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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Geologic Storage of Carbon Dioxide with Monitoring and Verification

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D.C. Thomas and S.M. Benson (Eds.)

Chapter 33

RISK ASSESSMENT METHODOLOGY FOR CO_2 STORAGE: THE SCENARIO APPROACH

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ABSTRACT

The ambition of the R&D work presented here was to further develop the "scenario approach" as a methodology for the long-term safety assessment of underground CO_2 storage and to demonstrate its applicability in an example of safety assessment.

The developed methodology consists of three main parts: scenario analysis, model development and consequence analysis. The scenario analysis focuses on a comprehensive inventory of risk factors (Features, Events and Processes, FEPs) and subsequent selection of the most critical factors that will be grouped into discrete CO_2 leakage scenarios. Quantitative physico-mathematical models need to be developed to enable a quantitative safety assessment of the scenarios in the consequence analysis.

The developed method was successfully applied to two virtual settings in the southern part of the North Sea. In these examples, two leakage scenarios were considered, leakage up a fault and through a failed well. Modeling showed that CO_2 concentrations and fluxes in the biosphere were largest in the case of a leaking well, compared to the leaking fault. However, the duration of release of CO_2 to the biosphere was longer in case of the leaking fault. The assessed scenarios did not include any monitoring or mitigation measures and thus represent worst-case situations in this respect. The outcome of the assessment enables the development of a monitoring system and mitigation plan so that the safety risks can be adequately managed.

INTRODUCTION

The R&D work presented here was directed to the improvement of the HSE risk assessment methodology for storage of CO_2 in various geological media. The specific objectives of the study were:

- To develop a methodology and computational tools for HSE risk assessment of geological CO_2 storage in various geological media. The method and related tools must be applicable to site-specific

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Abbreviations: BRGM, Bureau de Recherche Géologique et Minière (France); FEP, acronym for Feature, Event or Process; any factor that could potentially influence the future HSE performance of the CO_2 storage system; HSE, health, safety and environment; SA, safety assessment; SAMCARDS, acronym of the R&D-project presented here, the full title of which is Safety Assessment Methodology for Carbon Dioxide Storage; TNO, Netherlands Organization of Applied Scientific Research; TNO-NITG, Netherlands Institute of Applied Geoscience TNO.

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assessment of CO_2 storage in saline water bearing formations and gas fields, both in offshore and onshore settings.
- To demonstrate the method and tools by applying it two virtual storage sites in the southern North Sea region.

The research focused in particular on the potential *long-term* effects of subsurface CO_2 storage, i.e. the period after injection of CO_2. In the present work the *scenario approach* has been adopted, which was introduced earlier for and successfully applied to the long-term assessment of hazardous waste disposal [1] though CO_2 is not considered to be a hazardous waste. The full description of the methodology, the testing and its demonstration including input data can be found in the report compiled by TNO-NITG [9].

STUDY METHODOLOGY

The presented method for the assessment of long-term behavior of a CO_2 storage facility basically consists of three major phases, each of which can be divided in one or more sub-phases (see Figure 1).

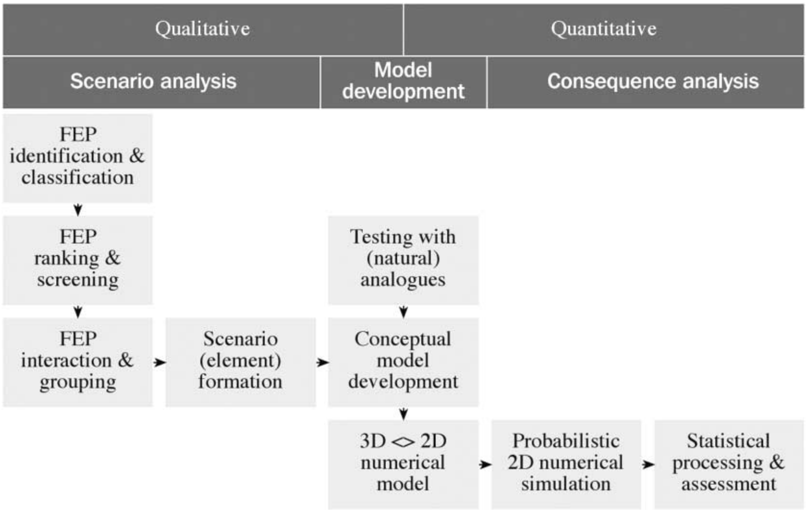


Figure 1: The scenario approach for safety assessment consists of three consecutive main phases, i.e. scenario analysis, model development and consequence analysis, each of which is divided into several sub-phases.

The core of the methodology is the systematic development of a limited number of scenarios that describe the possible future state or evolution of the storage site (scenario analysis). The basic elements for the development of the scenarios are features, events or processes (FEPs), a scenario consisting of an assemblage of interdependent FEPs. Once the scenarios have been defined, mathematical models are selected or developed that are able to quantify the consequences of these scenarios. Subsequently, the models are applied to quantify the consequences and assess the risks. A proper definition of the assessment basis is crucial for a successful execution of the safety assessment.

Assessment Basis

The constraints for the safety assessment are defined in the assessment basis (not presented in Figure 1). A well-focused definition of the assessment basis improves the quality of the work in all subsequent assessment phases, i.e. scenario formation, model development and consequence analysis. Its most crucial ingredients are:

1. *Assessment criteria*. Quantitative criteria that relate to acceptable levels of CO_2 exposure and acceptable consequences for health, safety and environment like the maximum acceptable CO_2 concentration or heavy metal concentration or the maximum individual lethality risk. These criteria can be defined in a safety or environmental regulation or in an industrial standard.
2. *Storage concept*. A clear description of the concept of underground CO_2 containment must be provided like the concept of structural trapping of CO_2, hydrodynamic trapping, dissolution trapping, mineral trapping or a combination of these. The specific requirements for the chosen storage concept must be elucidated and will vary depending on the storage concept that has been selected.
3. *Characteristics of the storage site*. A detailed description of the geological and geographical setting of the storage system including previous underground human activities in the area is very important to constrain the scope of the assessment. These concern the location, geological environment, lithology and past human underground activities. It is also important to have proper knowledge of the planned number of injection wells, the CO_2 injection rate over a certain time period and other design properties.
4. Additional items that can be included in the assessment basis are:
   - the times scale and spatial domain of the storage system;
   - type of assessment methodology to be used; and
   - any other requirement or constraint.

Scenario Analysis

A properly defined assessment basis establishes the starting-point for the scenario analysis. A scenario is a possible future state or evolution of the storage site that might lead to unintended leakage of CO_2 or to unintended (a) seismic movement of the earth's surface. Scenario analysis consists of two major phases, i.e. FEP analysis and scenario formation.

FEP database

The FEP database holds FEPs that may have a potential effect on the safety of the storage system. The current version of the database developed at TNO contains a total number of 665 FEPs that were extracted from various sources (see Table 1).

TABLE 1
NUMBERS OF FEATURES (F), EVENTS (E) AND PROCESSES (P)

F, E or P	Description	Number
F	All (static) factors and parameters describing the sequestration facility	239
E	Future occurrences, future changes to features (F) and future alteration of processes (P)	288
P	All surface and subsurface processes that describe the current and future physical, chemical and biological dynamical aspects of the sequestration facility	138
Total		665

The distinction between FEPs is made to support the scenario formation process subsequent to the FEP analysis. The status of features (F) is quite different from the status of events (E) and processes (P) in the database. Features are static input factors and/or parameters that characterize the state of the storage site. Features will be included in the reference and/or variant scenarios depending on the type of processes and events that will be incorporated. The reference scenario comprises events and processes (EPs) with a unit probability and represents the expected evolution of the storage system. Variant scenarios include—in addition to the EPs of the reference scenario—one or more EPs, the future occurrence of which is uncertain.

FEP analysis

The FEP database is used to support the FEP analysis process. It keeps track of all the steps and decisions that are made during the evaluation of individual FEPs. It is used to analyze interactions with other FEPs and supports the grouping process. The FEP grouping process is also supported by the visual analysis software “GRIN” [2]. This tool visualizes the interaction between FEPs as an influence diagram and provides options to present FEP groups. The analytical tools for the various stages of FEP analysis are provided either by the FEP database or by the visual analyzer “GRIN” (Figure 2).

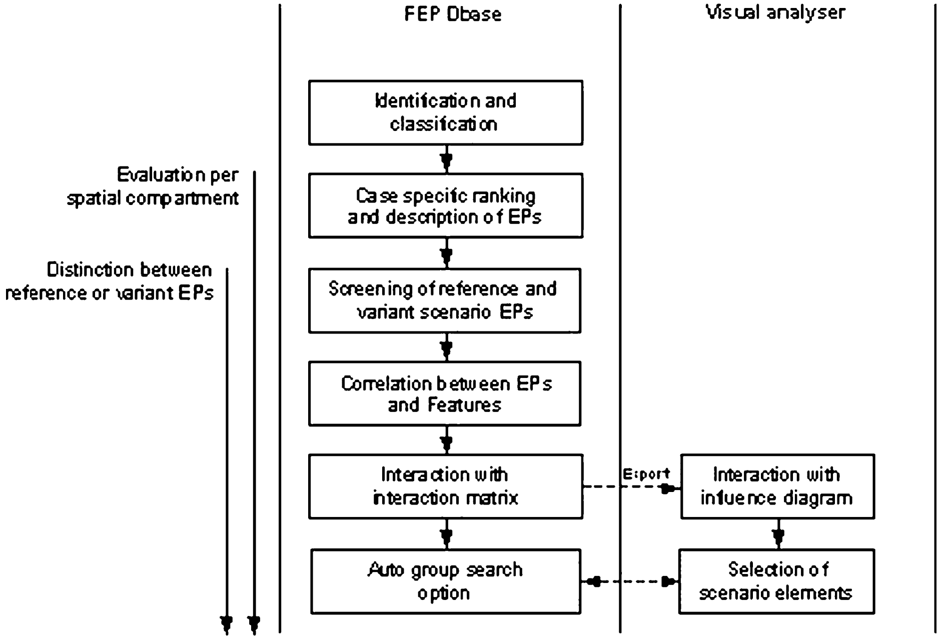
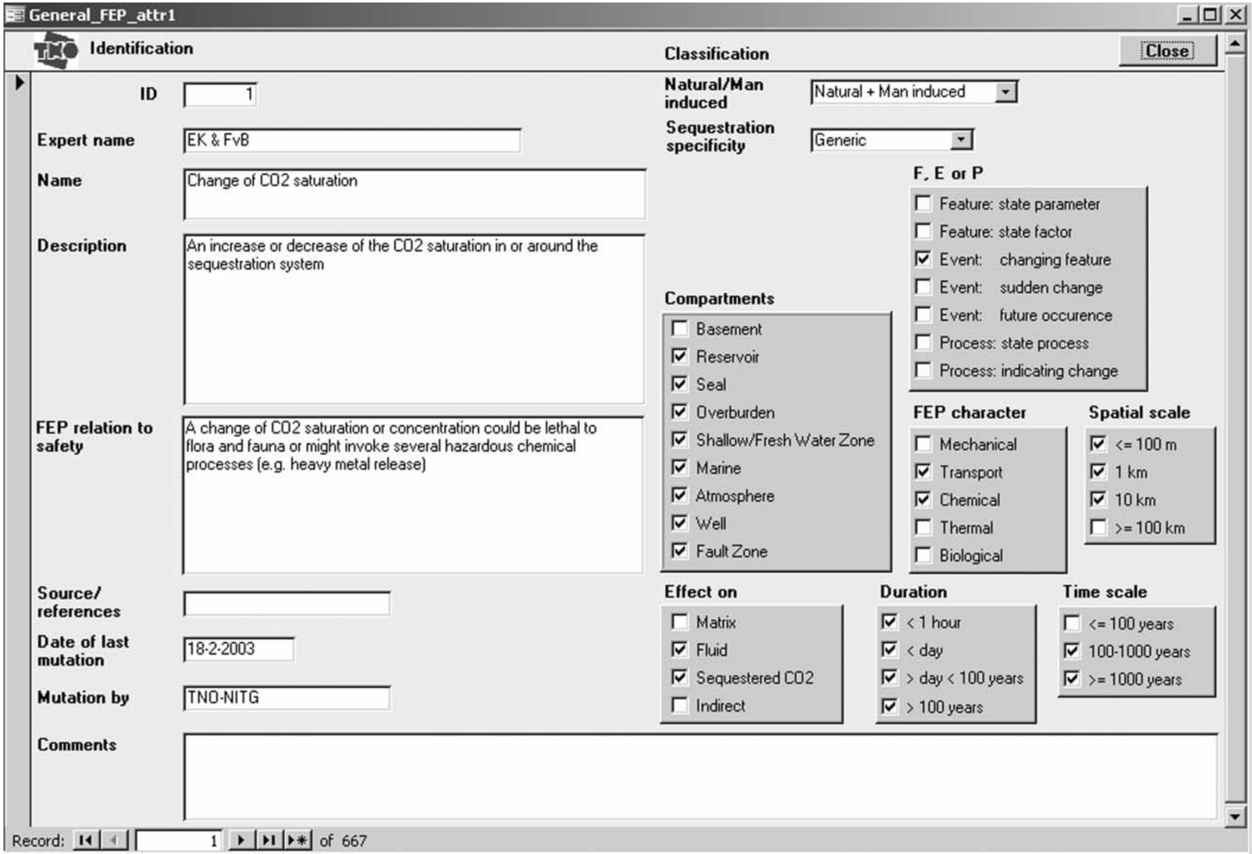


Figure 2: Scheme of the various phases in FEP analysis with special reference to the supporting software tools.

Identification and classification. All FEPs in the FEP database have a complete set of identification and classification attributes (Figure 3). The identification and classification of FEPs is performed in a qualitative generic way, independent of the storage site or assessment basis.

Ranking. The generic identification and classification attributes are used as the starting-point for assigning case-specific descriptions during the ranking phase. This and next phases of the scenario analysis are performed by experts or expert groups, for example in workshops. In the ranking phase, it is allowed to add case-specific information to the database. The expert evaluator has the option to split generic FEPs into several more detailed, case-specific FEPs, to which he can assign different semi-quantitative probability and impact levels.

During the ranking process, a distinction is made between features as static factors, on one hand, and EPs as dynamic factors on the other hand. Only the EPs will be ranked. The EPs represent potential future changes and dynamical aspects of the storage facility that may lead to unintended leakage of CO_2 or to unintended



Identification

ID 1

Expert name EK & FvB

Name Change of CO2 saturation

Description An increase or decrease of the CO2 saturation in or around the sequestration system

FEP relation to safety A change of CO2 saturation or concentration could be lethal to flora and fauna or might invoke several hazardous chemical processes (e.g. heavy metal release)

Source/ references

Date of last mutation 18-2-2003

Mutation by TNO-NITG

Comments

Classification

Natural/Man induced Natural + Man induced

Sequestration specificity Generic

F, E or P

- ☐ Feature: state parameter
- ☐ Feature: state factor
- ☑ Event: changing feature
- ☐ Event: sudden change
- ☐ Event: future occurence
- ☐ Process: state process
- ☐ Process: indicating change

Compartments

- ☐ Basement
- ☑ Reservoir
- ☑ Seal
- ☑ Overburden
- ☑ Shallow/Fresh Water Zone
- ☑ Marine
- ☑ Atmosphere
- ☑ Well
- ☑ Fault Zone

FEP character

- ☐ Mechanical
- ☑ Transport
- ☑ Chemical
- ☐ Thermal
- ☐ Biological

Spatial scale

- ☑ <= 100 m
- ☑ 1 km
- ☑ 10 km
- ☐ >= 100 km

Effect on

- ☐ Matrix
- ☑ Fluid
- ☑ Sequestered CO2
- ☐ Indirect

Duration

- ☑ < 1 hour
- ☑ < day
- ☑ > day < 100 years
- ☑ > 100 years

Time scale

- ☐ <= 100 years
- ☑ 100-1000 years
- ☑ >= 1000 years

Record: 1 of 667

Figure 3: Example of one of the input screens in the CO_2 FEP database showing stored generic information; identification attributes are shown to the left and classification attributes to the right.

seismic movement of the earth's surface. The most important attributes that are determined in the ranking phase are (1) the semi-quantitative probability that an EP will occur, (2) potential impact if the EP occurs, and (3) the relevance for assessment. These three attributes are assessed based on expert opinion.

The estimated probability of an EP reflects the probability that an individual EP may occur within the time frame of the assessment. No distinction is made between possible causes of the EP. In case of uncertainty with respect to the actual probability and impact, its estimation should be done in a conservative way. This means that the actual probability and impact might be overestimated.

Screening. Based on the semi-quantitative probability and impact, resulting from the ranking phase, a distinction is made between reference scenario EPs, variant scenario EPs and irrelevant EPs for the safety assessment. The semi-quantitative risk matrix in Table 2 is used to categorize the different types of EPs during the screening process. EPs with a low risk or very low risk are considered irrelevant for further analysis. Remaining EPs with a probability of very likely are the reference scenario EPs. Other EPs are categorized as variant scenario EP.

TABLE 2
SEMI-QUANTITATIVE RISK MATRIX

		Potential impact		
Significant	High risk	High risk	Medium risk (l)	Medium risk (s)
Marginal	Medium risk (l)	Medium risk (l)	Medium risk (s)	Low risk
Negligible	Low risk	Low risk	Low risk	Very low risk
Likelihood				
	Very likely	Likely	Unlikely	Very unlikely

Medium risk FEPs are sub-categorized as either (l) large or (s) small medium risk categories.

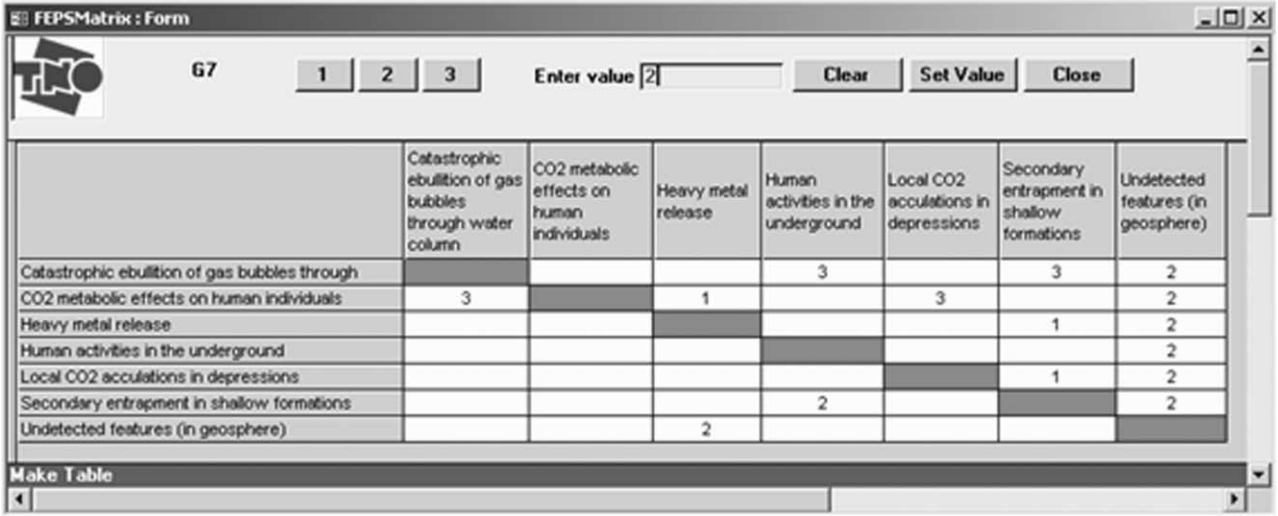
F-EP correlation. Features are correlated with the EPs in the F-EP screening evaluation form. The objective of the screening form is to register the cause–effect relationship between the dynamic risk factors (EPs) and static factors (features). If an EP has effect on one or more features of the storage facility, these features will be included in the scenario analysis.

Interaction. The FEP interaction matrix represents the relative intensity of the influence of an EP on another EP (see Figure 4). Three intensity levels are identified: three is high intensity and one is low intensity of this cause–effect relationship. Additional information on mutual features and process characteristics can be retrieved by double clicks on the input fields of the interaction matrix (Figure 4). A description of the interaction can be registered in the interaction information form.

The interaction between EPs can also be presented as an influence diagram (Figure 5) with the aid of the visual analysis software. The influence diagram visualizes the risk magnitude of the individual EP together with the direction and weight of interaction between EPs.

EP grouping. The influence diagram supports the EP grouping process with the aid of the automatic group search option provided in the FEP database. Criteria for EP groups can be based on the information that is available in the FEP database like

- common parameters (distinct features such as permeability, rock strength, etc.),
- process types (mechanical, chemical, thermal, hydraulic, biological),
- effect type (on matrix, fluid, sequestered CO_2, indirect),
- time scale of EP occurrence (in 100 years, in 1000 years, or in 10,000 years),
- duration scale of EP while occurring (hours, days, centuries and longer), and
- spatial scale (1 m, 1 km, 10 km, basin scale).



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	Catastrophic ebullition of gas bubbles through water column	CO2 metabolic effects on human individuals	Heavy metal release	Human activities in the underground	Local CO2 acculations in depressions	Secondary entrapment in shallow formations	Undetected features (in geosphere)
Catastrophic ebullition of gas bubbles through	▨			3		3	2
CO2 metabolic effects on human individuals	3	▨	1		3		2
Heavy metal release			▨			1	2
Human activities in the underground				▨			2
Local CO2 acculations in depressions					▨	1	2
Secondary entrapment in shallow formations				2		▨	2
Undetected features (in geosphere)			2				▨

Figure 4: Example of an interaction matrix in the CO_2 FEP database.

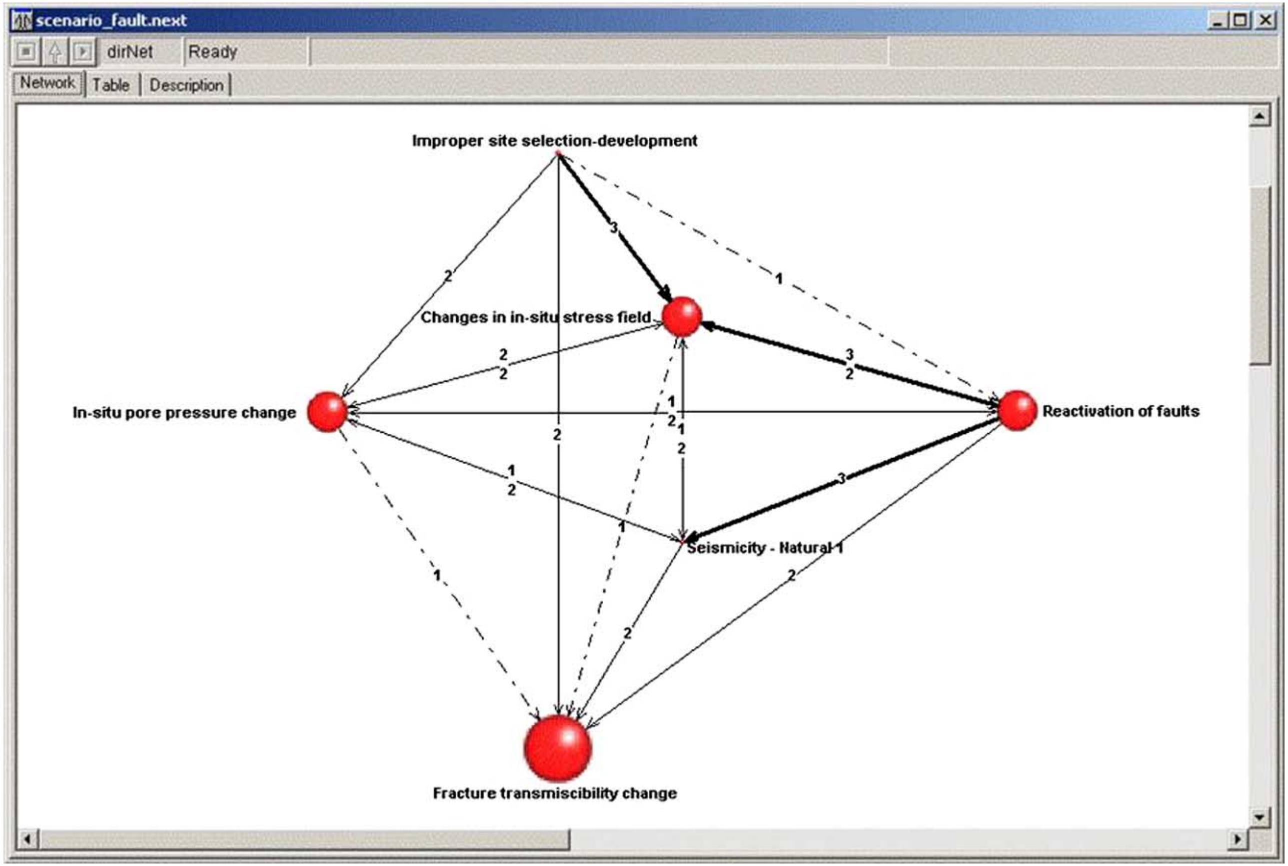


Figure 5: Example of an influence diagram.

Scenario elements. The way EP groups are assigned to specific compartments, depends on the type of compartment. An EP group is a combination of interrelated EPs that affect

1. the integrity of the containment zone consisting of the reservoir, seal, fault and well/engineering compartments,
2. the migration of CO_2 from the zone from the containment zone to the biosphere
3. the biosphere (see also Section on "Assessment basis"), which consists of the shallow/fresh water compartment, marine compartment and atmospheric compartment.

Per compartment one or more different EP groups (or scenario elements) can be defined depending on the spatial and temporal (in-)consistency of the individual EPs. Huge groups might be split in subgroups for mere practical reasons. Scenario elements are presented as tables and influence diagrams.

The core of a scenario element is formed by the EP or a group of EPs that directly affect the integrity of the containment zone, the migration of CO_2 in the overburden to the biosphere or health, safety and environment in the biosphere. Secondly, the EP or group of EPs that initiate or drive the EPs mentioned above should be identified. The grouping must be such that the resulting combination of EPs is consistent in time and space.

Scenario formation
Scenarios are formed through the logical combination of the scenario elements resulting in a complete description of a potential future state or evolution of the storage facility for every scenario. Temporal and spatial consistency of the assembled scenario elements must be checked. No specific software tools have been developed to support the scenario formation process itself. In this study, the scenarios are presented in a tree diagram.

The individual EPs in the conceptual models of individual scenarios are either represented as

- a parameter,
- a process or equation representing a physical law,
- a boundary condition, and
- other, e.g. a conservatively determined constant.

Or not represented.

The transfer of individual FEPs in a scenario element to the conceptual model representing the scenario element is discussed with the aid of tables. An example is given in Table 3.

Model Development
Scenarios are the starting-points for the development of conceptual physical/chemical models, on the basis of which mathematical models are constructed or selected from existing software libraries. A complete analysis of each of the scenarios requires simulations with the individual models for the different compartments that play a role in the transport of CO_2 from the geosphere to the biosphere.

In general, the inputs that are required for such models are inherently uncertain. Consequently, CO_2 fluxes and concentrations predicted with these models are uncertain. Quantification of this uncertainty requires Monte Carlo type simulations with the mathematical models. If these simulations are carried out with the complicated models for the different compartments, the computer resources required for such an analysis will be tremendous. Therefore, simplification of the models for the different compartments is then necessary, introducing more uncertainty in the final results. There are a number of ways these simplified models can be obtained:

- *Reducing the dimensionality of the problem.*A typical example of reduction of the dimensionality is the description of the transport of CO_2 in a radial symmetric system (2D) rather than in a fully 3D mode. This can, for example, be done for an injection well that starts leaking because of degradation of the well cementing and casing. However, one cannot give general rules when this simplification can be adopted.

TABLE 3
EXAMPLE OF A TABLE SHOWING THE INDIVIDUAL REPRESENTATION OF FEPS

A/G	**Scenario element**	**FEPs included**	**Parameter change**	**Physical law/ equation**	**Boundary condition**	**Not represented**	**Other**
A, G	Reservoir/ Seal-Ref-	Changed fluid chemistry	×				
		Alkalinity change	×				
		Chemical equilibrium reactions		×			
		Kinetics of chemical reactions		×			
		In situ pore pressure change	×				
		Stress change	×				
		P and *T* phase behavior of the CO_2-reservoir system		×			
		Water mediated transport of contaminants				×	

In this example the representation of reference scenario FEPs is listed.

In each specific case (site), transport paths for the CO_2 have to be studied with a full-scale model before adopting this approach.

- *Lumping of the effect of certain processes*. In case the dimensionality of the problem cannot be reduced, a different approach needs to be taken. That is, e.g. the case with the leaking fault scenario. The structure of the fault in relation to the injection well and the shape of the reservoir do not allow for a 2D radial symmetric description of the CO_2 transport. Since the vertical resistance to flow is one of the important properties of the system, lumping the horizontal layers in the model to a smaller number of layers, making sure the vertical resistance is the same, can be considered. Also, the lateral extend of the model might be reduced, thus constructing a simplified model that is still 3D, but requires much less grid blocks.
- *Neglecting the effect of certain processes*. Some of the physical processes taking place in the system are either highly non-linear, or pose numerical constrictions on the solution. A typical example of such processes is the dissolution of CO_2 in the water phase. One could consider neglecting this process, as was done in the reservoir/seal/overburden model.

For risk assessment, simplifications can only be accepted if they do not lead to underestimation of the CO_2 fluxes and/or concentrations. For some of the simplifications mentioned above the effect is obvious. If, for example, we neglect the dissolution of CO_2 in the reservoir and overburden, we are certain that the transport of CO_2 in this compartment will be overestimated. For other simplifications, this is not obvious, like the reduction of the number of vertical layers and the lateral extend in the case of the fault leakage scenario. In all cases, however, the simplified models should be calibrated on the basis of the results obtained with comprehensive models.

The Safety Assessment (SA) model quantifies the risks of the individual HSE scenarios. It is based on the results of the underlying simplified compartment models and Monte Carlo simulation with these models. Monte Carlo simulation is necessary to quantify the effect of the parameter uncertainty. The difficult part in this Monte Carlo simulation is to determine the probability distributions of the relevant physical parameters. In most cases these will be generated by expert judgment. Sensitivity analysis with the simplified models will be carried out to determine the number of required Monte Carlo simulations obtaining a good estimate of the probability distributions of the relevant outputs. The safety model comprises representations of all relevant components: the stored CO_2, the reservoir, the seal, the overburden, the soil and the atmosphere. It handles both the uncertainty in the input parameters and the uncertainty generated by the simplification of the detailed compartment models. Limited detailed modeling of individual processes is, however, still necessary to prove that the processes incorporated in the safety model have a sound physical basis. Basically, the safety model will generate probability distributions of CO_2 fluxes on the basis of limited input. It is based on interpolation using Parzen density functions [3].

Figure 6 gives an overview of the different model concepts that are being used in the construction of the safety assessment model and the interrelation between the concepts.

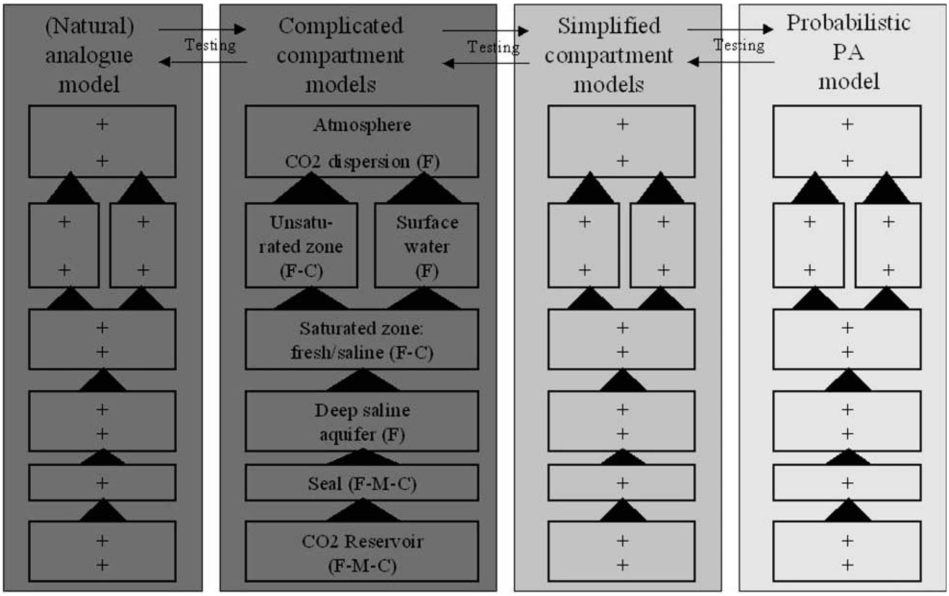


Figure 6: Relation between the different models to construct the safety assessment model.

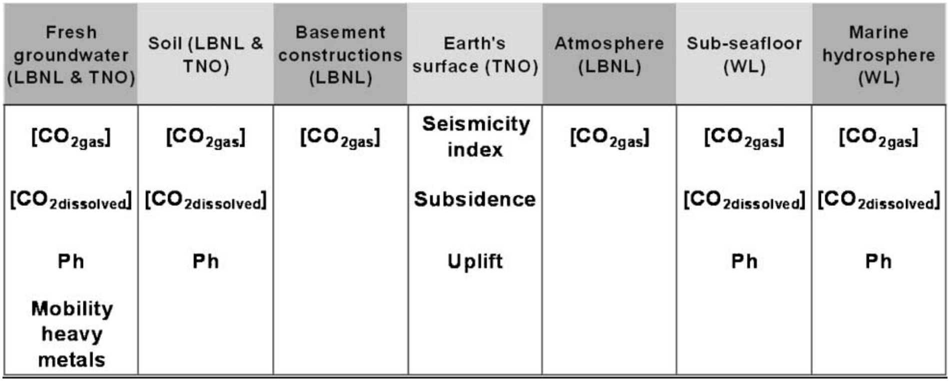
Testing and model validation is a very important and extensive activity in the model development. Test cases should relate to a specific storage option and a specific regional geological setting. Case histories for short-term assessment (< 100 years) can be found in already existing CO_2 storage projects (SACS or Weyburn). For the long-term assessment, natural analogues of CO_2 storage may be useful.

Consequence Analysis

Before the consequences of leakage can be assessed, one has to define the basis on which risks to human health and to the environment should be assessed. Figure 7 gives an overview of the assessment variables in different compartments. In almost all compartments, the concentration of CO_2 in the gas phase is an important assessment variable, because this determines among other things the risk to living creatures. Also the concentration of CO_2 in the water phase can play an important role. For example, in the shallow subsurface the CO_2 concentration in the water phase has an effect on the possible mobility of heavy metals, which might threaten the drinking water supply in populated areas.

The analysis of the consequences of the scenarios can be performed in two modes:

- Deterministic
- Probabilistic



Fresh groundwater (LBNL & TNO)	Soil (LBNL & TNO)	Basement constructions (LBNL)	Earth's surface (TNO)	Atmosphere (LBNL)	Sub-seafloor (WL)	Marine hydrosphere (WL)
[CO_{2gas}]	[CO_{2gas}]	[CO_{2gas}]	Seismicity index	[CO_{2gas}]	[CO_{2gas}]	[CO_{2gas}]
[$CO_{2dissolved}$]	[$CO_{2dissolved}$]		Subsidence		[$CO_{2dissolved}$]	[$CO_{2dissolved}$]
Ph	Ph		Uplift		Ph	Ph
Mobility heavy metals						

Figure 7: Assessment variables in the different compartments.

When the consequences of the scenarios are deterministically analyzed the relevant processes are modeled in a detailed way using fixed and time-independent parameter values. The selection of these fixed values is problematic as they can change in time or simply are unknown. Consequently, the results of the deterministic models will be highly uncertain. An approach often followed then is the selection of so-called conservative values. This means that realistic parameter values are selected in such a way that the consequences for CO_2 leakage are over-estimated. There, however, is not always a simple monotonic relation between the parameter values and the consequences. Even if conservative parameter values can be determined, it will still be difficult to compare the results for different scenarios as the amount of conservatism is unknown and most probable are different for the different scenarios. Furthermore, selection of "worst case" parameter values for all physical parameters in the system will result in a highly unlikely scenario, which is of little value to use as a basis for comparison.

For that reason we have adopted a probabilistic approach, in which the problem of the parameter uncertainty and model simplification is handled by a probabilistic interpolation technique (see previous section). This means that the result of this approach will consist of probability density functions for the assessment variables such as CO_2 fluxes, concentrations and pH, which will allow for a straightforward comparison of results for different scenarios.

RESULTS AND DISCUSSION

The example of a safety assessment is presented to illustrate the applicability of the developed methodology. The outcome of this assessment example should certainly not be considered as a formal site-specific safety assessment and thus should not be used for the actual assessment of the storage option or a site in the considered part of the North Sea region.

Assessment Basis

Assessment criteria

At the time of writing no formally accepted safety criteria for underground CO_2 storage are available. Benson et al. [4] did a literature review on safety and environmental aspects of underground CO_2 storage. Regulation in the US prescribes maximum limits of CO_2 concentration for various exposure times ranging from 5000 to 50,000 ppm. In the current assessment a concentration criterion of 10,000 ppm has been used. The criterion of maximum concentration of heavy metals in groundwater has been set according to regulations in the Netherlands.

Storage concept

In the current assessment the classical structural trap concept was adopted consisting of a CO_2 reservoir, a top seal and side seals. The majority of the stored CO_2 is assumed to be present as free gas.

Setting of the storage site

A domal trap structure typical for the UK sector in the southern North Sea [5] was considered. The reservoir consists of Bunter sandstone and the seal is predominantly rock salt. Exploration wells may be present that transect the reservoir. This geological setting was placed in two different geographical settings, a marine and a continental environment. The marine environment is typical of shallow waters in the southern North Sea. The continental setting is typical of a lowland area in the south-western Netherlands.

Timescale and spatial domain of the storage system

Potential risks within the next 10,000 years after termination of CO_2 injection will be assessed.

Scenarios and Related FEPs

A FEP analysis was performed with the aid of the FEP database and influence diagram software. FEPs were screened and assigned to either the reference scenario or to the variant scenarios. FEP groups were identified for the individual spatial compartments, resulting in one or more scenario elements per compartment. The elements have been logically combined in discrete scenarios. The objective is to identify the most critical scenarios.

Reference scenario

This scenario includes all EPs that are very likely to occur and might affect seal integrity and migration of CO_2 to the biosphere. The reference scenario EPs are included in both the reference scenario itself and all variant scenarios. The EPs assigned to the reference scenario are given in Table 4.

The following reference scenario EPs have not been evaluated in the conceptual models: soil mechanical behavior of CO_2 in the onshore shallow subsurface compartment, platform legs penetrating the overburden in the offshore shallow subsurface compartment and phase behavior of CO_2 in the atmospheric compartment. For purely practical reasons the atmospheric compartment has not been incorporated in the current safety assessment.

Variant scenarios

Next to the reference scenario, the scenario analysis has resulted in the identification of variant scenarios, the occurrence of which is uncertain. One or more scenario elements have been defined for each compartment or group of compartments and subsequently, scenarios have been constructed through assemblage of the scenario elements.

Reservoir/seal, fault and well compartments. About 40 EPs have been identified in the reservoir/seal compartment, the fault compartment and the well compartment, that could potentially affect the seal integrity. This number of EPs has been considered far too large for individual assessment and had to be split in subgroups of EPs.

The guiding principle here is to

1. identify those EPs that directly affect seal integrity and,
2. identify other EPs that initiate or force the EP that is directly affecting seal integrity.

The combination of these two types of EPs forms the central part of a variant scenario. Other interrelated EPs that are not directly affecting seal integrity or initiating the deterioration of the seal integrity will be included in the scenario element as well.

Two examples of scenario elements that represent potential reduction of seal integrity have been selected for further quantitative analysis:

- *Well scenario element*. Degradation of cement and casing might lead to unintended leakage of CO_2 to the biosphere.
- *Fault scenario element*. An undetected fault might lead to unintended leakage of CO_2 to the biosphere.

TABLE 4
REFERENCE SCENARIO EPS AND THEIR REPRESENTATION IN THE SAMCARDS CONCEPTUAL MODELS

On/ Off	Scenario element	FEPs included	Parameter change	Physical law/ equation	Boundary condition	Not repre- sented	Other
On, Off	Reservoir/ Seal-Ref-	Flow and fate of CO_2 over multiple phases		×			
		Changed fluid chemistry	×				
		Alkalinity change	×				
		Chemical equilibrium reactions		×			
		Kinetics of chemical reactions		×			
		In situ pore pressure change	×				
		Stress change	×				
		P and T phase behavior of the CO_2-reservoir system		×			
On, Off	Fault	None					
On, Off	Well/ engineering	None					
On, Off	Overburden-Ref-	Flow and fate of CO_2 over multiple phases		×			
		Phase behavior of CO_2		×			
On	Shallow subsurface-Ref-	Flow and fate of CO_2 over multiple phases		×			
		Phase behavior of CO_2		×			
		Soil mechanical behavior				×	
		Platform legs penetrating the overburden				×	
Off	Marine compartment-Ref-	Flow and fate of CO_2 over multiple phases		×			
		Phase behavior of CO_2		×			
		Soil mechanical behavior	×				
		Wind induced transport in water column		×			
		Tidal driven transport		×			
On, Off	Atmosphere-Ref-	Phase behavior of CO_2				×	

In the first column: On, onshore case; Off, offshore case.

Overburden and biosphere compartments. In the overburden compartment about 10 EPs have been identified that could affect the migration of CO_2 to the biosphere. Except for the fault and well scenario elements that transect the overburden, no variant scenario elements additional to the reference scenario element of the overburden have been selected for further quantitative analysis. The variant scenario EPs in the overburden have incorporated in the fault leakage scenario.

Four EPs have been identified for the shallow subsurface and marine compartments, of which secondary entrapment of CO_2 is considered to be most relevant. A variant scenario element with this particular EP has been constructed for the marine compartment.

The following variant EPs have not been evaluated in the conceptual models: undetected features, future man induced EPs (e.g. drilling, interference other projects), improved cap rock integrity, meteorite impact and local CO_2 accumulations in depressions. As explained earlier, the atmospheric compartment has not been included in the present safety assessment.

The summary of the identified scenario elements is given in Table 5. A scenario tree based on various possible future states of the individual model compartments is given in Figure 8.

TABLE 5
DESCRIPTION OF SCENARIO ELEMENTS

Compartment	**Reference scenario element**	**Variant scenario element**
Atmosphere	Regular atmospheric transport of CO_2 as a gas phase. *Not represented as scenario element*	Depression element: potential of accumulation of CO_2 in depressions under stable atmospheric conditions. *Not represented as scenario element*
Shallow subsurface	Multi-phase transport of CO_2 in a layered aquifer/aquitard system, slow process	Human intrusion element: unforeseen and sudden release of CO_2 from secondary entrapped CO_2 accumulations triggered by human activities in combination with neglect. *Not represented as scenario element*
Marine	Multi-phase transport of CO_2 in a layered aquifer/aquitard system below the seabed. Depending on the CO_2 flux, the majority of CO_2 will dissolve in the water column	Local ebullition of gas bubbles from secondary entrapped CO_2 accumulations as a result of natural processes or triggered by human activities in combination with neglect
Overburden	Transport of CO_2 in a layered aquifer/aquitard system, slow process	*See also leaking fault scenario element*
Fault	*No element*	Leaking fault scenario element: transmissibility increase as a result of natural and man-induced events and processes followed by transport of CO_2 from the reservoir into the overburden along the fault plane
Well	*No element*	Leaking well scenario element: release of CO_2 from the reservoir into the overburden along the well trajectory as a result of chemical processes (e.g. metallic corrosion and cement degradation) around the well bore
Reservoir/seal	Transmissibility increase of the seal as a result of interacting chemical and mechanical processes	*See also leaking fault and leaking well scenario elements*

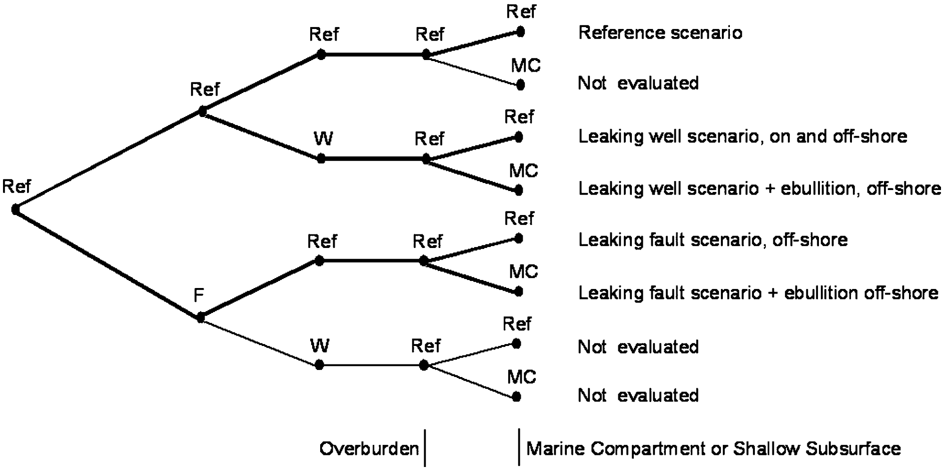


Figure 8: Scenario tree diagram resulting after combination of scenario elements.

HSE Consequences

Three different scenarios have been considered for the analysis of the consequences of CO_2 storage in the deep subsurface:

- The reference scenario, where the natural barrier is assumed to be intact.
- The leaking well scenario, where it is assumed that a conventional well completion degrades as a consequence of contact with high concentrations of CO_2. This will result in largely increased permeability around the well, thus creating a potential pathway for the CO_2 to the biosphere.
- The leaking fault scenario, where a fault in the vicinity of the injection well acts as a potential natural pathway for CO_2 to the atmosphere.

Reference scenario

For the Monte Carlo simulations in the reference scenario all relevant parameters are assumed to have uncertainty associated with them. These parameters are: the shale vertical permeability, the porosity, the reservoir sand horizontal permeability, the salinity and the seal vertical permeability. Table 6 shows the mean values and the probability distributions associated with these input parameters.

TABLE 6

PROBABILITY DISTRIBUTION OF SYSTEM PARAMETERS FOR THE REFERENCE SCENARIO

Parameter	Units	Type of distribution	Low	Mean	High
Salinity	kg/m^3	Triangular	8.5	10.5	12.5
Seal vert permeability	mD	Lognormal	− 0.5 In-unit	0.0001	+ 0.5 In-unit
Shale vert permeability	mD	Lognormal	− 0.5 In-unit	0.01	+ 0.5 In-unit
Sand horn permeability	mD	Lognormal	− 0.5 In-unit	100.0	+ 0.5 In-unit
Porosity average	Proporation	Triangular	0.12	0.17	0.20

The Monte Carlo simulation of the reference case results in a total containment of CO_2 within the reservoir and seal layers for all parameter realizations. No CO_2 migration is detected directly above the seal. A typical result is depicted in Figure 9, which shows that CO_2 partly migrated and partly remains in the reservoir.

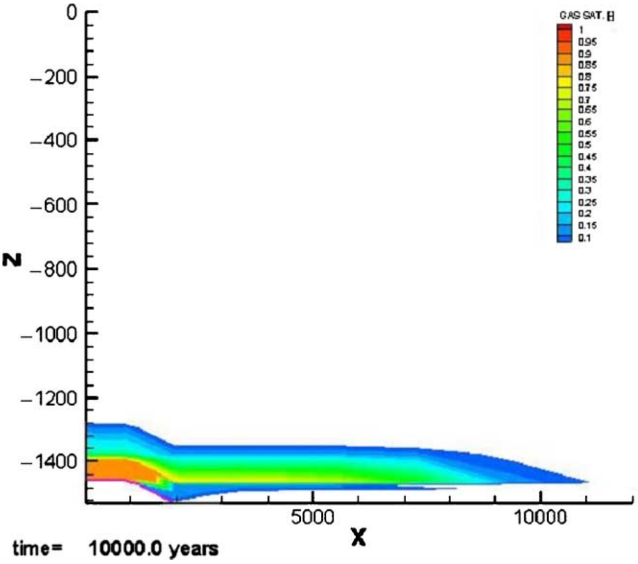


Figure 9: Areal distribution of CO_2 in reservoir and seal 10,000 years after start of injection of 1 Mt CO_2 per year for 100 years in the reference scenario.

Since no CO_2 appears above the seal in the reference scenario, no further probabilistic treatment of the biosphere compartments is necessary.

Well leakage scenario

For the Monte Carlo simulations for the leaking well scenario the relevant parameters that have uncertainty associated with them are: the shale vertical permeability, the porosity, the reservoir sand horizontal permeability, the salinity and the well zone permeability. For all parameters the same distribution as in the reference scenario were taken. The maximum well cement permeability is assumed to be log normally distributed with a mean of 10,000 mD [6] and a standard deviation of 0.5 (on a ln scale). Figure 10 shows a typical CO_2 distribution at 10,000 years after injection in the well leakage scenario.

The fluxes at 300 m below the surface/seafloor, as calculated by the reservoir/seal/overburden model (SIMED; [7]) are characterized by a limited number of characteristic values. For the 1000 Monte Carlo simulations carried out, the statistics of these parameters can be determined. Each of the results of the simulations with the reservoir/seal/overburden model has been used as input for both the marine compartment model (DELFT3D; [8]) and the continental shallow subsurface model (performed by LBNL). Stochastic analyses of the results of these models have been carried out for both environments individually.

Marine environment. Making a probability function from the 4D data allows us to compute marginal distributions and a distribution for the sum of the "build-up" time and the "decay" time of CO_2 in seawater. In the well leakage scenario the added CO_2 concentration in the water is of order of a few times 10^{-5} the normal concentration of HCO_3^- in water, the value of which is considered to be negligible (Figure 11, left).

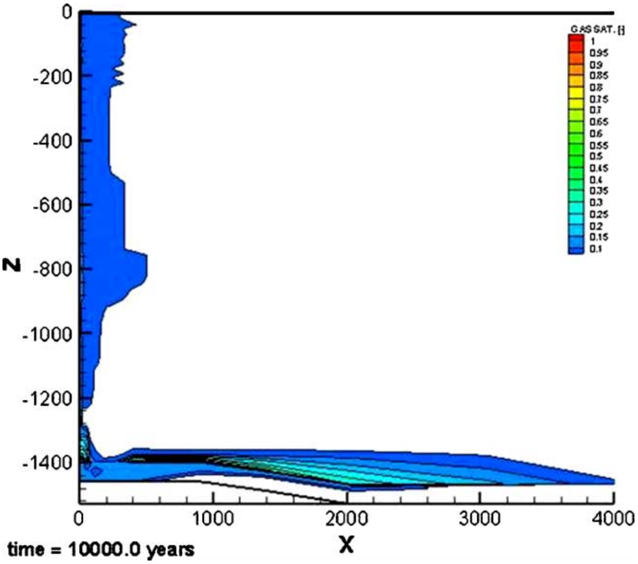


Figure 10: The CO_2 distribution pattern 10,000 years after injection for the well leakage scenario.

Transport process in seawater effectively dilutes CO_2 passing through the sea bottom. The surface area influenced by the surplus CO_2 is substantial at a lower limit of 1 g/m^3 extra CO_2.

An interesting special case of the well leakage scenario occurs when upward migrating CO_2 is trapped secondarily below shallow clay layers, below which CO_2 is able to accumulate. The CO_2 release happens only after pressure build-up. Cracks or channels do form when the clay is made to yield to the pressure, and substantial amounts of CO_2 are released in about a week's time. Part of this bulk release now gets into the atmosphere as well; it is more than the seawater can absorb.

The 2D probability density distribution (CO_2 concentration in water, kg of CO_2 released to the atmosphere) has been constructed in order to generate the marginal distribution of the CO_2 release into the atmosphere (Figure 11, right). An order of magnitude of typical CO_2 releases of 10^8 kg must be expected if this scenario occurred.

Continental environment. In the leaking well scenario has been investigated what would happen in the unsaturated zone, 1 m below ground level. As is seen from Figure 12 (left), the molar fraction of CO_2 exhibits a bi-modular distribution. So far, we have not been able to come up with an explanation for this bimodality. Figure 12 (right) pertains to the mass fraction of CO_2 dissolved in ground water at 40 m below ground level.

At both levels, the CO_2 content just below surface and CO_2 concentrations in water at 40 m, lateral spreading is quite small. The time scales at which the enhanced CO_2 concentrations are noticeable are up to a few thousand years.

Fault leakage scenario

For the Monte Carlo simulations for the leaking fault scenario the relevant parameters that have uncertainty associated with them are: the shale vertical permeability, the porosity, the reservoir sand horizontal permeability, the salinity, the distance from the well to the fault and the fault vertical permeability. For all parameters the same distribution as in the reference scenario were taken. The distance from the well to the fault is assumed to be normally distributed with a mean of 2000 m and a standard deviation of 50 m. The fault vertical permeability is assumed to be log normally distributed with

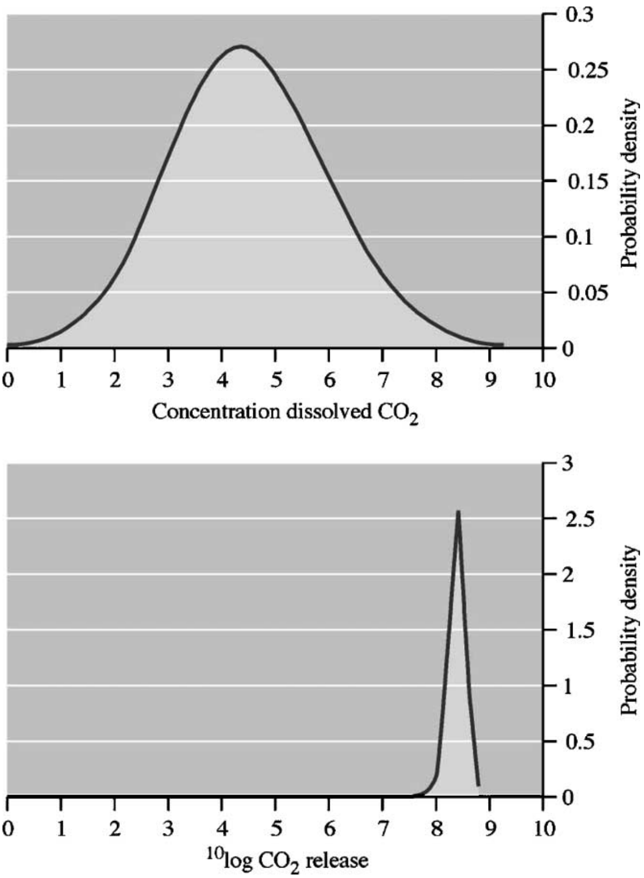


Figure 11: Marginal distributions for the well leakage scenario in a marine setting: CO_2 concentration in water in units of standard CO_2 concentration in seawater × 10^{-5} due to gradual CO_2 release from the seafloor (top) and $^{10}\log CO_2$ release (kg) to the atmosphere due to episodic release of CO_2 from the sea bottom in a week's time (bottom).

a mean, which is dependent on the surrounding lithology (1 mD in case of rock salt, 10 mD in case of shale/claystone and 25 mD in case of chalk), and a standard deviation of 2.3 on a ln scale. This standard deviation corresponds with a factor 10 variation in permeability. Figure 13 shows a typical spatial distribution of CO_2 after 10,000 years for one of the simulations carried out with the reservoir/seal/overburden model.

Each of the results of the simulations with the reservoir/seal/overburden model has been used as input for the marine compartment model. A stochastic analysis of the results of this model has been carried out. The CO_2 concentration increase in seawater due to the fault leakage scenario is typically an order of magnitude less than for the well leakage scenario, and is considered to be negligible.

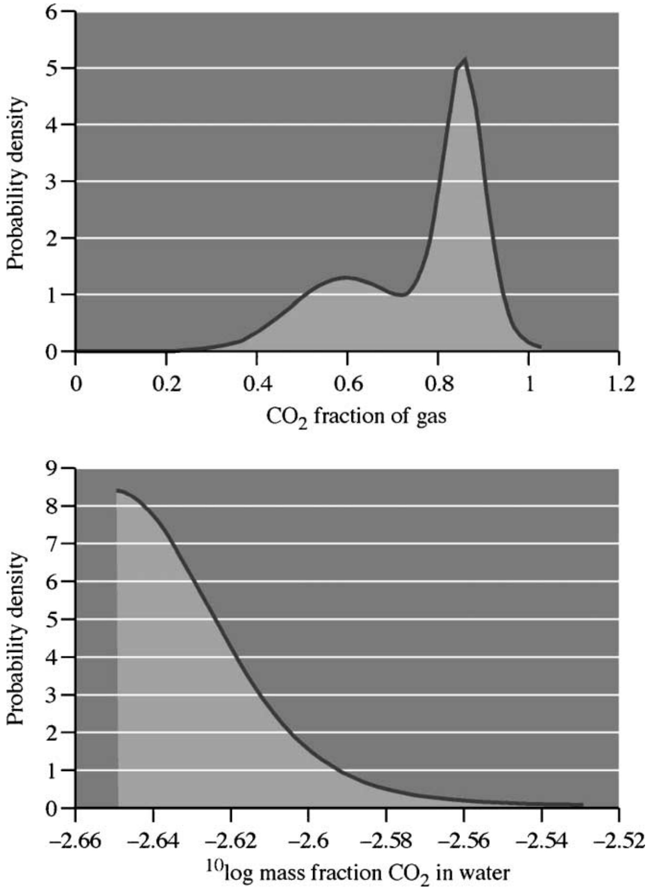


Figure 12: Marginal distributions for the well leakage scenario in a continental setting: CO_2 molar fraction in gas phase in unsaturated zone at 1 m below surface (top) and ^{10}log mass fraction CO_2 dissolved in water at 40 m below surface (bottom).

Secondary entrapment of CO_2 below shallow clay layers may also happen in the fault leakage scenario. Again here, the CO_2 releases to the atmosphere are somewhat less than in the well leakage scenario. Note that not the flux but the resulting CO_2 concentration is determining the impact in the atmosphere.

Discussion

Geologic storage of CO_2 must be secure for hundreds to several thousands of years. Little data is available on this timescale to support safety assessment. Furthermore, monitoring of the storage site will probably not take place indefinitely and the storage site will not only be subject to internal engineering factors of the storage system but also to external natural and human-induced factors.

These factors create special requirements for the methodology and tools for the long-term safety assessment of underground CO_2 storage. To start with, the method should be comprehensive and include all factors that could potentially affect the long-term safety of the site. These factors are both of storage engineering and of external human and natural origin. The method should account for the many

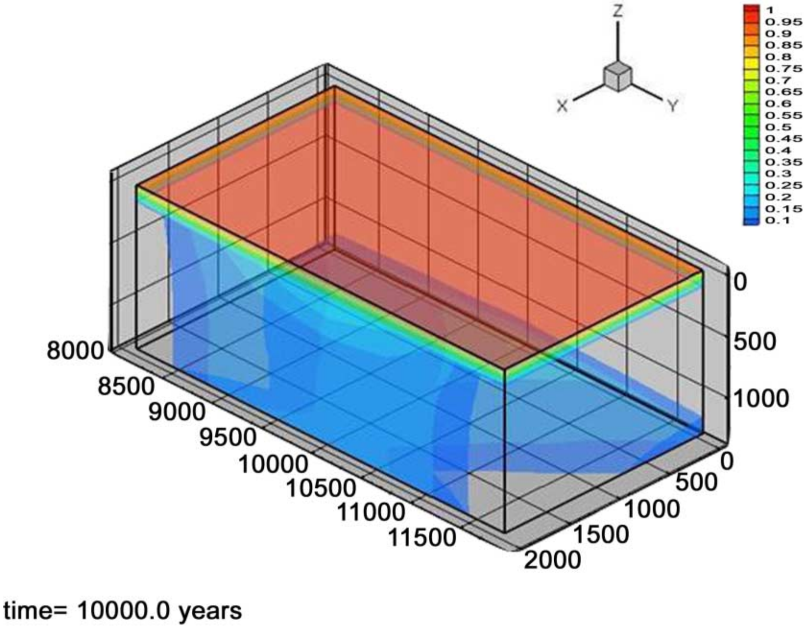


Figure 13: The CO_2 distribution pattern 10,000 years after injection for the fault leakage scenario.

uncertainties that are inherent to long-term assessment. The method should be based on sound physico-mathematical insight and should preferably not use “black-box” models. As case studies of long-term underground CO_2 storage are not yet available, natural or industrial analogues should be found that enable testing of the methods.

The objective of the prsesent research was to develop a methodology and related tools that can be used for the long-term safety assessment of underground CO_2 storage and to demonstrate its technical applicability by applying it in a safety assessment of a virtual storage site. As discussed, the overall methodology for long-term safety assessment of underground CO_2 storage is available and can be readily applied. The three individual basic components of the method, i.e. scenario analysis, model development and consequence analysis, were developed and applied to a realistic example.

Definition of the assessment basis forms the very crucial initial step in the safety assessment. It is extremely important to put substantial effort in this first step, because it contributes significantly to the success of the assessment. The assessment basis relies heavily on the results of the site characterization, information on the design of the storage facility, a clear understanding of the storage concept and knowledge of the HSE criteria that will be applied. A good assessment basis enables the definition of the containment zone and the biosphere in the domain of the storage facility and the assessment criteria that should be applied. Furthermore, it provides decision rules for the screening of the safety factors or FEPs.

Scenario analysis leads to the definition of possible future states or evolution of the storage facility that could lead to unintended leakage of CO_2 (or to unintended (a) seismic movement of the earth’s surface). It consists of two steps: FEP analysis and scenario formation. A FEP database and several supporting tools for the FEP analysis were developed and tested during two workshops. The workshops did not allow testing the full cycle of scenario analysis, though the outcome was promising. It was noted that the FEP database contained ambiguous descriptions of FEPs that caused problems in ranking the FEPs. Also the decision rules for screening of the FEPs should be more clearly stated and more effort should be put in the scientific rationale for assessing individual FEPs.

Detailed process models have been constructed for the different spatial compartments. Simplifications of these models have been constructed on the basis of results obtained with the full-scale detailed models. These simplified models gave results in terms of CO_2 fluxes comparable to the fluxes obtained with the detailed models. Carrying out Monte Carlo simulations with the simplified compartment models did not pose major problems. Statistical analysis of the results of the Monte Carlo simulation has been carried out with the stochastic safety model. This turned out to be a fast and easy tool to determine probabilities of occurrence of CO_2 concentrations exceeding standard values.

The application of the methodology in the consequence analysis is promising. In addition to the reference scenario, two leakage scenarios, i.e. the well leakage and the fault leakage scenario, were defined and quantitatively assessed. The results for the reference scenario showed that seepage of CO_2 to the biosphere would not occur within the period simulated (10,000 years). This was true for all (1000) parameter realizations considered. Statistical analysis was therefore not necessary. For both the well leakage and the fault leakage scenarios, CO_2 concentrations and fluxes showed a large variation as a result of parameter uncertainty in the compartment models. The safety model could easily evaluate probabilities of CO_2 concentrations exceeding certain standards, or CO_2 fluxes exceeding prescribed values.

The gradual release of CO_2 in the well leakage scenario has negligible effects on the marine environment. Sudden release of CO_2 from shallow secondary accumulations just below the sea-bottom results in migration of CO_2 to the atmosphere via the seawater. The impact of atmospheric CO_2 release on safety was not analyzed. Gradual release from a well leads to significant increase of the CO_2 concentration in the unsaturated zone within a limited area. The leaking fault scenario is less hazardous than the leaking well scenario.

Risk management of well leakage can be improved through proper design and implementation of new wells and plugs, and through proper assessment and remediation of old wells combined with a dedicated monitoring system and remediation plan. Risk management of fault leakage should primarily focus on proper site selection, site characterization and testing that is combined with the development of a dedicated monitoring system and a remediation action plan. The effects of monitoring and remediation on lowering the safety risks were, however, not part of the current study.

CONCLUSION

A workable method and supporting tools for the long-term safety assessment of underground CO_2 storage has become available that has been applied successfully to both a virtual onshore site and a virtual offshore site in the southern North Sea region. The method is the amalgamation of qualitative (scenario analysis) and quantitative risk assessment (model development and consequence analysis), which can be applied in all phases of the life cycle of a CO_2 storage facility.

RECOMMENDATION

Safety assessment is a crucial part of the risk management of future underground storage operations (Figure 14), the further development of which should be the prime focus in future research on CO_2 storage. The outcome of the assessment defines the scope for site selection and characterization, design of the facility, testing of the facility, injection operations, abandonment of the site and the period after abandonment. The development of monitoring and remediation plans is directed by the results of the safety assessment.

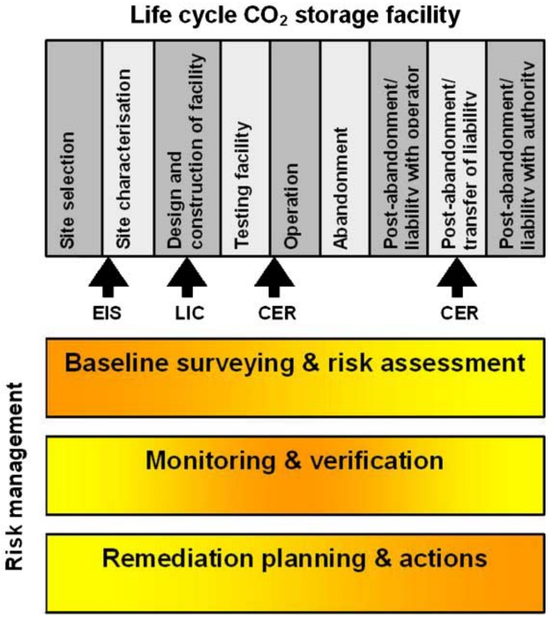


Figure 14: Risk management is the integration of risk assessment, monitoring and remediation through the whole life cycle of a storage facility. Important regulatory milestones for risk management are the Environmental Impact Statement (EIS), Licensing, Certification for (tradable) Carbon Credits and Certification for transfer of liability from operator to competent legal authority.

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