Carbon Dioxide Capture for Storage in Deep Geologic Formations – Results from the CO_2 Capture Project

Geologic Storage of Carbon Dioxide with Monitoring and Verification

Volume 2

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Carbon Dioxide Capture for Storage in Deep Geologic Formations – Results from the CO_2 Capture Project

Geologic Storage of Carbon Dioxide with Monitoring and Verification

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Chapter 31

FRAMEWORK METHODOLOGY FOR LONG-TERM ASSESSMENT OF THE FATE OF CO_2 IN THE WEYBURN FIELD

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ABSTRACT

A key objective of the IEA Weyburn CO_2 Monitoring and Storage Project is to determine the long-term fate of CO_2 injected into the reservoir. Such a determination involves an evaluation of the potential for CO_2 to migrate away from the reservoir along both natural and artificial (wellbore) pathways to the environment, and relies on the technical input from a number of disciplines. These disciplines include geology and hydrogeology, geochemistry, geomechanics, reservoir modeling and wellbore technology. This paper describes the framework used for carrying out the long-term assessment, thus ensuring that work being carried out by other research workers is properly integrated into the CO_2 migration modeling. The discussion focuses on the various components of systems analysis, including features, events and processes and their incorporation into scenario development.

INTRODUCTION

Background

In July 2000, a 4-year research project to study geologic storage of CO_2 in the Weyburn oilfield was launched. A key objective of this multidisciplinary project is to determine the long-term fate of CO_2 injected into the reservoir. Such a determination involves an evaluation of the potential for CO_2 to migrate away from the reservoir along both natural and artificial (wellbore) pathways to the environment, and relies on the technical input from a number of disciplines. These disciplines include geology and hydrogeology, geochemistry, geomechanics, reservoir modeling and wellbore technology. The long-term assessment starts at the end of enhanced oil recovery (EOR) operations, the results of which are reported elsewhere [1]. Separate reservoir simulations, that were not a part of this study, were conducted to determine the conditions at the end of EOR operations.

CO_2 storage is still a developing field of research technology and so assessments associated with CO_2 storage are just beginning. In the particular case of Weyburn, long-term storage or storage of CO_2 would be an additional benefit of EOR. However, 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.

Opportunely, many of the advances made in the last 20 years in the field of safety assessments for the geological disposal of radioactive wastes can also be applied to CO_2 storage [2]. As for CO_2 storage, the final storage of nuclear waste requires an understanding of complex coupled physical–chemical–mechanical processes occurring over hundreds to tens of thousands of years. It is this field of work that provides the framework for the long-term assessment of the fate of CO_2 left in place in the Weyburn field at

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Abbreviation: FEPs, features, events and processes.

the end of EOR operations. The reasons for this "transfer of technology" are three-fold:

- systems analysis provides a systematic framework for conducting safety assessments;
- systems analysis is used to identify features, events and processes (FEPs) over hundreds to thousands of years—the timescales of relevance in this project;
- the systems analysis approach is a useful method of documenting progress and why particular decisions were made.

SPECIFICS OF THE METHODOLOGY OF LONG-TERM ASSESSMENT

Components of Systems Analysis Approach

Systems analysis consists of several inter-related elements:

- definition of the "System" to be assessed;
- development of a list of FEPs which together describe the particular system being studied;
- differentiation between those FEPs which belong to the system itself and those which can be regarded as external to the system;
- identification of interactions between these FEPs;
- construction of scenarios;
- description of how the FEP–FEP interactions will be accommodated in the consequence analysis modeling to be undertaken for each scenario.

Each of these elements is discussed briefly below, providing examples relevant to the Weyburn Project, where appropriate. A more detailed account of these elements and the way in which they are combined in the systems analysis approach is described in Chapman et al. [3] and, more recently, in Stenhouse et al. [4].

Definition of the Weyburn System

One of the first steps in the methodology is to define what is meant by the "System" to be assessed. Figure 1 provides a schematic diagram of the basic components for the Weyburn System and their physical relationship; these components include:

- the *CO_2 storage reservoir*;
- the *geosphere*, which comprises a number of geological and hydrogeological units above and below the reservoir (not shown explicitly); and
- the surface or near-surface environment is also referred to as the *biosphere*.

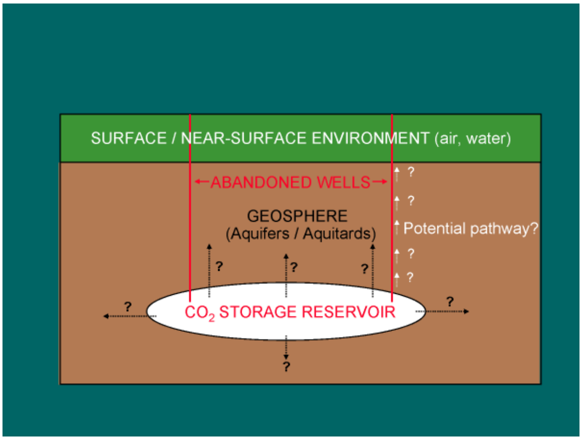


Figure 1: Schematic representation of the Weyburn CO_2 storage system.

The arrows shown in this schematic diagram are hypothetical representations of how CO_2 might migrate out of the storage reservoir. Two abandoned wells are also shown in Figure 1, representing wellbores as *potential* pathways for reservoir CO_2 to migrate to the surface or near-surface. Note that, although the geosphere is shown only as one uniform "compartment", the geosphere has been defined in much greater detail, so that the main features of the geosphere, principally those features that represent potential pathways or sinks for CO_2, may be incorporated in the migration modeling. Thus, Figure 2 shows the detailed layers of the System Model of the geosphere and biosphere, which comprise a series of aquitards and aquifers. The assessment area has been defined as covering an area 10 km beyond the outside of the EOR region (the perimeter is shown in red in Figure 2). Not included in this diagram are the numerous wells drilled through the area.

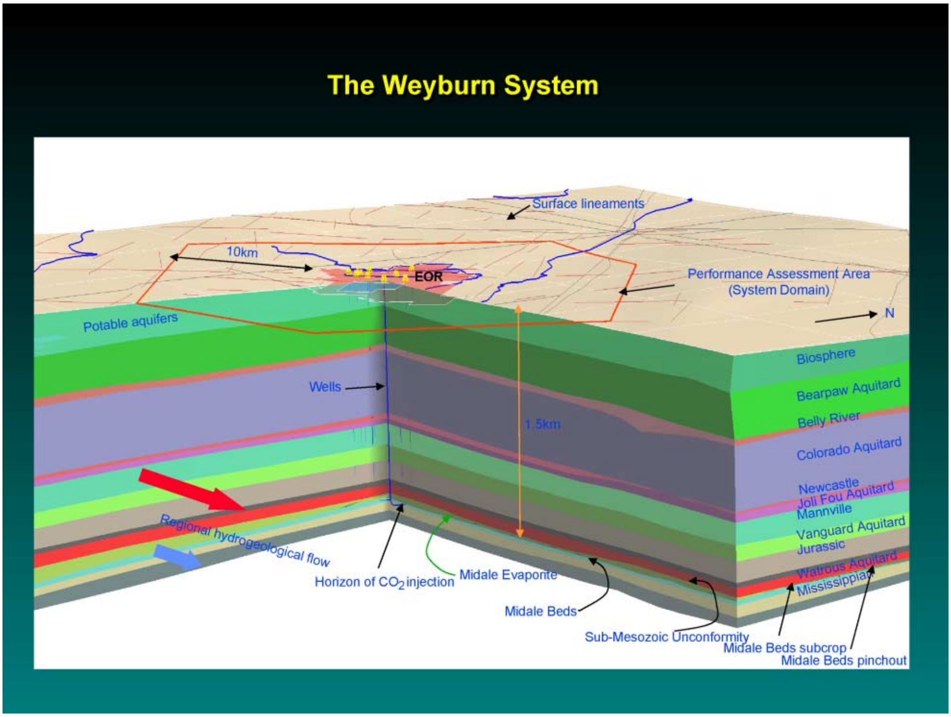


Figure 2: Weyburn System model—geosphere and biosphere (courtesy Steve Whittaker, Saskatchewan Industry and Resources). Note: The red perimeter defines the assessment area. Wells are not shown in this figure, for clarity.

FEPs

As stated above, FEPs is the acronym for *F*eatures, *E*vents or *P*rocesses, consisting of all factors that must be considered in describing/defining a system as well as assessing its performance.

- *Features* are typically specific components of the System being studied. For example, in the case of the geosphere, specific features would correspond to different geological and hydrogeological units, permeability and porosity of these units, and other important features such as faults and fractures. *Features* could also include inadequately sealed boreholes, and the quality (composition) of the injected carbon dioxide.
- *Events* are usually of short duration and can be of natural or human origin, such as seismic events, faulting, a well blow-out, or intrusion by people into the storage reservoir.

- *Processes* comprise the detailed individual scientific and engineering processes that govern the System. Examples are the variation of carbon dioxide's physical properties with pressure and temperature, multiphase flow of CO_2 and water, dissolution of CO_2 into the in situ reservoir fluids, and chemical reactions with reservoir and cap rocks. Examples of geochemical-type processes include the precipitation and dissolution of minerals.

FEP lists have been developed for safety assessment involving the final storage of nuclear waste in individual countries, not only by the national agency responsible for the waste management, but also by agencies responsible for overseeing or authorizing the process. Thus, Stenhouse et al. [5] compiled and categorized an FEP database consisting of FEPs from eight national and international FEP lists. Subsequently the Nuclear Energy Agency published an international FEP list database [6]. This list was available as a checklist for various individual safety assessment programs and could be used to provide "an aid to achieving and demonstrating comprehensiveness within an assessment".

Monitor Scientific developed a Weyburn-specific FEP List and Quintessa assembled independently a "generic" FEP database based on NEA's list but applicable for CO_2 disposal in general.

Weyburn working FEP list
FEPs in the Weyburn Working List were categorized in terms of:

- *System FEPs*: those FEPs that describe the Weyburn System, and
- *External FEPs*: those FEPs that are not part of this System. Examples of external FEPs are earthquakes, well drilling long into the future, development of new communities near the storage site and discovery of new mineral resources in the vicinity of the storage project. Such FEPs can affect CO_2 storage and migration within the system in some way, if they occur, thereby generating different *Scenarios*—ways in which the Weyburn System might evolve. For this reason, external FEPs are also known as scenario-generating FEPs. Figure 3 shows schematically the relationship between system FEPs and external FEPs.

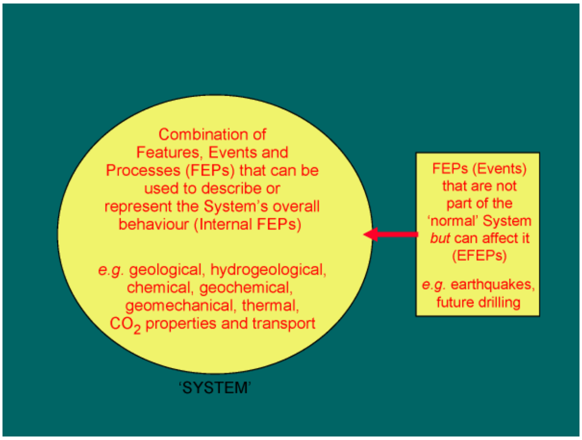


Figure 3: Relationship between system FEPs and external (scenario-generating) FEPs.

For convenience, the system FEPs were subdivided into a few arbitrary categories: geological, hydrogeological, chemical/geochemical, transport and miscellaneous. The resulting working list of FEPs for Weyburn was mapped to the generic FEP database (see below) to ensure that no relevant generic FEPs had been excluded from consideration in the Weyburn list.

The Weyburn-specific FEP list was also "mapped" to the FEPs generated at a workshop that was held in Rome, again to ensure that no relevant generic FEPs had been excluded from consideration in the Weyburn list.

The resultant, updated Weyburn-specific FEP list was reviewed at a Weyburn Workshop held in June 2002. Representatives of the Weyburn Project (Research Providers and the Management Committee) attended this Workshop, one of the objectives being to obtain a consensus on the working FEP list. The resultant working list of geosphere FEPs is reproduced here as Table 1.

TABLE 1
WORKING LIST OF WEYBURN SYSTEM GEOSPHERE FEPS

FEP title

Geological units
A series of units representing aquitards and aquifers within the Weyburn System

Abandoned wells
Annular space (integrity/quality)
Corrosion of borehole metal
Expansion/collapse of corrosion products
Degradation of borehole seal(s)

Rock properties
Mechanical properties of rock
In situ stress distribution
Lithology and mineralogy
Lithification
Presence and nature of faults
Presence and nature of fractures
Bounding seal system

Other geology
Natural seismicity
Temperature/thermal field
Uplift and subsidence
Presence of unconformities
Desiccation of clay

Hydrogeological properties
Cross-formation flow
Fluid characteristics of rock
Subsurface water flow
Hydraulic pressure
Hydrogeological properties of rock (basic)
Brine displacement
Mixing of water bodies

FEP title

Chemical/geochemical
Colloid formation and transport
Precipitation/dissolution of mineral (including surface processes)
Dissolution/exsolution of CO_2
Gaseous contaminants
Water chemistry
Purity of CO_2

Properties and transport of CO_2 and other phases
Hydrodynamic flow
Diffusion
Dispersion
Gas flow
Starting conditions (i.e. post-operational CO_2 distribution)
Interfacial tension and wettability
Capillary pressure
Bubble transport of CO_2
Transport of CO_2 (including multiphase flow)

Other/miscellaneous
Gas pressure (bulk gas)
Pressure gradient
Buoyancy
Coalescence of bubbles
Release and transport of other fluids
Operational artifacts

Generic FEP database

The generic FEP database for the geological storage of CO_2 includes around 200 FEPs in a hierarchical structure, with FEPs grouped into categories such as "assessment basis", "external factors" and "boreholes" [7]. Each FEP has a text description and a discussion of its relevance to performance and safety. Key references in the published literature are included to enable retrieval of more detailed information for each FEP.

The database is available online and incorporates hyperlinks to other relevant sources of information (reports, websites, maps, photographs, videos, etc.). The database is searchable in a variety of ways and provides a centralized "knowledge base". Essentially, the list of FEPs defines the process system and represents all the factors that help define CO_2 behavior and migration.

The FEP database was expanded following an “FEP Workshop” held in Rome in January 2002 through the EC-funded Weyburn/Nascent projects clustering process. For example, a list of FEPs appropriate to generic CO_2 storage technologies was identified at this meeting.

FEP–FEP Interactions

The Weyburn FEPs discussed in the previous section do not exist in isolation, nor should they be treated as such. Rather, each of them may affect the system by influencing another FEP in some way, or by causing a more specific interaction on/with another FEP. For example, in the geosphere, the mineralogy of different rocks is one factor which will determine what rock–water interactions (geochemical interactions) occur; the basic chemistry (pH, major ions) of the groundwater is another.

Each of these interactions should be identified so that the total system can be described in a comprehensive way. Interactions between FEPs may be presented in a variety of ways, namely:

- a list identifying the interactions in terms of the initial and final FEPs;
- a diagram depicting individual FEPs as boxes, e.g. with interactions shown as arrows connecting two boxes; or
- an interaction matrix, whereby the FEPs are laid out in a two-dimensional matrix and interactions are represented by filled cells within this matrix.

Again, irrespective of the way in which these FEP interactions/influences are represented, the objective is to ensure that all possible/potential interactions are included. The mode of presentation is secondary, though important in providing some clear form of visual display that is as readily understood as possible. Such presentations are described by Stenhouse et al. [4].

Interactions between FEPs are often classified in terms of those which are highly important and those of low importance. Highly important is normally intended to mean that such interactions *must* be treated within the assessment, i.e. cannot be ignored. In contrast, to ignore FEP interactions of low importance should not affect the consequence analysis significantly. These classifications are rather arbitrary and depend on expert judgment but as long as each decision is documented, there is a sound basis for subsequent discussion and, where necessary, for revising a decision.

Figure 3 provides the interaction matrix for the Weyburn geosphere FEPs. The system FEPs of Table 1 appear vertically on the left-hand side and also horizontally along the top of the matrix. Any interaction between two FEPs is identified by a filled cell within the matrix.

Scenario Development

Even for a well-characterized CO_2 storage reservoir such as Weyburn, there are unavoidable uncertainties about the future state or evolution of the system. Such uncertainties arise from uncertainty about the importance (impact) or rate of various natural processes which will act on the system, the timing or frequency of certain natural phenomena (e.g. seismic events), and essentially unpredictable human activities in the future. In the assessment of the impacts of the final geological storage of nuclear wastes, uncertainty in future states has traditionally been handled by carrying out assessment calculations for a number of stylized conceptual descriptions of future state or evolution termed *scenarios*. Scenarios have become widely used in business and industry as planning and brainstorming tools and were first applied to the disposal of radioactive waste in the early 1980s by Sandia National Laboratory for the US Nuclear Regulatory Commission [8]. Regarding 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 behaviors and states of a carbon storage system, for the purposes of making or evaluating a safety case, or for considering the long-term fate of CO_2.

Scenarios form the basis for calculations of consequence analysis or risk. It is not necessary, or indeed possible in our view, to describe all possible scenarios. Thus, using the approach described by Chapman et al. [9], scenarios are viewed as *illustrative examples* of future behavior. There is no intent (indeed there is no possibility) to be either comprehensive or mutually exclusive, since there is no international consensus on applying probability theory to scenario analysis (see, e.g. NEA [10]). However, consideration of a set of scenarios should provide an adequately robust test of safety by addressing the most likely possible evolutions of the system together with less likely futures which exhibit features of possible concern [11].

Weyburn scenarios

A brainstorming session was held at EnCana (Weyburn Scenario Development Workshop, June 18, 2002) focusing on identifying scenario-generating events and characterizing them in terms of likelihood and severity of impact (consequence). The key output from this Workshop is the list of scenario-generating events provided in Table 2. A summary text description of the Base Scenario was also developed at this Workshop, and this is provided in Table 3.

TABLE 2
LIST OF SCENARIOS (SCENARIO-GENERATING EVENTS) IDENTIFIED FOR WEYBURN SYSTEM

Scenario-generating event
Mining (salt dissolution and other resources)
Leaking wells (slow, fast—including self-propagating gas-pressure-driven fracture)
Overpressuring of reservoir
Alternative techniques for resource recovery (CO_2 identified as resource)
Tectonic activity (including seismic events)
Fault movement/re-activation (covers undetected conductive feature)
Influence of shallow trapping feature
Accidental or intentional surface casing damage
Future drilling (above, to, through reservoir)
No wellbores (geosphere evaluation)
Extensive dissolution leading to subsidence
Open borehole (failure of top and bottom internal casing seals)
Annular open borehole
Thermally induced fracture
Additional CO_2 injection ($>$75-pattern)
Blowdown (CO_2 recycle)
Reversibility (CO_2 access)
Exploration for oil/other resources
Brines identified as resource
Other storage activities (concerning other fluids)
Geothermal exploitation

Scenario-generating event
Geothermally induced instability
Igneous activity (causing change in thermal gradient)
Glaciation/unloading post-glaciation
Marine transgression
Lack of quality control of injection
Lack of records/knowledge
Migration of CO_2 to other wells/formations/surface
CO_2 phase change, volumetric changes
Displacement by other formation fluids
Unknown pyrite zone or similar (accelerated corrosion/degradation)
No surprises (no degradation of seals)
Favorable mineral/fluid chemistry (mineral fixation of CO_2)
Population changes above reservoir
Topographic changes
Terrorist attack/sabotage
Change of supply of CO_2
Previously unobserved event
Gross exothermic reactions
Meteorite impact
Political changes

Note: Not all these scenarios will be addressed in the initial safety assessment; they are available, however, as the basis for future work.

Treatment of FEP–FEP Interactions: Modeling/Data Needs

The information contained in a FEP interaction matrix such as Figure 3 needs to be processed in order to show how each interaction will be dealt with during the assessment stage. The major ways in which these interactions translate to some form of action for the assessment are as follows:

- provision of data;
- one or more (robust) assumptions made;

TABLE 3
TEXT DESCRIPTION OF BASE CASE SCENARIO FOR WEYBURN CO_2 STORAGE SYSTEM

- The injected CO_2 starts off in the reservoir at the conclusion of commercial operations. (The CO_2 characteristics (pressure and phase distributions) at the end of EOR operations are predicted from reservoir simulations)
- Some CO_2 will exist as a supercritical fluid; some will be dissolved in oil and water phases; and some CO_2 may be mineralized. (The extent of mineralization is determined by geochemical modeling of conditions within the reservoir)
- The migration pathways are a combination of natural (geosphere) and manmade (abandoned wells). These two categories of migration pathways are treated independently, but eventually combined to represent the true long-term CO_2 storage conditions
- CO_2 can migrate from the reservoir by a number of different processes:
  - Pressure-driven flow
  - Density-driven flow
  - Diffusion

  Hydrodynamic flow (advection)
- CO_2 flux out of the reservoir is dependent upon the hydrogeological properties of rock in the Weyburn field and surrounding formations as well as the state of the wellbores (including annulus). The wellbore seals do not leak at time zero
- The Base Scenario takes into account all hydrogeological units above the reservoir and those units within the Mississippian below the reservoir. Note that the CO_2 may not reach many of these units
- CO_2–water–rock interactions can occur along the CO_2 fluid pathways. (Geochemical modeling is used to identify the chemical changes that occur and any resultant changes in hydrogeological properties caused by these chemical changes.) The timescale and pathways addressed by geochemical modeling are compatible with the corresponding predictions of CO_2 migration
- Long-term performance of abandoned wells:
  - Long term degradation of well seals (including annulus) and metal components will occur and will be governed by appropriate degradation rates consistent with the materials considered, e.g. corrosion rate of steel for casing metal
  - Such degradation may affect the CO_2 pathways and resultant flux; the impact of wellbore degradation will be reflected in modified transport properties of the wellbore (including annulus)
  - The responses of different formations to wellbore degradation or collapse are factored into the estimates of modified transport properties

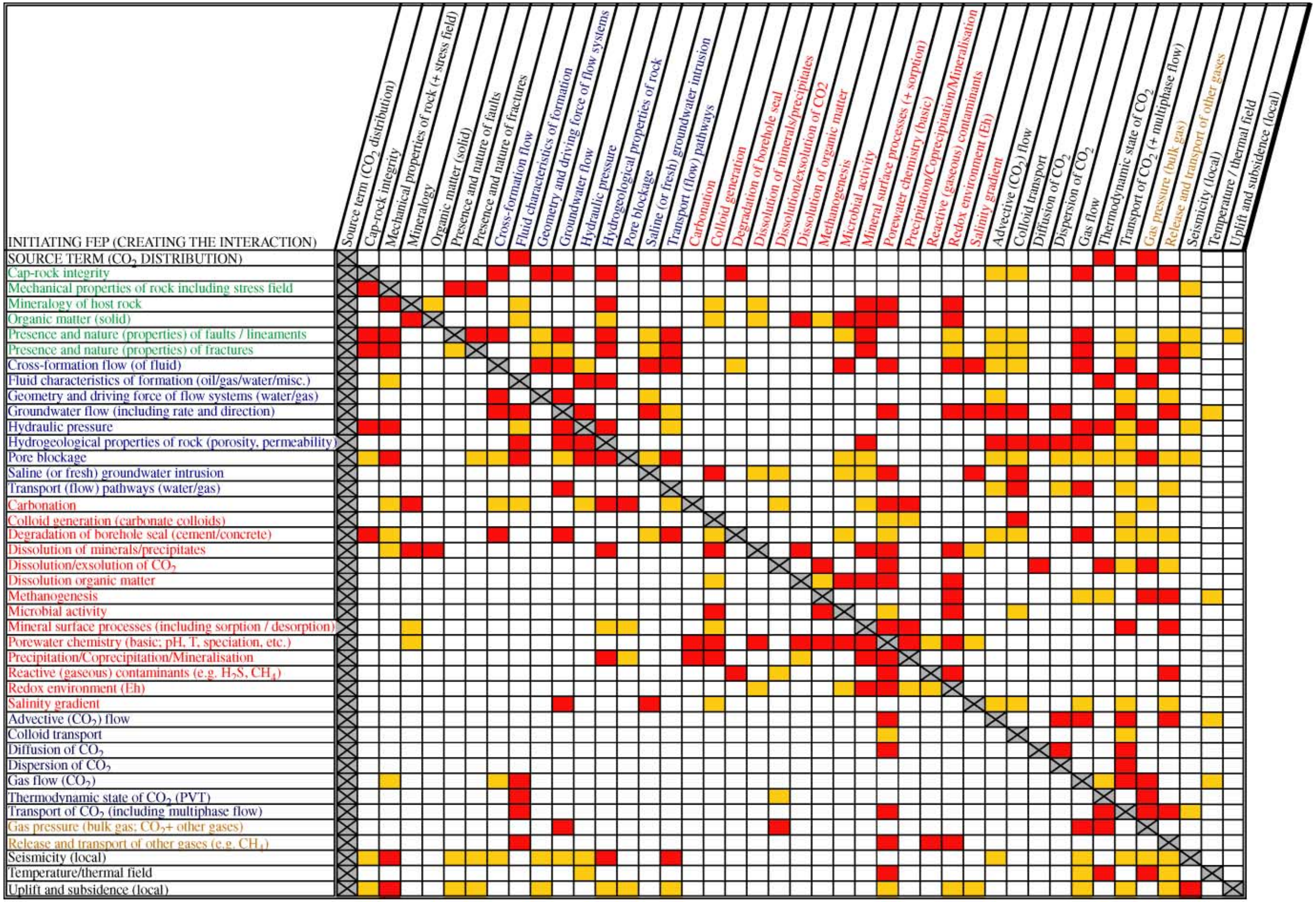
- scoping calculations to provide bounding limits for one or more parameters; or
- detailed modeling.

For example, in the case of the influence of basic groundwater chemistry on precipitation/mineralization, geochemical modeling requiring solubility/thermodynamic data is needed. Similarly, as the result of an EFEP such as fault movement/activation, changes in the transport properties of the rock matrix (porosity, permeability) might be expected; in such a case, some bounding assumption may be made about the resultant increase in porosity/permeability.

In order to facilitate and document the process of identifying actions such as the examples discussed above, a spreadsheet was prepared outlining the assessment needs corresponding to the matrix shown in Figure 4. An extract from this spreadsheet is shown in Figure 5.

SUMMARY

The assessment of the long-term performance of geological systems for CO_2 storage safety is one of the most important issues for the feasibility of the widespread use of geologic storage. The systems analysis approach used for the long-term assessment of the fate of CO_2 in the Weyburn field is based on an understanding of the storage system constructed through an analysis of relevant FEPs the development



INITIATING FEP (CREATING THE INTERACTION)	Source term (CO_2 distribution)	Cap-rock integrity	Mechanical properties of rock (+ stress field)	Mineralogy	Organic matter (solid)	Presence and nature of faults	Presence and nature of fractures	Cross-formation flow	Fluid characteristics of formation	Geometry and driving force of flow systems	Groundwater flow	Hydraulic pressure	Hydrogeological properties of rock	Pore blockage	Saline (or fresh) groundwater intrusion	Transport (flow) pathways	Carbonation	Colloid generation	Degradation of borehole seal	Dissolution of minerals/precipitates	Dissolution/exsolution of CO2	Dissolution of organic matter	Methanogenesis	Microbial activity	Mineral surface processes (+ sorption)	Porewater chemistry (basic)	Precipitation/Coprecipitation/Mineralisation	Reactive (gaseous) contaminants	Redox environment (Eh)	Salinity gradient	Advective (CO_2) flow	Colloid transport	Diffusion of CO_2	Dispersion of CO_2	Gas flow	Thermodynamic state of CO_2	Transport of CO_2 (+ multiphase flow)	Gas pressure (bulk gas)	Release and transport of other gases	Seismicity (local)	Temperature / thermal field	Uplift and subsidence (local)
SOURCE TERM (CO_2 DISTRIBUTION)	☒								🟥																											🟥		🟥				
Cap-rock integrity	☒	☒						🟥		🟥	🟥		🟥			🟥			🟥												🟨	🟨			🟥		🟥		🟥			
Mechanical properties of rock including stress field	☒	🟥	☒			🟥	🟥																																	🟨		
Mineralogy of host rock	☒		🟥	☒	🟨				🟨				🟥					🟨		🟨					🟥	🟥			🟥													
Organic matter (solid)	☒			🟥	☒				🟨				🟨					🟨		🟨		🟥	🟨	🟥	🟥	🟥			🟥													
Presence and nature (properties) of faults / lineaments	☒	🟥	🟥			☒	🟥	🟥		🟨	🟥		🟥		🟨	🟥								🟨	🟥				🟨		🟨	🟨			🟥		🟨		🟨	🟨		🟨
Presence and nature (properties) of fractures	☒	🟥	🟥			🟨	☒			🟨	🟨		🟥		🟨	🟥									🟥				🟨		🟨	🟨			🟥		🟨		🟥	🟨		
Cross-formation flow (of fluid)	☒							☒		🟥	🟥	🟨			🟥	🟥			🟨					🟥		🟥			🟥	🟥	🟨	🟨			🟥		🟥		🟥			
Fluid characteristics of formation (oil/gas/water/misc.)	☒		🟨						☒			🟥	🟥																							🟥		🟥				
Geometry and driving force of flow systems (water/gas)	☒							🟥		☒	🟥				🟨																🟨						🟨		🟨			
Groundwater flow (including rate and direction)	☒							🟥	🟥		☒	🟥			🟥	🟨										🟥			🟥	🟥	🟥	🟥		🟥			🟥		🟥		🟨	
Hydraulic pressure	☒	🟥	🟥						🟨		🟥	☒	🟥			🟨																			🟥	🟥	🟨	🟥		🟨		
Hydrogeological properties of rock (porosity, permeability)	☒								🟥		🟥	🟥	☒												🟥						🟥	🟥	🟥	🟥	🟥		🟨					
Pore blockage	☒	🟨	🟥				🟨	🟨	🟥		🟨	🟥	🟥	☒	🟨	🟥								🟨	🟨						🟨	🟨		🟨	🟨	🟨	🟨	🟥	🟨	🟨		
Saline (or fresh) groundwater intrusion	☒														☒			🟥		🟨	🟨			🟨	🟨	🟥				🟥		🟥										
Transport (flow) pathways (water/gas)	☒										🟥					☒															🟨	🟥		🟨	🟥		🟨		🟨			
Carbonation	☒		🟨	🟥				🟨	🟨			🟨	🟥	🟥		🟨	☒				🟨				🟨	🟥	🟥											🟨				
Colloid generation (carbonate colloids)	☒																	☒								🟨	🟨					🟥					🟨					
Degradation of borehole seal (cement/concrete)	☒	🟥	🟨					🟥			🟥				🟨	🟥		🟨	☒					🟨		🟨					🟨	🟨			🟥		🟨	🟨	🟨			
Dissolution of minerals/precipitates	☒		🟨	🟥	🟥								🟥					🟥		☒		🟥			🟥	🟥			🟥	🟨												
Dissolution/exsolution of CO_2	☒																				☒		🟥			🟥							🟥			🟥	🟨	🟥	🟨			
Dissolution organic matter	☒																	🟨				☒	🟨	🟥	🟥	🟥			🟥													
Methanogenesis	☒																						☒						🟥						🟨	🟨		🟥	🟥		🟨	
Microbial activity	☒																	🟥					🟥	☒		🟨			🟥			🟨										
Mineral surface processes (including sorption / desorption)	☒			🟨									🟨	🟨				🟨							☒	🟥	🟥									🟥		🟥				
Porewater chemistry (basic; pH, T, speciation, etc.)	☒			🟨													🟥	🟥		🟥		🟥	🟥	🟥	🟥	☒	🟥	🟨	🟥	🟨												
Precipitation/Coprecipitation/Mineralisation	☒												🟥	🟨			🟥	🟥				🟨			🟥	🟥	☒															
Reactive (gaseous) contaminants (e.g. H_2S, CH_4)	☒																		🟥		🟨					🟥		☒	🟥										🟥			
Redox environment (Eh)	☒																			🟨				🟨	🟥	🟥	🟨	🟨	☒													
Salinity gradient	☒										🟥				🟥			🟨												☒	🟨	🟨			🟨		🟨		🟨			
Advective (CO_2) flow	☒																									🟥					☒			🟥	🟥		🟥		🟥		🟨	
Colloid transport	☒																									🟨						☒					🟨					
Diffusion of CO_2	☒																									🟥							☒	🟥			🟥					
Dispersion of CO_2	☒																																	☒			🟥					
Gas flow (CO_2)	☒		🟨					🟨	🟥																										☒	🟨	🟥	🟥			🟨	
Thermodynamic state of CO_2 (PVT)	☒								🟥												🟨															☒		🟥				
Transport of CO_2 (including multiphase flow)	☒								🟥																	🟥										🟥	☒	🟥	🟥	🟨		
Gas pressure (bulk gas; CO_2+ other gases)	☒										🟥										🟥														🟥	🟥		☒				
Release and transport of other gases (e.g. CH_4)	☒								🟥																	🟥		🟥	🟥										☒			
Seismicity (local)	☒	🟨	🟥			🟨	🟨	🟨		🟨	🟨	🟨	🟥			🟥															🟨				🟨		🟨	🟨	🟨	☒		
Temperature/thermal field	☒											🟨														🟥									🟨	🟥		🟥	🟨		☒	
Uplift and subsidence (local)	☒	🟨	🟥			🟨	🟨			🟨			🟨	🟨		🟨										🟨			🟨	🟨					🟨		🟨		🟨	🟥		☒

NOTE: Filled cells represent a FEP-FEP interaction; 🟨 =Moderate interaction; 🟥 = Strong interaction

Figure 4: FEP interaction matrix for Weyburn System FEPs.

Initiating FEP	FEP Influenced / Affected	How Interaction is Treated
Source term (CO_2 distribution) *COMMENT: Basic input for long-term assessment*	Fluid characteristics of formation	Output from reservoir simulations of EOR period
	Thermodynamic state of CO_2	Output from reservoir simulations of EOR period
	Gas pressure (bulk gas)	Output from reservoir simulations of EOR period
Cap-rock integrity *COMMENT: For the Base Scenario, the cap-rock is assumed to be tight. Loss of integrity will enhance flow and transport of CO_2, both dissolved in groundwater and as a gas; migration not necessarily to the surface, but possibly to other groundwater bodies or formations, providing alternative pathways to the environment.*	Cross-formation flow	Incorporate additional formations as modelling results dictate
	Geometry and driving force of flow systems	Change hydraulic gradient as necessary
	Groundwater flow	Change hydrogeological parameters as necessary
	Hydrogeological properties of rock	Change hydrogeological parameters as necessary
	Transport (flow) pathways	Change hydrogeological parameters as necessary
	Degradation of borehole seal (cement / concrete)	Change transport properties with degradation
	Advective flow (CO_2)	Change hydrogeological parameters as necessary
	Colloid transport	Change hydrogeological parameters as necessary
	Gas flow (CO_2)	Change hydrogeological parameters as necessary
	Transport of CO_2 (including multiphase flow)	Change hydrogeological parameters as necessary
	Release and transport of other gases	Change hydrogeological parameters as necessary
Mechanical properties of rock (+ stress field) *COMMENT: Properties will have an impact on stability of formations, as will degradation of these properties*	Cap-rock integrity	Assume perturbation (increased stress) creates fractures in cap-rock
	Presence and nature (properties) of faults / lineaments	Assume perturbation (increased stress) generates fault
	Presence and nature (properties) of fractures	Assume perturbation (increased stress) creates fractures
	Seismicity (local)	Assume perturbation (increased stress) increases local seismicity
Mineralogy of host rock *COMMENT: Type of minerals (e.g. hard / soft) will affect stability of rocks, pore structure, chemical properties and the likelihood of colloids*	Mechanical properties of rock (+ stress field)	Qualitative assessment of stability of different formations
	Organic matter (solid)	Small interaction; ignore (reverse interaction important)
	Fluid characteristics of formation	Small interaction; ignore
	Hydrogeological properties of rock	Change hydrogeological parameters as mineralogy changes
	Colloid generation	Indirectly via porewater chemistry; consider carbonate colloids only
	Dissolution of minerals / precipitates	Chemical / geochemical modelling
	Mineral surface processes (including sorption / desorption)	Chemical / geochemical modelling; carbonate sorption / desorption
	Porewater chemistry (basic; pH; major ions etc.)	Chemical / geochemical modelling; rock-water interactions
	Redox environment	Chemical / geochemical modelling; rock-water interactions
Organic matter (solid) *COMMENT: Nature and quantity of solid organic components could affect rock-water interactions; effects are mainly chemical although mechanical stability expected to be a function of organic content.*	Mineralogy of host rock	Establish organic content of rocks
	Fluid characteristics of formation	Pore structure will change with changing organic content
	Hydrogeological properties of rock	Small interaction; ignore
	Colloid generation	Only carbonate colloids relevant; chemical modelling
	Dissolution of minerals / precipitates	Chemical / geochemical modelling; rock-water interactions
	Dissolution of organic matter	Chemical / geochemical modelling; include organics
	Methanogenesis	Chemical modelling to determine limits of occurrence
	Microbial activity	Assess importance of microbes in presence of solid organic matter
	Mineral surface processes (+ sorption / desorption)	Chemical / geochemical modelling; carbonate/CO_2 sorption
	Porewater chemistry (basic; pH; major ions etc.)	Chemical / geochemical modelling; include organic complexants
	Redox environment	Assess whether reducing / oxidising conditions exist

Figure 5: Extract of data modeling needs addressing FEP−FEP interactions.

of scenarios to represent the evolution of the system, and calculations of potential impacts using mathematical models to represent key processes. Over time, this methodology will be tested and if successful, confidence will build in our ability to accurately assess the health, safety and environmental risks of geologic storage projects.

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