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Experience of the application of a database of generic Features, Events and Processes (FEPs) targeted at geological storage of CO_2

Russell Walke[a]*, Richard Metcalfe[a], Laura Limer[b], Philip Maul[a], Alan Paulley[b], David Savage[c]

[a]*Quintessa Limited, The Hub, Station Road, Henley-on-Thames, Oxfordshire, RG91AY, United Kingdom*
[b]*Quintessa Limited, Birchwood Park, Chadwick House, Warrington, Cheshire, WA36AE, United Kingdom*
[c]*Savage Earth Associates Limited 32 St Albans Avenue, Queens Park, Bournemouth, BH8 9EE, United Kingdom*

Abstract

This paper reviews the application of a freely accessible on-line database of generic Features, Events and Processes (FEPs), designed to support the analysis of geological CO_2 storage systems during performance assessments. The Generic CO_2 FEP Database was established by Quintessa in 2004 through international collaboration under the auspices of the Weyburn project. Subsequently, development of the database has continued and its use has become widespread, with over 1000 people having registered to access the database. Most commonly, the database has been used as an audit tool to help build confidence that a systems analysis covers all relevant FEPs and to document transparently those FEPs that are not being considered. In other applications the generic FEP database has been screened to identify relevant FEPs that are then used directly to build conceptual models.

As a generic resource, the Generic CO_2 FEP Database covers the range of FEPs that might be relevant to assessments, from those associated with the storage formation and cap rock to potential impacts on humans and the environment. The range of applications to date demonstrates its use in support of different scales of assessment for different components of the system. Examples include total-systems models, assessments focusing solely on potential loss of containment from the storage formation and natural analogue studies of potential impacts.

Over the past five years the use of the Generic CO_2 FEP database has helped to build confidence in assessments relating to long-term geological storage. Additionally, the database represents a knowledge base relating to the potential performance and safety of storage systems. The experience gained from application of the database to date helps to inform the way in which it can be applied in future.

The database continues to be developed, based on experience gained in its application. Recently references and links have been updated and a targeted review has revised descriptions and FEPs relating to the marine environment. Further targeted reviews and updates are planned. For the database to continue to structure the latest knowledge and understanding relating to geological storage, on-going feedback from its user base is sought.

Keywords: FEPs; Performance Assessment; Scenarios; On-line database

* Corresponding author. Tel.: +44-1491-636246; fax: +44-1491-636247
E-mail address: russellwalke@quintessa.org

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1. Introduction

Features, Events and Processes (FEPs) provide a means of describing the characteristics of a system of interest in a way that is amenable to structured and transparent analysis. A "system of interest" could in principle refer to the object of any investigation. In the context of CO_2 storage, the system could be the entire storage system (reservoir, caprock, overburden, sideburden, underburden, wells etc.), or some component of this system, such as a well and its immediate surroundings. There are many slightly different formal definitions of the term 'FEP' (e.g. IAEA [1][2]; Wilson and Monea [3]), but fundamentally:

- A 'Feature' is a physical component of a system (in the context of CO_2 storage, 'faults' or 'cap rock' would be features of the system), or a physical entity that influences a system.
- An 'Event' is a process that influences the evolution of the system over a time period that is short compared to the time frame being considered (in the context of CO_2 storage, an earthquake would normally be considered to be an "event").
- A 'Process' is a dynamic interaction between 'Features', which may operate over any particular time interval of interest (in the context of CO_2 storage, displacement of formation fluids would normally be considered to be a "process").

Thus, there is an overlap between the definition of 'Events' and 'Processes'. To a large extent the time frame being considered will determine whether or not a phenomenon is classified as an 'Event' or a 'Process'.

'FEP analysis' refers to the systematic, structured evaluation of which FEPs should be included in an assessment of system performance and the interactions between these FEPs. The FEPs to be considered and the ways in which they are evaluated will depend upon the nature of the assessment (what is being assessed, the purpose of the assessment, and the performance measures, such as risks of specific impacts to the environment, injectivity, storage capacity etc.).

During the 2000s FEP analysis was applied to CO_2 storage projects, leading to the development of Quintessa's on-line Generic CO_2 FEP Database (Savage et al. [3]; Maul et al.[4]; Stenhouse et al. [5]), which may be accessed freely at http://www.quintessa.org/co2fepdb/.

This database was initially developed through international collaboration under the Weyburn project via a series of expert workshops. Subsequently, the database has been developed further and has been widely used and referenced, over 1000 people have registered to access the database. Systems level analysis of geological storage of CO_2 has come a long way since the database was first published (Maul et al. [6]). The present paper reviews the applications of the generic FEP database, illustrating the different ways in which it has been used and seeking to help future assessments to build on this experience.

2. Description of the on-line Generic CO_2 FEP Database

The on-line Generic CO_2 FEP Database, which is presently at version 1.1.0, contains details of FEPs associated with the geological storage of CO_2. The database is generic, in that it is not specific to any particular storage concept or location, but can provide the basis for project-specific and/or site-specific databases and can be cross-referenced from these databases. The FEPs included have been chosen for their relevance to the long-term safety and performance of the storage system after CO_2 injection has ceased, and the injection boreholes have been sealed. FEPs associated with the injection phase are included where these can affect long-term performance and the status of the system at closure.

Each entry in the database includes a FEP description and a note on its relevance to long-term safety and the performance of the system. Further information is provided in the form of references to relevant publications and websites (Figure 1).

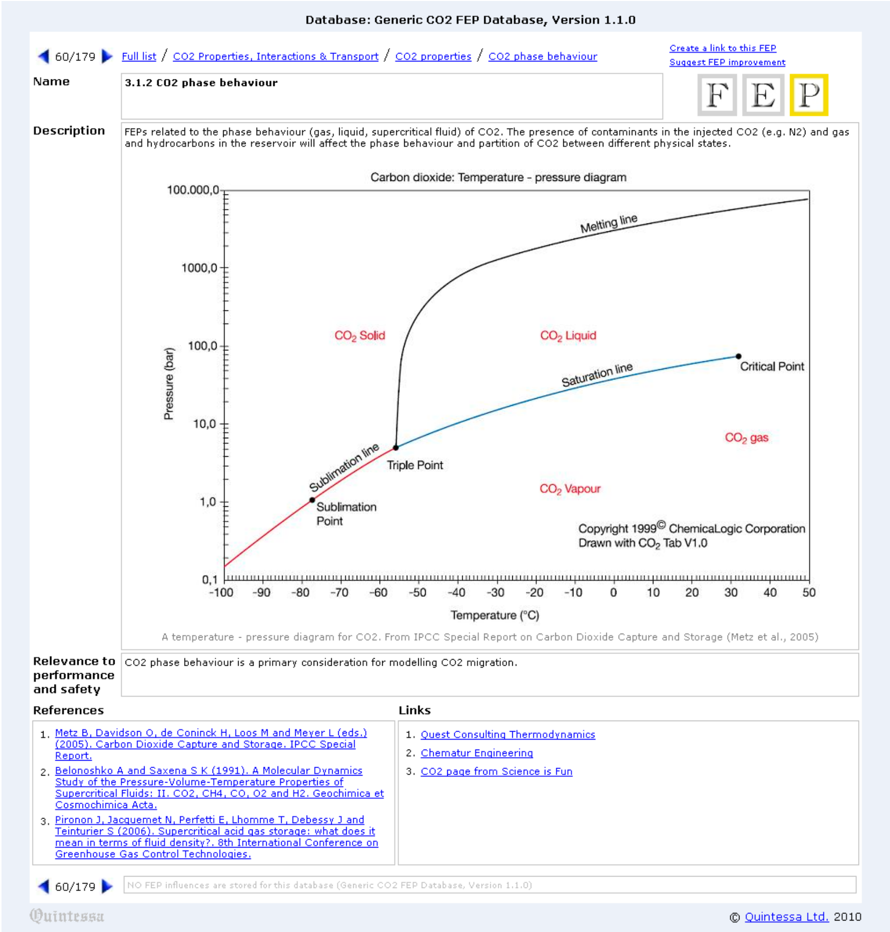

Figure 1: Example from Quintessa's on-line Generic CO_2 FEP Database showing links to sources of information.

The database provides a source of information on the geological storage of carbon dioxide, and can be used as a tool to support systemic assessments of safety and performance. The database is structured hierarchically, with FEPs being grouped into categories and classes. 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.
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 'CO_2 Storage' category of FEPs specifies details of the pre- and post-closure storage concept under consideration.
3. The 'CO_2 Properties, Interactions and Transport' category of FEPs is concerned with those FEPs that are relevant to the fate of the sequestered fluid.
4. The 'Geosphere' category of FEPs is concerned with the geology, hydrogeology and geochemistry of the storage system.
5. The 'Boreholes' category of FEPs is concerned with the way that activity by humans alters the natural system.
6. The 'Near-Surface Environment' category of FEPs is concerned with factors that can be important if sequestered CO_2 returns to the environment that is accessible by humans.

7. The ‘Impacts’ category of FEPs is concerned with endpoints that could be of interest in an assessment of performance and safety.

The most recent development of the database, released in June 2010, involved updating certain FEP entries and adding a new FEP for ‘Impacts on Oceans’, to enhance the relevance of the database for supporting performance assessments of offshore CO2 storage sites, such as Sleipner and Snøvhit. The revision also includes up-to-date references and hyperlinks to information relevant to offshore storage.

3. Applications of the On-line CO2 FEP Database

3.1. Projects that have used the FEP database

The present review concerns only projects that have reported applications of the FEP database in the public domain. There are other projects that have used the database, where details have not been published. The projects reviewed are of three main kinds:

- projects where CO_2 injection is on-going (e.g. Weyburn in Canada (Wilson and Monea [3]), In Salah in Algeria (Paulley et al. [7]) and the Decatur Project in Illinois (Hnottavange-Telleen et al. [8]));
- desk studies aimed at evaluating the feasibility of CO_2 storage (e.g. Kalundborg in Denmark (Larsen et al. [9]), Valleys in Wales (Chadwick et al. [10]) and Williston Basin in North Dakota (Ayash et al. [11])); and
- studies aimed at comparing different performance- and safety- assessment methods with a view to developing refined methodologies and establishing best practices (e.g. CSLF [12] and Oldenburg [13]).

3.2. General approaches to FEP analysis

There are two main approaches to FEP analysis, which have been described as (e.g. Wildenborg et al. [14]; CSLF [12]; Paulley et al. [7]):

1. a ‘top-down’ approach, in which the most important ‘high-level’ FEPs and groups of FEPs are identified and then combined to produce scenarios, which are described in progressively more detail until conceptual models that are amenable to numerical analysis are developed; and
2. a ‘bottom-up’ approach in which detailed site descriptions are used to identify a large number of FEPs that are then combined to produce conceptual models, which are combined further to derive scenarios.

The Generic CO_2 FEP Database has been mainly used to support the first of these approaches (Wilson and Monea [3]; Paulley et al. [7]), although specific applications have some elements of the second kind of approach (Larsen et al. [9]; Chadwick et al. [10]; Ayash et al. [11]). Example workflows associated with the different approaches to using the Generic CO_2 FEP Database are illustrated in Figure 2. The Generic CO_2 FEP Database may be used directly to support assessments (as illustrated in Figure 2), or may be used as the basis for developing or reviewing a project-specific FEP database/list, for which a greater level of detail may be possible and appropriate. The Generic CO_2 FEP Database is often applied as an audit tool in review of project-specific FEP lists and for building confidence that all of the relevant factors have been taken into account in an assessment.

FEP databases are a tool to be used in support of systematic safety and performance assessments and, as such, there is no ‘right’ or ‘wrong’ way to apply them. The choice of approach is made on a case by case basis, depending on the assessment context, with the associated degree of rigour that is appropriate, and on the way in which the assessment team works best. It is evident from Figure 2 that there is a certain degree of overlap between the different approaches and distinctions are somewhat subjective. A practical distinction is that the ‘bottom-up’ approach involves screening out only clearly unimportant FEPs and developing scenarios by considering the remaining, potentially large number of FEPs and interactions between them, whereas the ‘top-down’ approach involves developing scenarios by considering a relatively small number of important FEPs. An important point is that neither ‘top-down’ and ‘bottom-up’ approaches *require* the application of a generic FEP database, but conversely, generic FEP databases can be used to support either approach.

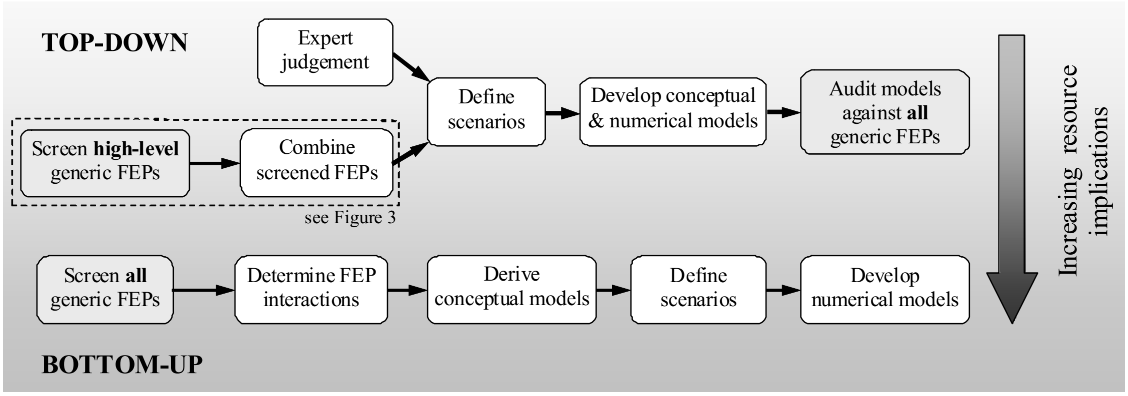

Figure 2: Examples of top-down and bottom-up approaches using the Generic CO_2 FEP Database.

3.3. Example applications of FEP analysis and scenario development

The FEP analyses and scenario development exercises in the Weyburn Project (Wilson and Monea [3]) and the In Salah Project (Paulley et al. [7]) are examples of 'top-down' approaches. During the Weyburn Project, a project-specific FEP list was developed by means of expert workshops, in parallel with the development of the first version of the Generic CO_2 FEP Database (Wilson and Monea [3]). The site-specific FEP list was developed at a general level, with the emphasis being on the use of expert judgment to determine the site characteristics that could impact significantly on risk. The site-specific FEP list was then audited against the Generic CO_2 FEP Database. A broadly similar approach was used when developing scenarios for In Salah, (Paulley et al. [7]). In this case, the main characteristics of the Krechba site at In Salah were identified through an expert workshop and the main events and processes that might affect the site's future evolution were elicited. In both the Weyburn Project and the In Salah Project, scenarios were developed by making distinctions between 'system FEPs' and external FEPs, or 'EFEPs' that originate outside the system but operate upon it. The FEP analyses involved defining the system's boundaries and identifying these two kinds of FEPs. The resulting scenarios then describe alternative potential representations of key FEPs and interactions and/or reflect conceptual uncertainties associated with the potential impact of EFEPs on the system. The general approach is illustrated in Figure 3.

Several projects have used the Generic CO_2 FEP Database directly to identify FEPs that are relevant to a particular site. Although these applications have some similarities to the 'bottom-up' approach (in that they involve assessing a large number of FEPs initially), they are distinguished from it by selecting only a small number of important FEPs and by developing scenarios in a broadly similar fashion to that illustrated in Figure 3. For example, during the CO2STORE project, a risk analysis of the proposed Kalundborg CO_2 storage site in northern Denmark involved evaluating each FEP in the Generic CO_2 FEP Database in turn. The treatment of each FEP in the assessment was determined in light of site data and documented (Larsen et al. [9]). In this way, the most important FEPs were identified. Also during the CO2STORE project, a similar approach was adopted for the proposed Valleys CO_2 storage site in southern Wales, UK (Chadwick et al. [10]). In both cases, a few scenarios were developed involving those FEPs perceived to be most important. These scenarios were then used as a basis for defining numerical simulations. Although in these projects a formal distinction was not made between 'system FEPs' and EFEPs, in the manner of the Weyburn and In Salah Projects, in practice, the 'scenario-generating FEPs' were drawn largely from the external FEPs category of the Generic CO_2 FEP database.

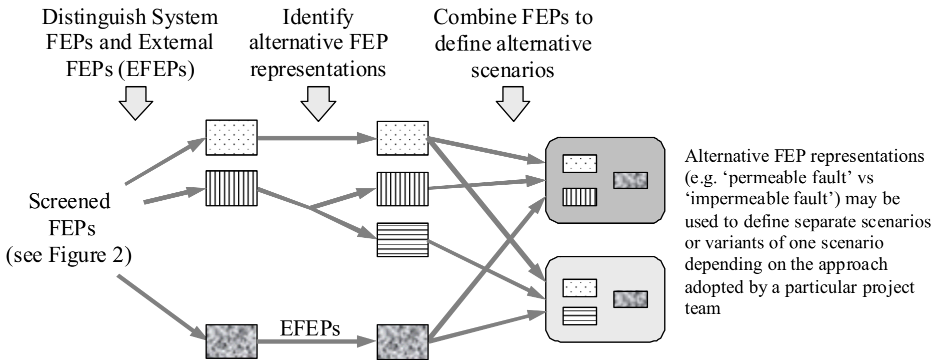

Figure 3: Schematic illustration of the 'top-down' approach to scenario development, which has been adopted at Weyburn (Wilson and Monea, [3]) and at In Salah (Paulley et al. [7]).

Whereas the Kalundborg and Valleys assessments used only expert judgment to select important FEPs from the Generic CO_2 FEP Database, an approach to selecting FEPs based on a combination of expert judgment and numerical analysis was developed by Ayash et al. [11]. In this approach, the probability of a FEP's occurrence is multiplied by its impact to give the risk attributable to the FEP. The probability and impact are calculated by a numerical approach applied in combination with relevant information selected by expert judgment. For example, the risk due to the FEP 'Induced seismicity' in the Williston Basin of North Dakota was calculated. To do this the likelihood of fault movement was estimated using fracture orientation statistics and stress data, and the impact was estimated using historical seismic data. Hence it was judged that the risk of induced seismicity is very small. In so far as the approach developed by Ayash et al. [11] involves the detailed appraisal of each FEP in the Generic CO_2 FEP database, it is similar to the 'bottom-up' approach. However, the approach does not consider interactions between the different FEPs in the database. Furthermore, although not stated by Ayash et al. [11], scenarios would presumably be developed 'top-down' from the small number of FEPs deemed to represent the most significant risks.

Some projects have used the Generic CO_2 FEP Database to derive project- or site-specific FEP databases/lists. In the Decatur Project, Illinois (Hnottavange-Telleen et al. [8]), the Generic CO_2 FEP Database was extended by adding additional FEPs that were defined based on site data. A structured approach involving expert workshops was then followed to identify the impact and probability of occurrence of each FEP on each of several pre-defined performance indicators. The risk of a negative impact being caused on each performance indicator was again defined by combining the impact with the probability of occurrence and was used to determine FEPs of greatest significance. These FEPs were then the subject of more detailed evaluation. Thus, the approach was broadly similar to that of Ayash, but was entirely based on expert judgments and categorised impacts according to performance indicators. Like the approach by Ayash et al. [11], the approach of Hnottavange-Telleen et al. [8] can be regarded as 'top-down' albeit with some 'bottom-up' aspects.

The closest reported approach to the 'bottom-up' approach, as originally specified by Wildenborg et al. [14], is an assessment of hypothetical Japanese sites which used a specially extended version of the Generic CO_2 FEP Database (Ueta et al. [15]). In this application, the Japan-specific context and the method of intended application meant that the level of detail was extended to include around 80 more FEPs than the standard Generic CO_2 FEP Database. Unimportant FEPs were first screened out and the probability of occurrence and the impact of the remaining FEPs was then assessed by expert judgment. Estimates of risk (combination of probability of occurrence and risk) were then used to rank the FEPs and identify those that should form the basis of scenarios.

3.4. Comparisons with Other Approaches

All approaches to performance- and risk- assessment employ FEP analysis, even though they don't necessarily refer to system characteristics and influencing processes using the FEP terminology. However, several other approaches have been proposed that differ from those described above.

Oldenburg [13] compared a ‘Certification Framework’ with approaches that employ explicit FEP databases such as the Generic CO_2 FEP Database. The ‘Certification Framework’ evaluates CO_2 and brine leakage risks at storage sites by assuming that there are only two possible CO_2 leakage scenarios at any site, one involving leakage through boreholes and the other leakage through faults. Several ‘compartments’ are defined, which represent vulnerable entities or collections of vulnerable entities. These compartments are connected to the CO_2 reservoir by boreholes and/or faults. The risk to each compartment is then judged as the product of the probability that a CO_2 plume intersects a borehole or fault pathway, the probability that a compartment intersects the pathway and the impact of the CO_2 on the compartment. The probabilities are determined by a combination of expert judgment and either carrying out site-specific numerical simulations or consulting a catalogue of generic simulation outputs. Impacts of CO_2 are evaluated by modelling CO_2 concentrations or fluxes, which are taken as proxies for impacts. Although simple and transparent, by focusing solely on evaluating potential leakage pathways the ‘Certification Framework’ has relatively little flexibility with respect to different assessment contexts, nor does it provide a direct link to a comprehensive knowledge base, unlike the Generic CO_2 FEP Database.

Bouc et al. [16] compared the application of FEP databases, such as the Generic CO_2 FEP Database, with a ‘risk event’ approach. This approach involves an expert group defining lists of events that could cause risks, such as earthquakes or borehole seal failure, and potential target groups/spatial domains that could be impacted by the event, such as humans or aquifers. When assessing a given site, scenarios are then generated by another expert group that selects from the list ‘risk events’ that could plausibly occur, and for each ‘risk event’ determines which ‘targets’ might be affected; combinations of ‘risk events’ and ‘targets’ then form the basis of scenarios.

Both the ‘Certification framework’ and ‘risk event’ approaches bear large similarities with the ‘top-down’ FEP-based approaches described above, but with assumptions regarding key features, events and processes forming part of the approach rather than being explicitly included in the analysis. The phenomena considered by both approaches can be regarded as FEPs, such that the Generic CO_2 FEP Database could be used to support their application, e.g. by providing a transparent basis for their review. Both Oldenburg [13] and Bouc et al. [16] considered their approaches to be less resource-intensive than the application a generic FEP database. However, the review of projects in Section 3.3 illustrates that the ‘top-down’ approach to FEP analysis need not be more resource-intensive than either of these alternative approaches; it appears that these authors’ principle criticism of the application of FEP databases relates to the more resource-intensive ‘bottom-up approach’.

4. Discussion and Summary

FEP databases are tools that can be used to support systematic safety and performance assessments of geological CO_2 storage systems. They are primarily used as an audit tool to help build confidence that a systems analysis covers all relevant FEPs and to transparently document those FEPs that are not being considered. Over the past five years, the Generic CO_2 FEP database has been widely used in this way and has proved a valuable tool to help build confidence in assessments relating to long-term geological CO_2 storage.

Approaches to FEP analysis and scenario development are variously classified in the literature as being either ‘top-down’ (progressively more detailed scenarios are developed from a few important FEPs) or ‘bottom-up’ (scenarios are developed by combining many FEPs that collectively aim to provide a comprehensive description of a site). However, in practice, the distinction between these approaches is not clear-cut. The Generic CO_2 FEP Database has been used almost exclusively to support ‘top-down’ assessments, although several applications had aspects in common with ‘bottom-up’ approaches.

While several other approaches besides FEP analysis have been proposed for scenario development, in reality these other approaches have much in common with FEP analysis; none of the approaches are exclusive of the others and the Generic CO_2 FEP Database could be used to help support any approach by being applied as an audit tool.

The Generic CO_2 FEP Database continues to build on experience of its application, with updates to references and links and a targeted review that has strengthened descriptions and FEPs relating to the marine environment. Further targeted reviews and updates are planned, for example in relation to FEPs that associated with the injection phase that have the potential to affect long-term performance and the initial status of the system. Feedback from the user base is sought in order that the database can continue to incorporate the latest knowledge and understanding relating to geological storage.

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