Soils and sediment	Represented explicitly.
6.1.3**	Erosion and deposition	Outside assessment context.
6.1.4*	Atmosphere and meteorology	CO_2 concentrations in the atmosphere close to a surface release are calculated.
6.1.5	Hydrological regime and water balance	Represented explicitly.
6.1.6	Near-surface aquifers and surface water bodies	Represented explicitly.
6.1.7**	Terrestrial flora and fauna	Calculations stop at flux to the atmosphere.

6.1.8**	Terrestrial ecological systems	Outside assessment context.

Table 15: Illustrative FEP Audit for FEP Class 6.2, Marine Environment.

FEP number	Description	Audit
6.2.1**	Coastal features	Terrestrial environment assumed.
6.2.2**	Local oceanography	Terrestrial environment assumed.
6.2.3**	Marine sediments	Terrestrial environment assumed.
6.2.4**	Marine flora and fauna	Terrestrial environment assumed.
6.2.5**	Marine ecological systems	Terrestrial environment assumed.

Table 16: Illustrative FEP Audit for FEP Class 6.3, Human Behaviour.

FEP number	Description	Audit
6.3.1**	Human characteristics	Calculations do not consider impacts on humans, therefore no description of human behaviour is required.
6.3.2**	Diet and food processing	Calculations do not consider human behaviour.
6.3.3**	Lifestyles	Calculations do not consider human behaviour.
6.3.4**	Land and water use	Calculations do not consider human behaviour.

6.3.5**	Community characteristics	Calculations do not consider human behaviour.
6.3.6**	Buildings	Calculations do not consider human behaviour.

Table 17: Illustrative FEP Audit for FEP Class 7.1, System performance.

FEP number	Description	Audit
7.1.1	Loss of containment	Represented explicitly.

Table 18: Illustrative FEP Audit for FEP Class 7.2, Impacts on the physical environment.

FEP number	Description	Audit
7.2.1	Contamination of groundwater	Only for dissolved CO_2.
7.2.2	Impacts on soils and sediments	Outside assessment context.
7.2.3	Release to the atmosphere	CO_2 concentrations in the atmosphere close to the surface release are calculated.
7.2.4*	Impacts on exploitation of natural resources	May need to be considered in assessing human intrusion probabilities.
7.2.5	Modified hydrology and hydrogeology	Represented explicitly.
7.2.6**	Modified geochemistry	Outside assessment context.
7.2.7**	Modified seismicity	Outside assessment context.
7.2.8**	Modified surface topography	Outside assessment context.

Table 19: Illustrative FEP Audit for FEP Class 7.3, Impacts on Flora and Fauna.

FEP number	Description	Audit
7.3.1**	Asphyxiation effects	Impacts on flora and fauna not calculated.
7.3.2**	Effect of CO_2 on plants and algae	Impacts on flora and fauna not calculated.
7.3.3**	Ecotoxicology of contaminants	Impacts on flora and fauna not calculated.
7.3.4**	Ecological effects	Impacts on flora and fauna not calculated.
7.3.5**	Modification of microbiological systems	Impacts on flora and fauna not calculated.

Table 20: Illustrative FEP Audit for FEP Class 7.3, Impacts on Humans.

FEP number	Description	Audit
7.3.1**	Health effects of CO_2	Impacts on humans not calculated.
7.3.2**	Toxicity of contaminants	Impacts on humans not calculated.
7.3.3**	Impacts from physical disruption	Impacts on humans not calculated.

7.3.4**	Impacts from ecological modification	Impacts on humans not calculated.

6 Conclusions

The main areas of progress that have been reported include:

- ▲ experience with systems analysis methods from other fields has been applied to safety and performance assessments of the geological storage of carbon dioxide.
- ▲ A generic FEP database has been developed that provides a powerful tool with potential for use as both a 'knowledge base' and an input to systems-level modelling studies.
- ▲ Important scenarios have been identified that need to be considered in the evaluation of the system performance and safety.
- ▲ The use of interaction matrices to investigate interactions between FEPs has been demonstrated.
- ▲ The use of the FEP database to audit systems-level models has been demonstrated.

The main output from the project is the generic FEP database. In order for this database to continue to be relevant to the assessment of the performance and safety of carbon dioxide storage systems, it is important that the database is maintained and developed. In particular, advantage needs to be taken of the capability to link to project-specific databases (which has not been demonstrated in the present project).

The development of systems-level models for the geological storage of CO_2 is at an early stage of development, and the development of such a model was not part of the present project. Advantage can be taken of experience gained in performance assessment studies for radioactive waste disposal and reservoir simulation models used in the petroleum industry, but, because of the variation of the properties of carbon dioxide with pressure and temperature, there are significant technical challenges to be overcome. It is suggested that systems-level models could be developed and applied to natural systems where significant quantities of carbon dioxide are released to the accessible environment. If such models can help to produce an understanding of the key processes and potential impacts in such systems, this will provide confidence in their suitability for application to 'engineered' systems.

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