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International Features, Events and Processes (IFEP) List for the Deep Geological Disposal of Radioactive Waste

Version 3.0

OECD
BETTER POLICIES FOR BETTER LIVES

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Radioactive Waste Management Committee

International Features, Events and Processes (IFEP) List for the Deep Geological Disposal of Radioactive Waste

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The mission of the NEA is:

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– to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

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Executive summary

The Nuclear Energy Agency (NEA) has been carrying out activities related to the compilation and use of lists and databases containing features, events and processes (FEPs) of relevance to deep geological repositories (DGRs) since the early 1990s, most notably through its Integration Group for the Safety Case (IGSC) and its predecessors.[1]

The NEA International FEP (IFEP) List is a comprehensive and structured list of generic FEPs, relevant to assessments of the post-closure safety of any DGR, which has been assembled through a long-term international collaboration between radioactive waste management organisations (RWMOs) in the framework of the NEA. It is intended to support national programmes in the production of their safety cases through the provision of a comprehensive and internationally accepted list of factors that may need to be considered when assessing the post-closure safety of DGRs.

RWMOs have complemented the generic IFEP List with so-called "Project-specific" FEP (PFEP) Lists that are tailored to the specific wastes, geological environments and disposal concepts of interest to them, and are therefore of less general applicability than the IFEP List. PFEP Lists are often mapped to the IFEP List by RWMOs to demonstrate their consistency and completeness.

In addition to the IFEP List, the NEA has commissioned the production of a number of electronic FEP Databases, which are designed to store the IFEP and PFEP Lists in an easily navigable and searchable format.

This report contains version 3.0 of the IFEP List, which the NEA released in 2019. To coincide with this release, a major revision has also been made to the most-recent NEA FEP Database, transitioning it to a public web-based system accessible from the NEA website.[2] This database has been designed to allow full version control and is intended to provide a home for all releases of the IFEP List in the future.

Version 3.0 of the IFEP List has been updated to reflect the latest relevant scientific understanding with FEPs organised into a hierarchy reflecting their location in the DGR:

- External Factors;
- Waste Package Factors;
- Repository Factors;
- Geosphere Factors; and
- Biosphere Factors.

Each FEP contains a description, category, commentary on its relevance to performance and safety, and mapping to related FEP(s) in the previous public version of the IFEP List. 268 IFEPs (including FEP groups and subgroups) are contained within version 3.0 of the IFEP List.

[1] The predecessor of the IGSC was the NEA Performance Assessment Advisory Group (PAAG).

[2] www.oecd-nea.org/fepdb

List of abbreviations and acronyms

DGR	Deep geological repository
EBS	Engineered barrier system
EDZ	Excavation damaged zone
FEP	Feature, event and/or process
HLW	High-level waste
IFEP	International FEP (NEA)
IGSC	Integration Group for the Safety Case (NEA)
ILW	Intermediate-level waste
LLW	Low-level waste
NAPL	Non-aqueous phase liquid
NEA	Nuclear Energy Agency
OECD	Organisation for Economic Co-operation and Development
PAAG	Performance Assessment Advisory Group (NEA)
PEG	Potential exposure group
PFEP	Project-specific FEP
RWMO	Radioactive waste management organisation
SF	Spent fuel

Introduction

1.1. Background

The Nuclear Energy Agency's (NEA) Integration Group for the Safety Case (IGSC), and its predecessor, the Performance Assessment Advisory Group (PAAG), have carried out activities related to the compilation and use of lists and databases containing features, events and processes (FEPs) of relevance to safety and performance assessment studies for deep geological repositories (DGRs) since the early 1990s.

The NEA International FEP (IFEP) List is a comprehensive and structured list of generic FEPs, relevant to assessments of the post-closure safety of any DGR, which has been assembled through a long-term international collaboration between Radioactive Waste Management Organisations (RWMOs) through the NEA. It is intended to support national programmes in the production of their safety cases through the provision of a comprehensive and internationally accepted list of factors that may need to be considered when assessing the safety of DGRs.

RWMOs have complemented the generic IFEP List with so-called "Project-specific" FEP (PFEP) Lists that are tailored to the specific wastes, geologies or disposal concepts of interest to them and therefore are of less general applicability than the IFEP List. Individual Project FEPs have been related to relevant International FEPs.

In addition to the IFEP List, NEA has commissioned the production of a number of FEP Databases, which are designed to store the IFEP List and PFEP Lists, in an easily navigable and searchable format.

This document contains version 3.0 of the IFEP List, which the NEA released in 2019. To coincide with this release, a major revision has also been made to the most-recent NEA FEP Database, transitioning it to a public web-based system accessible from the NEA website. This database has been designed to allow full version control and is intended to provide a home for all releases of the IFEP List in future.

1.2. Scope of update

This version of the International FEP (IFEP) List has been developed in light of a review of various project-specific lists and databases [Ref. 1] undertaken in 2012. The resulting revisions to the structure of the IFEP List [Ref. 2] were subsequently approved by the NEA Integration Group for the Safety Case (IGSC). This is the finalised version of the interim IFEP List, published in 2015 [Ref. 3], with additional information provided for each IFEP.

In commissioning the update, the IGSC agreed that the renewed IFEP List should be:

- relevant to all stages of a repository development programme, from inception to repository closure;
- relevant to both safety assessors and individual topic experts;
- limited to the post-closure safety of deep geological disposal facilities;
- relevant to all designs of geological disposal facilities;
- relevant to all categories of radioactive waste proposed for disposal in geological disposal facilities; and
- relevant to the assessment of the radiological and non-radiological impacts of contaminant releases on both humans and non-human biota.

The reader should note that operational safety is beyond the scope of the current list, as are surface and near-surface disposal facilities (i.e. those on or within 30 m of the surface) and borehole disposal.

1.3. History

Both the IFEP List and the FEP Database have been updated a number of times since the early 1990s. The following subsections provide a brief history of the evolution of these products.

1.3.1. NEA IFEP List

In 2000, the NEA released in a public report[3] the first version of the IFEP List (version 1.0) and developed an electronic database for its illustration and use. As further explained in the next section, this FEP Database has been updated several times in the following years to improve its usability and quality.

After ten years, improvements to underlying scientific understanding[4] and developments in safety assessment methodologies led the NEA to review the work carried out in 2000. In 2010, the NEA sent a questionnaire to IGSC members to:

- examine the use of FEPs or equivalent concepts in safety assessment; and
- provide a basis for judging the need for any future IGSC activities related to further development of the IFEP List, FEP Database or underlying methodologies.

Responses from the questionnaire led to the conclusion that:

- the IFEP List released in 2000 had been widely used but many RWMOs were concerned that it was out of date and did not reflect more recent experience in safety assessments, including their wider and more detailed scope;
- the FEP Database has been less widely used in spite of the several updates, but was regarded as important by those who used it; and
- the IGSC strongly supported the maintenance and a new update of the IFEP List and the FEP Database.

In light of these results, the NEA decided to support a revision of the IFEP List and FEP Database to ensure that both remain useful and relevant to the work of NEA member countries.

A work programme was undertaken comprising the following activities:

- to review recent and available project-specific lists and databases provided by RWMOs;
- to identify, agree and document proposed revisions to the IFEP List in light of this review; and
- to implement the revised IFEP List in a new web-based FEP Database.

[3] NEA (2000), "Features, Events and Processes (FEPs) for Geologic Disposal of Radioactive Waste. An international Database," OECD Publishing, Paris.

[4] For example concerning thermal, hydraulic, mechanical, chemical, geological, radiological and biological processes.

In 2015, the NEA produced an interim[5] IFEP List (version 2.0). This interim list included information on:

- the relevance of each FEP to the "performance and safety of the disposal system"; and
- references and/or web-links to provide further information about each FEP.

The list was developed in light of a review of various project-specific lists and database contents [Ref. 1] undertaken in 2012 and the resulting revisions to the structure of the IFEP List [Ref. 2] that were subsequently approved by the IGSC group.

In 2019, the interim IFEP List produced in 2015 was finalised and published in this report (version 3.0). At the same time, a new web-based FEP Database (see Section 1.3.2) was launched, which also contained this list. Table 1 illustrates the evolution of the NEA IFEP List.

Table 1. NEA International FEP List releases

Version	Release year	Alternative name
1.0	2000	2000 IFEP List
2.0	2015	2015 IFEP List
3.0	2019	2019 IFEP List

1.3.2. NEA FEP Database

The NEA FEP Database is an electronic database, which is used to store:

- the International FEP (IFEP) List;
- Project-specific FEP (PFEP) Lists.

The software allows each PFEP item to be related to one or more IFEPs and has been updated several times, as reported in Table 2. Each release potentially includes a different number of PFEP Lists, which may also be different versions, as available at the time.

5 Not publicly available.

Table 2. NEA FEP Database releases

<table>
<tr><th>Standalone Database Version</th><th>Web Database Version</th><th>Release year</th><th>Software</th><th>IFEP List version</th><th>Number of PFEP Lists</th><th>Notes</th></tr>
<tr><td>1.0</td><td>-</td><td>2000</td><td>Claris FileMaker Pro™ 3.0</td><td rowspan="5">1.0</td><td>7</td><td>Standalone version 1.0 was circulated for review and private use to members of the FEP Working Group.</td></tr>
<tr><td>1.1</td><td>-</td><td rowspan="2">2000</td><td rowspan="4">Claris FileMaker Pro™ 4.0[6]</td><td rowspan="2">8</td><td>Standalone version 1.1 was released publicly by the NEA on CD-ROM and for download. It is identical to 1.2 but with some restrictions on functionality.[7]</td></tr>
<tr><td>1.2</td><td>-</td><td>Standalone version 1.2 was released to NEA FEP Working Group participants, who had funded its development.</td></tr>
<tr><td>2.0</td><td>-</td><td rowspan="2">2006</td><td rowspan="2">10</td><td>Standalone version 2.0 was not publicly released, but internally distributed for testing.</td></tr>
<tr><td>2.1</td><td>-</td><td>The restrictions on functionality in version 1.1 was been removed, i.e. the distinction between 1.1 and 1.2 becomes redundant.</td></tr>
<tr><td>-</td><td>2.0[8]</td><td>2019</td><td>Web-browser based</td><td>3.0</td><td>See note</td><td>Web database version 2.0 has a modern graphical interface for a more engaging user experience.</td></tr>
</table>

1.4. Revised structure and content of the IFEP List

The IFEP List has been revised both in terms of its structure and its content in comparison with the 2000 IFEP List. Consistent with many of the more recent project-specific FEP (PFEP) Lists (e.g. those from Finland, Japan and Sweden), the new IFEP List is structured around a classification scheme based on external factors and disposal components (waste package, repository, geosphere and biosphere), rather than on the 2000 IFEP List scheme that used external, environment and contaminant factors. The new structure is hierarchical with the first and second level shown in Table 3.

Table 3. IFEP List structure (FEP groups and subgroups only)

FEP Number and Title	
1.	External Factors
1.1	Repository Issues
1.2	Geological Factors
1.3	Climatic Factors

6 Version 1.1 is a "run-time" solution produced under licence from FileMaker Pro Inc. The FileMaker Pro software is not needed to run Version 1.1, but is required for Version 1.2.

7 For example print capability and access to mapping information had been disabled and the user could not modify the database.

8 Web database version 1.0 was developed between 2014 and 2017 and used for internal testing and discussion only.

FEP Number and Title	
1.4	Future Human Actions
1.5	Other External Factors
2.	Waste Package Factors
2.1	Waste Form Characteristics and Properties
2.2	Waste Packaging Characteristics and Properties
2.3	Waste Package Processes
2.4	Contaminant Release (from waste form)
2.5	Contaminant Transport (waste package)
3.	Repository Factors
3.1	Repository Characteristics and Properties
3.2	Repository Processes
3.3	Contaminant Transport (repository)
4.	Geosphere Factors
4.1	Geosphere Characteristics and Properties
4.2	Geosphere Processes
4.3	Contaminant Transport (geosphere)
5.	Biosphere Factors
5.1	Surface Environment
5.2	Human Behaviour
5.3	Contaminant Transport (biosphere)
5.4	Exposure Factors

In total, there are 268 IFEPs (including FEP groups and subgroups) in the 2019 IFEP List.

1.5. Uses of the new IFEP List

The new IFEP List can be used in a number of ways:

- It can be used as a starting point for the development of a new PFEP List for geological disposal programmes that are in the early stages of planning. The PFEP List produced can then be used in the post-closure safety assessment of the repository, e.g. for the identification and development of scenarios and/or conceptual models for performance assessment.

- For more developed programmes, the IFEP List can be used to provide an audit to check the completeness of scenarios, conceptual models and/or their implementation in software tools for a particular safety assessment. Such an audit could be carried out by either the assessor or by a reviewer of the assessment.
- For PFEP Lists that have been developed independently from the updated IFEP List, the IFEP List can be used as an audit tool to check their completeness.

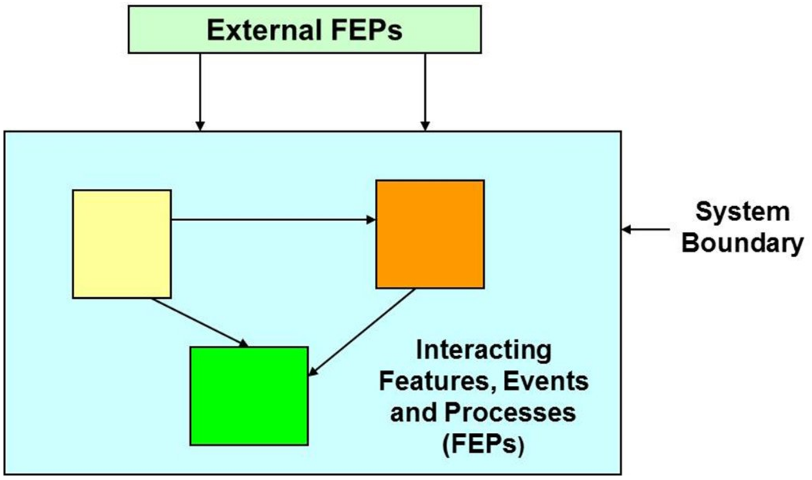
1.6. Specification

Each IFEP has a unique identification number and title, and utilises the properties listed in Table 4. Links to references, from which further information can be obtained (documents or web-links), are included, as are media items, for example graphs, drawings or photos.

Table 4. IFEP properties

<table>
<tr><th>Description</th></tr>
<tr><td>Description of the FEP.</td></tr>
<tr><th>Category</th></tr>
<tr><td>Categorisation as a Feature, Event and/or Process.
• “Features” are physical components of the disposal system and environment being assessed. Examples include waste packaging, backfill, surface soils. Features typically interact with one another via processes and in some cases events.
• “Events” are dynamic interactions among features that occur over time periods that are short compared to the safety assessment timeframe such as a gas explosion or meteorite impact.
• "Processes" are issues or dynamic interactions among features that generally occur over a significant proportion of the safety assessment timeframe and may occur over the whole of this timeframe. Events and processes may be coupled to one another (i.e. may influence one another).
The classification of a FEP as an event or process depends upon the assessment context, because the classification is undertaken with reference to an assessment timeframe. In this generic IFEP List, many IFEPs are classified as both Events and Processes; users will need to decide which of these classifications is relevant to their context and its timeframes.</td></tr>
<tr><th>Comments</th></tr>
<tr><td>The “Comments” field, when present, contains any additional explanation of the IFEP, beyond that implicit in the FEP's description and provided in the “Relevance to Performance and Safety” field. This additional explanation may include, where appropriate, the IFEPs characteristics, the circumstances under which it might be relevant and its relationship to other (especially similar) IFEPs.</td></tr>
<tr><th>Relevance to Performance and Safety</th></tr>
<tr><td>The “Relevance to Performance and Safety” field contains an explanation of how the IFEP might influence the performance and safety of the disposal system under consideration through its impact on the evolution of the repository system and on the release, migration and/or uptake of repository-derived contaminants.</td></tr>
<tr><th>2000 List</th></tr>
<tr><td>A reference to the related FEP(s) within the 2000 NEA IFEP List.</td></tr>
</table>

- ## FEP 1: External factors

Description	The FEPs with causes or origins outside the assessed disposal system or prior to repository closure (waste, repository, the surrounding geosphere and overlying biosphere). See Figure 1. **Figure 1: Relationship between external FEPs and system FEPs** 
Category	FEP Group
2000 List	1
References	[Ref. 5]

FEP 1.1: Repository issues (pre-closure)

Description	The factors related to decisions taken and events occurring during the life cycle of the repository programme (e.g. site investigation, design, construction, operation and closure).
Category	FEP Subgroup
2000 List	1.1
References	[Ref. 6], [Ref. 7], [Ref. 161], [Ref. 163], [Ref. 176]

FEP 1.1.1: Quality assurance and control

Description	The quality assurance and control procedures and tests undertaken during site investigation, design, construction, operation and closure of the repository, including the manufacture of the waste forms, containers and construction of engineered features and the quality assurance of performance and safety assessments, including data clearance. It can be expected that a range of quality control measures will be applied during the repository life cycle, as well as to the manufacture of the waste forms, containers, etc. There may be specific regulations governing quality control procedures, objectives and criteria.
Category	Process

Relevance to Performance and Safety	Quality control measures will influence the achieved quality of the overall barrier system, consisting of both engineered barriers and natural barriers. Quality control measures during site characterisation will influence the quality of information obtained and hence impact upon the quality of repository designs and the planning and implementation of operations within a repository. The quality control measures will therefore influence the quality of performance and safety assessments, since it provides key data for these. Quality control measures during construction of a repository will influence whether wastes can be emplaced, and engineered barriers can be constructed, to maximise the effectiveness of the overall barrier system (e.g. by minimising excavation damaged zones (EDZs), or locating galleries remote from water-conducting features of the rock mass). Quality control measures during the manufacture / emplacement of engineered barriers will help ensure that they perform effectively in the post-closure period. Failure to implement appropriate quality control measures could cause the performance of the various emplaced barriers to be impaired and /or not to work effectively in concert with each other and/or the natural barriers during the post-closure period.
2000 List	1.1.08
References	[Ref. 35], [Ref. 50]

- **FEP 1.1.2: Site investigations**

Description	The investigations carried out to characterise the repository site, both prior to and during repository construction and operation.
Category	Process
Relevance to Performance and Safety	These activities establish baseline conditions and provide site-specific data for the post-closure safety assessment. The extent of site investigation affects the degree of uncertainty associated with the assessment. Investigation boreholes could be conduits for groundwater flow if not correctly sealed and so need to be sealed appropriately.
2000 List	1.1.01
References	[Ref. 36], [Ref. 37], [Ref. 38]

- **FEP 1.1.3: Design**

Description	The design and layout of the repository, including both the safety concept, i.e. the general features of design, including the repository barriers and their safety functions, and the more detailed engineering specification for repository construction, operation and closure. Initially, the repository conceptual design and layout are based on expected host rock characteristics, waste and backfill characteristics, construction technology, and economics and there may be a range of potential options. As the repository project proceeds, the number of options will reduce to one. As the repository is constructed, modifications might need to be made to the layout or other aspects of design to account for specific rock conditions. In certain cases, the repository might be developed from an existing mine and thus its layout could be pre-determined to a significant extent.
Category	Feature
Relevance to Performance and Safety	The design, layout and safety concept of the repository will influence the contribution of each engineered and natural barrier to overall safety. The design, layout and the safety concept must be appropriate for meeting the required safety criteria in the specific geological environment within which the repository is to be constructed. The design must be matched to the kinds of wastes that are to be emplaced, accounting for the

	packaging of the wastes, and must allow operations to be undertaken. The layout of the repository will determine the density with which wastes are emplaced and the locations of the emplaced wastes with respect to natural barriers and permeable features such as transmissive fracture zones. These factors will influence safety. The safety concept defines the safety functions of each natural and engineered component of the repository.
2000 List	1.1.07
References	[Ref. 35], [Ref. 36], [Ref. 38], [Ref. 39], [Ref. 190]

- **FEP 1.1.4: Schedule and planning**

Description	The sequence of events and activities occurring during repository construction, operation and closure. Relevant events may include phased excavation of emplacement rooms and emplacement of wastes, backfilling, sealing and closure of sections of the repository after wastes are emplaced and monitoring activities.
Category	Process
Comments	Schedule and planning (this FEP, 1.1.4) covers the *planning and sequencing* of Construction (FEP 1.1.5), Operations (FEP 1.1.6) and Closure (FEP 1.1.7), rather than the details of these processes.
Relevance to Performance and Safety	The scheduling and planning of activities to develop and operate a repository influence the conditions of the wastes and barriers at the time of closure (e.g. the heat emitted by a given kind of heat-generating radioactive waste at the time of repository closure will depend upon the length of time between generation of the waste and closure). The initial condition of the waste and barriers at the time of closure (FEP 1.1.7) will then influence the long-term performance of the barrier system and hence safety e.g. decay of activity and heat production from the wastes, material degradation, chemical and hydraulic changes during the operational phase. The development and operation of a repository (FEP 1.1.6) needs to be scheduled and planned to emplace the wastes and engineered barriers in a way that promotes long-term performance and safety. Monitoring (FEP 1.1.10) needs to be scheduled and planned to obtain information that is relevant for assessing long-term performance and safety.
2000 List	1.1.09
References	[Ref. 36], [Ref. 39], [Ref. 190]

- **FEP 1.1.5: Construction**

Description	The excavation of shafts, tunnels, waste emplacement galleries, silos, holes etc. of a repository, the stabilisation of these openings and installation/assembly of structural elements. This includes rock bolting, shotcrete, grouting construction of tunnel/shaft linings, drain layers and installation of services and waste handling components.
Category	Process
Comments	There are some similarities between Construction (this FEP, 1.1.5), Operations (FEP, 1.1.6) and Closure (FEP 1.1.7). FEP 1.1.5 covers excavation and related activities, whereas FEP 1.1.6 covers activities other than excavation (e.g. emplacement of wastes in a disposal hole), excluding final closure (covered by FEP 1.1.7). FEP 1.1.5 does not cover emplacement of backfill and seals during closure, or associated activities, such as reaming of the EDZ. The sequencing of construction activities, as opposed to the activities themselves, is covered by FEP 1.1.4 (Schedule and planning).

Relevance to Performance and Safety	Construction of a repository results in mechanical disturbance to the host rock formation and adjacent rock formations (particularly the overlying rock formations, but also possibly deeper rock formations and adjacent rock formations). Construction methods affect the properties of the excavation damaged and disturbed zones around the repository and shafts (FEP 3.1.6). Excavation has the potential to create pathways such as excavation-disturbed zones around tunnels. If not subsequently sealed, these pathways could allow the transport of gas and/or water and contaminants, including radionuclides, in the post-closure period. Any waste package emplacement holes must be excavated in such a way that they meet the required specifications (e.g. suitably low groundwater inflows). The process of construction also disturbs the hydrogeological and geochemical environment of the host rock and its surroundings. For example, groundwater flow directions may be perturbed if pumping is required during repository construction. Geochemical conditions are also perturbed, for example by oxygen ingress due to ventilation of excavations, or the introduction of alkalis owing to the use of cement. These chemical perturbations may cause changes in the properties of engineered and natural barriers. The hydrogeological and geochemical disturbances may potentially influence the migration and retardation of radionuclides in the post-closure period and need to be treated appropriately in performance and safety assessments. Quality control (FEP 1.1.1) during construction also has the potential to influence the effectiveness of natural barriers and engineered barriers that are emplaced subsequently. Failure to carry out construction appropriately could result in impaired performance of the barrier systems in the post-closure period.
2000 List	1.1.02
References	[Ref. 39], [Ref. 40], [Ref. 190]

- **FEP 1.1.6: Operation**

Description	The operation of the repository including the placing of wastes (usually in containers) in their final position within the repository, placing of any buffer and backfill materials (including any sealing of emplacement rooms/tunnels), and the management of any water and gas in the repository prior to closure.
Category	Process
Comments	There are some similarities between Construction (FEP 1.1.5), Operations (this FEP, 1.1.6) and Closure (FEP 1.1.7). FEP 1.1.5 is intended to cover activities concerned with construction (notably excavation), whereas FEP 1.1.6 covers activities other than excavation (e.g. emplacement of wastes in a disposal hole), except for activities concerned with the emplacement of final closure engineering. Emplacement of buffer and backfill materials, or seals in part of a repository, while waste emplacement is ongoing elsewhere, is covered by FEP 1.1.6. However, emplacement of backfill and seals after waste emplacement has stopped is covered by FEP 1.1.7. The sequencing of operations, as opposed to the activities themselves, is covered by FEP 1.1.4 (Schedule and planning).
Relevance to Performance and Safety	Operations impact upon performance and safety by governing the effectiveness with which wastes are contained within the system of engineered and natural barriers. Potential operational issues that might impact post-closure performance and safety include container damage during handling, errors in backfill or buffer emplacement and poor sealing of emplacement rooms/tunnels. Waste packages must be emplaced in their final positions without damaging them to the extent that their performance is compromised. Any buffer and / or backfill required by the design must also be emplaced to achieve its required function. Generally, operations will need to ensure that buffer emplacement and / or backfilling and closure of emplacement rooms achieves the required degree of sealing against gas and water movement, and contaminant migration, including radionuclide migration. However, in certain concepts, where the potential for

	gas generation from wastes or packaging to result in high gas pressures and associated damage to the barrier system is a concern, operations may need to ensure that there are gas migration pathways through the barriers to mitigate gas pressurisation.
2000 List	1.1.03, 1.1.06
References	[Ref. 36], [Ref. 190]

- **FEP 1.1.7: Closure**

Description	The cessation of waste emplacement operations in a repository and the backfilling and sealing of access tunnels, shafts and site investigation/monitoring boreholes.
Category	Process
Comments	There are some similarities between Closure (this FEP 1.1.7), Schedule and planning (FEP 1.1.4) and Operation (FEP 1.1.6). Whereas FEP 1.1.7 concerns final closure of the whole repository, FEP 1.1.6 covers closure of individual sections in sequence. FEP 1.1.4 covers the planning and sequencing of closure, rather than the actual closure itself. FEP 1.1.7 is different from Construction (FEP 1.1.5), which concerns only the development of the repository. Individual sections of a repository may be closed in sequence (FEP 1.1.4), but, in the present context, closure refers to final closure of the whole repository (including the sealing of any open site characterisation boreholes) and will probably include removal of surface installations.
Relevance to Performance and Safety	Closure activities are undertaken to prevent human access into and limit the migration of contaminants, including radionuclides from the repository post-closure. Closure of the repository must be done in such a way as to ensure that post-closure migration of water or gas does not compromise repository performance and safety by transporting contaminants, including radionuclides, from the repository to the biosphere. If they are not closed appropriately then boreholes within the repository footprint and / or excavations that are part of the repository (rooms, access tunnels, shafts) could potentially form pathways for this migration to occur. Such pathways could arise due to ineffective seals (e.g. degraded concrete plugs) or due to damaged rock surrounding the excavations. Some of the pathways could connect the wastes directly to the biosphere (e.g. a shaft with ineffective seals) or could connect the waste to a natural pathway (e.g. where an ineffective seal within a tunnel allows water or gas to be transported to a transmissive fault). It may be necessary to examine in the post-closure safety assessment the consequences of the use of poor closure techniques that might not be detected by the quality control programme. It may also be necessary to consider the potential for degraded performance of shaft and borehole seals, particularly over the long time frames over which those seals might be required to contribute to safety.
2000 List	1.1.04
References	[Ref. 36]

- **FEP 1.1.8: Accidents and unplanned events**

Description	The accidents and unplanned events during construction, operation and closure that might have an impact on long-term performance and safety of the repository. Accidents and other unplanned events are those events outside the range of normal operations although the possibility that certain types of accident may occur should be anticipated in repository operational planning. Unplanned events include deliberate deviations from

	operational plans, e.g. in response to an accident, unexpected geological events or unexpected waste arising during operations.
Category	Event
Relevance to Performance and Safety	Accidents and unplanned events during construction, operation and closure could have one or more performance/safety-relevant consequences: damage to waste packages; poor emplacement of wastes; inadequate implementation of the engineered barrier system (EBS); and damage to the geosphere barrier (e.g. if there is a rockfall). If mitigating actions are not taken, then post-closure performance and safety could be impaired by such accidents and unplanned events.
2000 List	1.1.12
References	[Ref. 41]

- **FEP 1.1.9: Administrative control**

Description	The administrative measures used to oversee and control events at or around the repository site during site investigation, construction, operation and closure, and after closure. The administrative measures may be active (e.g. involving specific checks that relevant procedures have been undertaken) or passive (e.g. setting out the general safety principles under which a repository is operated. The type of administrative control may vary depending on the stage in the repository lifetime.
Category	Process
Relevance to Performance and Safety	The administrative measures (this FEP, 1.1.9) will influence strongly the processes of repository construction (FEP 1.1.5), operation (FEP 1.1.6) and closure (FEP 1.1.7). As detailed in the corresponding FEP descriptions, activities during construction, operation and closure may impact upon post-closure performance and safety. Administrative measures will also apply to any monitoring (FEP 1.1.10) that is undertaken before and after repository closure and any mitigation measures that might need to be implemented should monitoring identify unexpected repository behaviour. The effectiveness of any monitoring and/or mitigation will depend in part on the administrative measures that are enacted.
2000 List	1.1.10
References	[Ref. 42], [Ref. 191]

- **FEP 1.1.10: Monitoring**

Description	The continuous or periodic observation of a relevant property over a specified time periods or measurement of a parameter or the sum of all such observations or measurements. Includes monitoring that is carried out during site investigation, construction, operation and after closure of sections of, or the total, repository. This includes monitoring of parameters related to long-term safety and performance, as well as monitoring undertaken for operational safety reasons that might have an impact on long-term safety. The extent and requirement for such monitoring activities may be determined by a number of factors, such as repository design, geological setting, regulations and stakeholder requirements.
Category	Process

Relevance to Performance and Safety	Monitoring could potentially influence mitigating actions in the event that unexpected behaviour of the repository is identified. The timing and nature of these mitigating actions has the potential to influence repository performance and safety. Certain kinds of monitoring involve invasive techniques, such as borehole drilling, which must be undertaken in such a way that repository performance and safety are not compromised. Monitoring could also improve confidence in performance and safety assessment models, if predictions agree with monitoring outcomes. If there is no such agreement, monitoring could play a role in developing better process understanding and ultimately improved models.
2000 List	1.1.11
References	[Ref. 43], [Ref. 44], [Ref. 45], [Ref. 57], [Ref. 196], [Ref. 197]

- **FEP 1.1.11: Records and markers**

Description	The retention of records of the content and nature of a repository after closure and also the placing of permanent markers at or near the site.
Category	Feature
Relevance to Performance and Safety	These records and markers will allow future generations to recall or identify the existence and nature of the repository following closure, and influence the likelihood of events such as future intrusion into the repository. The loss of such records and markers will increase the likelihood of inadvertent intrusion sometime in the future (FEP 1.4).
2000 List	1.1.05
References	[Ref. 35], [Ref. 46], [Ref. 47], [Ref. 194], [Ref. 195]

FEP 1.2: Geological factors

Description	The factors related to the long-term processes and events arising from the wider geological setting and their effects on the performance and safety of the disposal system.
Category	FEP Subgroup
2000 List	1.2
References	[Ref. 7], [Ref. 170]

- **FEP 1.2.1: Tectonic movement**

Description	Movement of lithospheric plates (which comprise the Earth's outermost layer) due to convection cells in the underlying mantle. These movements give rise to large-scale processes such as continental drift, mountain building (orogeny), crustal deformation (including basin formation), faulting, folding and subduction and typically occur over periods of millions of years.
Category	Process
Comments	Short-term effects of tectonic movement (this FEP, 1.2.1) are covered by Seismicity (FEP 1.2.4), Magmatic and volcanic activity (FEP 1.2.5) and Deformation (elastic, plastic, or brittle) (FEP 1.2.3)

Relevance to Performance and Safety	Movements of the lithospheric plates into which the solid outer layer of the earth is divided affect both regional and local processes of safety relevance to a repository. The general environmental characteristics of the repository environment (e.g. distance from the ocean, elevation above sea level, climatic conditions) will be influenced strongly by tectonic movements. For example, mountain building (FEP 1.2.2) due to these movements may influence atmospheric circulation and local rainfall. The frequency, magnitude and proximity to a repository of seismic events (FEP 1.2.4) will depend upon the location of the repository relative to the deformation caused by tectonic movements. The spatial distribution, magnitude and characteristics of magmatic activity (FEP 1.2.4), including volcanism, are influenced by tectonic movements. Tectonic movement may alter the separation between a repository and the biosphere during the post-closure period. Weathering and erosion (FEP 1.2.5) accompanying uplift may cause the repository to approach the ground surface. Conversely, sedimentation that may accompany subsidence (FEP 1.2.5) would cause the repository to be buried at greater depths below the ground surface. Deformation due to tectonic movements (FEP 1.2.3) has the potential to create or seal pathways via which water or gas may transport radionuclides and other contaminants from a repository. Such deformation may lead to a displacement of waste packages, damage to engineered barriers or damage to the geosphere barrier. For example, active faulting (FEP 1.2.3 and FEP 1.2.4) due to tectonic movements may generate transmissive fracture pathways. Tectonic deformation may also influence the forces that could drive fluid flow through the repository, for example by influencing water pressures and pressure gradients. Thermal gradients within the geosphere surrounding the repository may also be influenced by tectonic movements, owing to these movements causing uplift and subsidence, influencing the locations and characteristics of magmatism and influencing fluid flow.
2000 List	1.2.01
References	[Ref. 21], [Ref. 48]

- **FEP 1.2.2: Orogeny**

Description	The forces and processes leading to a large structural deformation of the Earth's lithosphere due to the movement of tectonic plates resulting in the formation of mountains and related geomorphological features (e.g. intermontane basins). Orogeny typically occurs over time periods of millions of years. Orogeny generally occurs at tectonic plate margins where different plates are in contact and is associated with crustal deformation, faulting, folding and subduction and resulting seismicity and magmatic/volcanic activity.
Category	Process
Relevance to Performance and Safety	Orogeny is a consequence of tectonic movements (FEP 1.2.1) and its potential influences on repository performance and safety are similar to those described for tectonic movements (FEP 1.2.1). 'Orogeny' is associated with crustal deformation, faulting, folding, sub- and obduction and resulting seismicity and magmatic/volcanic activity. In the post-closure period these processes may affect: the general environment of a repository (e.g. distance from the ocean, elevation above sea level, climatic conditions); the proximity of a repository to the ground surface; the potential for damage to waste containers and engineered barriers within a repository, and/or to the surrounding geosphere, as a result of active faulting or magmatism; the forces driving movements of groundwater, other liquids and gases from and around a repository; and the thermal gradients in the geosphere surrounding a repository.
2000 List	1.2.01
References	[Ref. 7]

- **FEP 1.2.3: Deformation (elastic, plastic or brittle)**

Description	The physical deformation of rocks to produce geological structures in response to, or involved in, geological processes such as tectonic movement, orogeny, magmatism, diapirism, and differential vertical movements, caused e.g. by loading and unloading of the crust by glaciation/deglaciation or by sedimentation/erosion. Deformation includes faulting, fracturing, extrusion, (de)compression of rocks and can result in basin formation or mountain formation. Compressional or tensional forces in the Earth's crust may result in the activation of existing faults and the generation of new faults. It also includes deformation caused by the movement of high plasticity and low density material, such as salt, mud or magma, into more brittle and dense overlying rocks.
Category	Event, Process
Relevance to Performance and Safety	Deformation, whether elastic, plastic or brittle has, depending upon its spatial scale, the potential to affect the spatial disposition of a repository with respect to potential environmental receptors (e.g. the future spatial separation between a repository and the biosphere). Plastic or brittle deformation may impact upon the integrity of engineered barriers within a repository and upon the integrity of the surrounding natural geosphere barriers. Plastic deformation may cause thickening or thinning of barriers, whether engineered or natural (e.g. thinning of halite due to creep). Brittle deformation could potentially produce transmissive faults and fractures through which groundwater, other liquids and gas might flow, transporting radionuclides and other contaminants as they do so. Deformation could also influence the forces that may drive the movement of water, other liquids and gases through and around the repository. For example, deformation may affect the orientations and magnitudes of water pressure gradients. Deformation may be initiated by tectonic movements (FEP 1.2.1) or take place during orogenesis (FEP 1.2.2). However, other processes could cause deformation, such as magmatism (FEP 1.2.5), diapirism, and loading and unloading of the crust by glaciation/deglaciation (FEP 1.3.5) or by sedimentation/erosion (FEP 1.2.8).
2000 List	1.2.02
References	[Ref. 7]

- **FEP 1.2.4: Seismicity**

Description	The release of energy accumulated in rocks via rapid relative movements within the Earth's crust and/or mantle, usually along faults or geological interfaces. Seismic events are most common in tectonically active or volcanically active regions at or near crustal plate margins. Human-induced or triggered seismic events (i.e. caused by human activities such as fluid injection) may occur both in naturally seismically active areas and in areas characterised by low background seismicity.
Category	Event
Relevance to Performance and Safety	Seismicity has the potential to physically disturb the waste, EBS, the surrounding rocks and the ground surface. Observations have shown that the effects of a seismic event are greater at the surface than underground. Seismicity could affect the pressure gradients in fluids (aqueous- and non-aqueous liquids and gases) in and around the repository, thereby leading to movements of these fluids. Seismic pumping of fluids along faults, characterised by cyclical pressure increases and decreases during repeated seismic events, is an example of this kind of phenomenon. Releases of energy during seismic events are characterised by the propagation of vibrations (seismic waves). These waves may disturb the geosphere and engineered structures, both at the ground surface and underground, although the intensity of these waves and the consequent likelihood of significant disturbances decreases at progressively greater depths. If the seismic event originates within or close to a

	repository (i.e. a fault moves within or in close proximity to a repository) then a pathway could be created for migration of fluids from the repository. The underground pressure pulse from such an event could also drive the movement of such fluids. The potential effects of seismic events on the repository include liquefaction of the seal or backfill materials, shaking and damage to waste packages, rockfalls, modification of the properties of the excavation damaged zone (EDZ) around the repository and shafts, and extension or creation of fractures near the repository and shafts. The geosphere might be affected by the growth of existing faults or the creation of new faults. Seismicity may affect the nature of surface and near-surface environments, including the biosphere, in the vicinity of a repository. Thus, seismicity may influence the nature of receptors that might be impacted by any radionuclides or other contaminants that might be transported from a repository in the post-closure periods. Tsunamis, land-slips, liquefaction of soil and collapse of surface structures are examples of changes in the surface and near-surface environment that might be caused by seismicity.
2000 List	1.2.03
References	[Ref. 7], [Ref. 21], [Ref. 48]

- **FEP 1.2.5: Magmatic and volcanic activity**

Description	The processes and events associated with sub-surface molten rock (magma), and the direct and indirect effects of sub-surface molten rock at the earth's surface, expressed in volcanoes. These effects may include eruption of molten rock as lava and/or eruption of fragmented rock (pyroclastic activity). Intrusion of molten rock into solid rock in the sub-surface (plutonism) may occur beneath volcanoes or in the sub-surface remote from volcanic activity. A volcano is a vent or fissure in the Earth's surface through which one or more of the following may flow/be expelled: magma; mud; solid and plastic fragments; liquid droplets; and hot gases. Around 95% of active volcanoes occur at lithospheric plate boundaries. The other 5% are associated with lithospheric hot spots and rifts which correspond to weak areas in the Earth's crust and are caused by plumes of rising magma that have their origin within the asthenosphere. The high temperatures and pressures associated with magmatic and volcanic activity may result in permanent changes in the surrounding rocks (FEP 1.2.6).
Category	Event, Process
Relevance to Performance and Safety	Magmatic and/or volcanic activity could influence the performance and safety of a repository by: compromising the integrity of the engineered and / or natural barriers; by influencing the chemical environment in the repository and its environs; and by influencing the characteristics and fluxes of fluids that may flow within and through the repository and surrounding geosphere. Magmatic and volcanic activity could also influence the characteristics of surface and near-surface environments, including the biosphere, in the vicinity of a repository. Thus, magmatic and volcanic activity could affect the types of receptors that could be impacted by any radionuclides or other contaminants that leave a repository during the post-closure period. Moving magma in the subsurface could impact directly upon a repository that is sited sufficiently close to a centre of magmatic activity. Direct effects on a repository might include intersection of repository rooms by an igneous dike. Additionally, magma would impact upon geothermal gradients, even at some distance from the magma itself. Modified geothermal gradients could in turn cause convection of groundwater (hydrothermal activity), other fluids in the subsurface. The modified geothermal gradient would also impact upon chemical reactions between these fluids and wastes, engineered barriers and rock. Certain magmas could themselves be sources of water and gases. Moving magma and / or the associated movements of other fluids could cause creation, activation and sealing of faults, which in the vicinity of a repository could potentially act as pathways for the migration of radionuclides and other contaminants. Flowing magma and/or associated fluids that intersect the repository and that also reach the surface may

	give rise to dispersion of wastes in a plume of volcanic ejecta and in lava flows. Magmatism and volcanic activity could be accompanied by changes in topography, changes in rock stress and rock deformation. These changes could be sudden (e.g. volcanic caldera collapse) or more gradual (e.g. regional uplift). Volcanic activity could lead to unloading or loading of rocks, by ejection of rock or deposition of ejecta or lava respectively, even at considerable distances (many tens or even hundreds of kilometres) from the volcanic centre. Magmatic and volcanic activity are closely related to seismicity (FEP 1.2.4).
2000 List	1.2.04
References	[Ref. 21], [Ref. 48]

- **FEP 1.2.6: Metamorphism**

Description	The processes by which rocks are changed by the action of heat and/or pressure at depth (often several kilometres) beneath the Earth's surface or in the vicinity of magmatic activity or active faulting.
Category	Event, Process
Comments	"Metamorphism" is not a precisely defined term but refers to the dominantly solid-state alteration of rock under conditions of pressure and/or temperature that are substantially higher than those of the ground surface in areas of normal geothermal gradient (i.e. excepting the effects of near-surface magmatism or hydrothermal activity). Alteration of rocks at relatively low temperatures and/or pressures (but still substantially elevated compared to those near the ground surface) is generally termed "metamorphism" if the rocks are igneous or have previously been altered (metamorphosed) at even higher pressures and/or temperatures; alteration of sedimentary rocks under such lower pressure/temperature conditions is termed "diagenesis" (FEP 1.2.9). Some researchers consider hydrothermal alteration to be a form of metamorphism. However in this FEP list such alteration is covered by FEP 1.2.7 (Hydrothermal activity).
Relevance to Performance and Safety	Metamorphism has the potential to influence the performance and safety of a repository by affecting the repository's chemical environment and the chemical and physical properties of the host rock and / or rocks in the wider groundwater flow system within which the repository presently resides or might reside in future. During metamorphism there may be, depending upon the nature of the affected rock types, a wide range of organic and inorganic chemical reactions. These reactions will influence the fluid chemistry in these rocks. Metamorphism will also influence the pressures of pore fluids and hence the potential for pore fluids to flow, by generating or consuming fluids and changing the porosity of the rock. Mineral reactions (precipitation, dissolution and alteration) may change the connectivity of pore spaces and the nature of mineral surfaces on which migrating radionuclides or other contaminants might sorb. Any past metamorphism of the host rocks or surrounding rocks will have affected their physical and chemical characteristics. Certain of these characteristics (porosity, mineralogy etc.) may influence the transport and retardation of radionuclides and/or other contaminants that were to leave the repository. Any characteristics of a repository's host rock or rocks in the surroundings of the repository that were acquired during past metamorphism will influence the future evolution of the rock during the post-closure period. At the depths typically proposed for repositories (< 1 km) temperatures and pressures are likely to be relatively low. Consequently, significant metamorphism of rocks at repository depth and shallower will be unlikely to occur during usual timescales considered by performance assessments (often c. 1 Ma) unless there is magmatism (FEP 1.2.5), hydrothermal activity (FEP 1.2.7) or active faulting (FEP 1.2.4). However, on-going metamorphism at greater depths than a repository could still influence the composition of groundwater, other liquids and gases at repository depths, and the pressure gradients that influence flow of these fluids. For example, metamorphism of limestone at depths substantially

	greater than a repository could liberate CO_2 which could then be transported to repository depths. Such changes in environmental conditions in and around a repository that are caused by metamorphic processes could influence the migration of radionuclides and other contaminants from the repository.
2000 List	1.2.05
References	[Ref. 7]

- **FEP 1.2.7: Hydrothermal activity**

Description	The processes associated with high-temperature water and/or related fluids, including processes such as heat-driven groundwater flow and hydrothermal alteration of minerals in the rocks through which the high temperature groundwater flows. These processes are often complex and strongly coupled; for example, mineral precipitation and/or alteration could cause fracture infilling, thereby impeding groundwater flow, and potentially modifying groundwater salinity, resulting in the occurrence of a new set of mineral alteration reactions, and so forth. Groundwater temperature is influenced by large-scale geological and hydrogeological properties of the rock, such as the location of geothermal heat sources, thermal conductivity, location of recharge and discharge areas and hydraulic conductivity.
Category	Event, Process
Comments	Alteration of rocks by reactions involving hydrothermal fluids may be considered to be "hydrothermal metamorphism" by some researchers. There is therefore potential overlap between Hydrothermal activity (this FEP, 1.2.7) and Metamorphism (FEP 1.2.6).
Relevance to Performance and Safety	Hydrothermal activity has the potential to influence the performance and safety of a repository by: • affecting the rates of water flow through and around the repository; • potentially causing multi-phase fluid flow (owing to boiling and / or degassing if pressures and temperatures decrease along flow paths) with consequent partitioning of radionuclides between liquid and gaseous phases; • influencing the chemical conditions in the repository and the surrounding rocks; and • by causing fluid-rock reactions that affect the contaminant transport / retardation properties of the engineered barriers, the host rocks of the repository and the surrounding rock formations. Temperature gradients may result in convection of groundwater. Elevated temperatures will also cause reactions between the water and the engineered and natural barriers to be more rapid than at lower temperatures. Hydrothermal fluids will typically transport a wide range of dissolved chemicals and gases and may therefore influence the chemical conditions in the repository. The hydrothermal fluids may dissolve or precipitate minerals as pressures and temperatures vary along flow paths. The hydrothermal fluids also have the potential to react with and alter the solid phase assemblages in wastes, engineered barriers and rocks. The mineral dissolution, precipitation and alteration reactions that may occur should hydrothermal fluids circulate through a repository or the surrounding geosphere could potentially affect the physical and chemical properties of the wastes, engineered barriers and rocks.
2000 List	1.2.06
References	[Ref. 7]

- **FEP 1.2.8: Regional erosion and sedimentation**

Description	The large-scale (geological) removal and accumulation of sediments, with associated changes in topography and geological/hydrogeological conditions at the repository site. Regional erosion and sedimentation could result in localised incisions that remove large volumes of rock from a small area or broader-ranging actions that remove large volumes of surface soil and rock from a widespread area. The eroded material could be transported and deposited elsewhere (sedimentation) for example on lake bottoms and in till sheets, moraines and eskers.
Category	Process
Relevance to Performance and Safety	Regional erosion and sedimentation have the potential to affect repository performance and safety by: • changing the separation/lengths of transport pathways between the repository and the biosphere; • changing hydraulic gradients through and around the repository; • leading to changing chemical conditions in and around the repository; • changing the stresses on the repository; and • affecting the nature and spatial distributions of environmental receptors, including the biosphere, that could be impacted should radionuclides and/or other contaminants leave the repository. Erosion would tend to reduce the separation / lengths of transport pathways between a repository and the biosphere, whereas sedimentation would have the opposite effect. Differential erosion, or sedimentation in localised topographical lows would change not only the separation/lengths of transport pathways, but also topographical gradients driving groundwater flow. Changes in the chemical environment in and around a repository could accompany erosion or sedimentation, because these processes would also change the flow path lengths between groundwater recharge zones and the repository. Erosion would tend to decrease these lengths, increasing the likelihood that relatively fresh, oxidising water could penetrate towards the repository. Conversely sedimentation would tend to increase these lengths, resulting in a greater likelihood that water/rock interactions would establish reducing conditions along the flow path following recharge. Erosion, by removing rock above the repository, would reduce stresses upon it, whereas sedimentation above the repository would increase stresses upon it. These stress changes could lead to dilation or contraction of pre-existing faults and fractures in the repository's host rock and surrounding rock formations, affecting the ability of these faults and fractures to conduct water, other liquids and gases.
2000 List	1.2.07
References	[Ref. 7], [Ref. 21]

- **FEP 1.2.9: Diagenesis**

Description	The processes by which deposited sediments undergo physical, chemical and biological alteration during compaction, cementation and crystallisation, leading to the formation of sedimentary rocks. Diagenesis occurs at relatively low pressure and temperature, under conditions of temperature and pressure normal to the upper few kilometres of the Earth's crust.
Category	Process
Comments	There is no universally accepted distinction between Diagenesis (This FEP, 1.2.9) and Metamorphism (FEP 1.2.6). However, FEP 1.2.9 applies only to sedimentary rocks,

	whereas FEP 1.2.6 may be applied to any kind of rock. Additionally, FEP 1.2.6 extends to higher pressures and temperatures than FEP 1.2.9. FEP 1.2.9 differs from FEP 4.2.1 (Thermal processes [Geosphere]), FEP 4.2.2 (Hydraulic processes [Geosphere]), FEP 4.2.3 (Mechanical processes [Geosphere]) and FEP 4.2.4 (Geochemical processes [Geosphere]), which do not involve fundamental lithological changes. That is, FEP 1.2.9 involves the formation of a rock from sediment, FEP 4.2.1, FEP 4.2.2, FEP 4.2.3 and FEP 4.2.4 may involve changes to the properties of a particular lithology (e.g. a decrease or increase in its porosity), but the affected rock type remains unchanged (e.g. if they affect a shale, then the shale does not transform into another rock type).
Relevance to Performance and Safety	Diagenesis affects sediments and sedimentary rocks. Thus, diagenesis is relevant to repository performance and safety where sedimentary rocks host a repository and / or where sediments and sedimentary rocks occur in the wider groundwater flow system within which the repository resides or might reside in the future. Diagenesis has the potential to influence the performance and safety of a repository by affecting the repository's chemical environment and the chemical and physical properties of the host rock and surrounding rock formations. During diagenesis there may be, depending upon the nature of the sediments or sedimentary rock types, a wide range of organic and inorganic chemical reactions. These reactions will influence the chemistry of groundwater, other liquids and gases in these rocks. Diagenesis will also influence the fluid pressures and hence the potential for fluids to flow, by generating or consuming fluids and changing the porosity of the rock. Mineral transformations (precipitation, dissolution and alteration) may change the connectivity of pore spaces and the nature of mineral surfaces on which migrating radionuclides or other contaminants might sorb. Diagenesis in the past may have influenced the physical and chemical characteristics of these rocks. Certain of these characteristics (porosity, mineralogy etc.) may influence the transport and retardation of radionuclides and/or other contaminants that were to leave the repository. Any characteristics of a repository's host rock or rocks in the wider area around the repository that were acquired during past diagenesis will influence the future evolution of the rock during the post-closure period. Future diagenesis may occur in repository host rocks and / or surrounding rocks, potentially within timescales that are typically considered by performance assessments (often c.1 Ma).
2000 List	1.2.08
References	[Ref. 7]

- **FEP 1.2.10: Pedogenesis**

Description	The origin and development of soils, with reference to the factors responsible for the formation of soil from parent material, including hydrological, atmospheric and biological processes. Pedogenesis depends upon climatic conditions and their impact on weathering processes, as well as on rock type, mineral composition, topography and biological processes.
Category	Process
Relevance to Performance and Safety	Pedogenesis may influence repository performance and safety primarily by: • affecting the behaviour of any radionuclides or other contaminants that are transported from the repository to the ground surface during the post-closure period; and • by affecting the nature of the biosphere that might be impacted by these radionuclides and contaminants.

	Pedogenesis will control the physical and chemical characteristics of soils which in turn will control the partitioning of any radionuclides and other contaminants present among solid organic and inorganic phases, groundwater, gas and organisms present in the soil. These processes will control the concentration, mobility and bioavailability of any radionuclides or other contaminants. The nature of the biosphere that might be impacted reflects the kinds of fauna and flora that might develop within a soil. These fauna and flora depend in turn upon the characteristics of pedogenesis. Climatic and other environmental factors, such as human actions, may affect pedogenesis. Consequently, the soils generated are likely to vary throughout the timescale considered by a performance assessment (often c. 1 Ma). Pedogenesis is of primary concern to environments at and very near the Earth's surface. However, 'fossil' soils (palaeosols) produced by ancient surface exposure could conceivably occur at some depth within certain sedimentary rock sequences that might occur near a repository. Ancient pedogenesis would have influenced the radionuclide/contaminant transport and retention properties of such palaeosols.
2000 List	Not explicitly mentioned
References	[Ref. 7],

- **FEP 1.2.11: Salt dissolution**

Description	The dissolution of evaporite minerals (halite, sylvite, etc.) by water, which may be the dominant component of a rock formation (e.g. a bedded halite formation or halite diapir), or which may be a minor component of a rock formation.
Category	Process
Relevance to Performance and Safety	Salt dissolution may influence the safety and performance of a repository by impacting upon the physical and chemical characteristics of a repository's environment. Dissolution of salt may reduce the thickness of a salt formation or produce voids through which water and/or gas may move and transport radionuclides and / or other contaminants from the repository to the biosphere. These voids may occur where the salt has been removed by dissolution, or where overlying rocks have collapsed into the space produced by the salt dissolution. Salt dissolution will impact upon the salinity and composition of the groundwater. Very high groundwater salinities may be reached. The dissolved constituents originating in the salt will complex to some degree with any radionuclides and / or other contaminants with which they come into contact, affecting the partitioning of the radionuclides and / or contaminants between immobile and mobile phases. The solutes acquired by groundwater during salt dissolution will also influence the physical and chemical evolution of wastes and engineered barriers should such water enter the repository. For example, high Cl concentrations could act to promote corrosion of steel barrier components. The high groundwater salinities that may be acquired by groundwater due to salt dissolution will also influence the density of the groundwater. Density gradients may be established that will impact upon groundwater flow rates and directions.
2000 List	1.2.09
References	[Ref. 192], [Ref. 193]

- **FEP 1.2.12: Hydrological/hydrogeological response to geological changes**

Description	The effect on regional groundwater flow and pressures arising from large-scale geological changes. These effects could include changes in groundwater flow and pressures caused by the effects of uplift/erosion on topography, and changes to hydraulic properties of geological units caused by changes in geological conditions.

Category	Process
Relevance to Performance and Safety	The hydrogeological responses to geological changes will influence the flux and directions of groundwater flow through and around a repository. These processes may be coupled to changes in groundwater chemistry along flow paths through and around a repository, for example by influencing mixing patterns between chemically distinct groundwater bodies. These responses could therefore impact upon the transport of radionuclides and/or other contaminants from the repository to the biosphere. The hydrological / hydrogeological regime around a repository at the start of repository development will reflect to some degree past hydrological / hydrogeological responses to geological changes. These responses will have occurred more slowly in lower permeability rocks than in higher permeability rocks. Groundwater head gradients in lower permeability rocks in and/or around a repository may be out of equilibrium with present hydraulic heads at the boundaries of the groundwater system within which the repository resides. In higher permeability rocks within and around a repository, groundwater head gradients may be at equilibrium with present heads at the boundary of the groundwater system. However, irrespective of whether head gradients are presently in a state of equilibrium, the chemistry of groundwater may still record past groundwater movements in response to past geological changes. Geological change in the post-closure period, such as uplift/erosion and subsidence/sedimentation, and their influences on topography, could cause future hydrological and hydrogeological changes. The rates of these changes would be more rapid in higher permeability rocks than in lower permeability rocks.
2000 List	1.2.10
References	[Ref. 49]

- **FEP 1.2.13: Geomorphological response to geological changes**

Description	The surface landform changes on a regional and local scale, i.e. the general configuration of the Earth's surface, caused by large-scale geological changes. In turn, these can impact hydrological and ecological conditions which also affect landscape evolution. Examples of landforms directly resulting from geological changes are fold mountains, rift valleys and volcanoes.
Category	Process
Relevance to Performance and Safety	Geomorphological responses to geological changes, such as development of mountains, valleys, or volcanoes, could impact upon the performance and safety of a repository by: • impacting on the chemical and physical environment of the repository, its host rocks and rocks in the wider hydrogeological system within which the repository presently resides or may reside in future; and • the nature and spatial distribution of environmental receptors, including the biosphere, that might be impacted should radionuclides and/or other contaminants be transported from the repository. Geomorphological responses to geological changes may cause the characteristics and spatial distributions of surface water bodies, rivers and coastlines to change. There would be consequent influences on the spatial distributions of groundwater recharge and discharge zones. These geomorphological responses will also impact upon the rates of groundwater recharge, for example by influencing atmospheric circulation, and hence rainfall. Therefore, geomorphological responses impact upon the fluxes and directions of groundwater flow through and around a repository and the potential distances over which radionuclides and / or other contaminants may be transported between a repository and the biosphere. There will be a corresponding influence on the chemical

	conditions in and around a repository since these are coupled to groundwater fluxes, flow directions and flow path lengths. For example, groundwater that flows from the recharge zone to a repository very slowly and over a great distance will be more likely to be reducing by the time it reaches the repository than groundwater that flows from the recharge zone to the repository rapidly over a short distance. The characteristics of the biosphere will be markedly impacted by changes in geomorphology. Flora and fauna will be affected by factors such as altitude and proximity to surface water bodies, rivers or coastlines.
2000 List	Not explicitly mentioned

- **FEP 1.2.14: Climatic responses to geological changes**

Description	The climatic responses due to geological changes such as orogeny or volcanic activity caused by plate tectonics. Responses could be short-term (months to years), such as atmospheric cooling caused by volcanic eruptions, or long-term, such as the impact on atmospheric circulation caused by orogeny.
Category	Event, Process
Comments	FEP 1.2.14 concerns geological impacts on climate, which may be global or local. In contrast FEP 1.3.1 (Global climate change) covers global climate change due to non-tectonic processes, such as changes in solar insolation or anthropogenic CO_2 emissions. FEP 1.3.2 (Regional and local climate change) covers local climate change due to non-tectonic factors, such as weathering and erosion influencing the local topography and hence local atmospheric circulation, anthropogenic activity or the action of other living organisms.
Relevance to Performance and Safety	Climatic responses to geological changes could impact upon repository performance and safety by: 1) influencing groundwater fluxes and patterns of groundwater flow in and/or around a repository; 2) influencing the chemistry of the groundwater in and/or around the repository; and 3) influencing the nature and spatial distribution of receptors that could be impacted by any radionuclides or other contaminants that are transported from the repository. Effects on the groundwater flow regime in and / or around a repository could arise from changes in the geographical distribution and rate of recharge. Changes in the flow regime could influence the transport of radionuclides and other contaminants from the repository to the locations of groundwater discharge. Changes in recharge could also lead to changes in the chemical conditions in and / or around the repository (e.g. higher recharge leading to fresh, oxidising, meteoric water penetrating to greater depth). Changes in temperature and/or the magnitude and kind of precipitation (i.e. rain or snow) could also influence the rates of erosion or sediment deposition, which could affect the depth of the repository below the surface in the long term. Changes in erosion/sedimentation and development/drying out of surface water bodies (i.e. lakes) all have the potential to influence mechanical loading of a repository
2000 List	Not explicitly mentioned
References	[Ref. 52]

FEP 1.3: Climatic factors

Description	The factors related to the long-term processes arising from global climate changes and consequent regional effects on repository performance and safety.
Category	FEP Subgroup

2000 List	1.3
References	[Ref. 12], [Ref. 14], [Ref. 15], [Ref. 166], [Ref. 167], [Ref. 168], [Ref. 182]

- **FEP 1.3.1: Global climate change**

Description	The possible future, and evidence for past, long-term change of global climate.
Category	Process
Comments	Global climate change (this FEP, 1.3.1) is distinct from changes that may occur at specific locations according to their regional setting and also local climate fluctuations, c.f. FEP 1.3.2 (Regional and local climate change). FEP 1.3.1 concerns climate change due to global processes other than plate tectonic processes, such as variations in solar insolation or anthropogenic CO_2 emissions. In contrast, FEP 1.3.2 covers climate change due to local or regional processes other than plate tectonic processes, such as weathering and erosion affecting local topography and hence local atmospheric circulation. Climatic responses to geological processes related directly to plate tectonics, such as volcanic activity or orogeny, are covered by FEP 1.2.14 (Climatic response to geological changes).
Relevance to Performance and Safety	Global climate change could impact upon repository performance and safety by: 1) influencing the fluxes and patterns of groundwater flow in and/or around a repository; 2) influencing the chemistry of the groundwater in and/or around the repository; and 3) influencing the nature and spatial distribution of receptors that could be impacted by any radionuclides or contaminants that are transported from the repository. These influences arise from the effect of global climate change on regional and local climate near the repository (FEP 1.3.2), global sea level change (depending on the repository's location relative to the coast and the topography, FEP 1.3.3) and glacial loading / unloading (depending upon the repository's latitude and the local topographical elevation, FEP 1.3.5). Effects on the groundwater flow regime in and /or around a repository could arise from changes in the geographical distribution and rate of recharge. Changes in the flow regime could influence the transport of radionuclides and other contaminants from the repository to the locations of groundwater discharge. Changes in recharge could also lead to changes in the chemical conditions in and / or around the repository (e.g. higher recharge leading to fresh, oxidising, meteoric water penetrating to greater depth). Changes in temperature and/or the magnitude and kind of precipitation (i.e. rain or snow) could also influence the rates of erosion or sediment deposition, which could affect the depth of the repository below the surface in the long term. Global climate change could lead to changes in erosion/sedimentation, glaciation / deglaciation, sea-level change and development/drying out of surface water bodies (i.e. lakes). All these factors have the potential to influence mechanical loading of a repository.
2000 List	1.3.01
References	[Ref. 51], [Ref. 52], [Ref. 198], [Ref. 199], [Ref. 200]

- **FEP 1.3.2: Regional and local climate change**

Description	The possible future changes, and evidence for past changes of climate, immediately surrounding a repository site and in the wider geographical region.
Category	Event, Process
Comments	Responses to regional climate change are discussed under FEPs 1.3.4 to 1.3.10. Regional and local climate change (this FEP, 1.3.2) is distinct from Global climate change (FEP 1.3.1) in so far as regional and local climate change is caused by regional and local

	processes that are not directly caused by plate tectonics (e.g. weathering and erosion of hills removing a rain shadow), whereas global climate change is caused by global processes (e.g. global increases in atmospheric CO_2, leading to global warming). Climatic responses to geological processes related directly to plate tectonics, such as volcanic activity or orogeny, are covered by FEP 1.2.14 (Climatic response to geological changes) and may be global or local.
Relevance to Performance and Safety	Regional and local climate change could impact upon repository performance and safety by: 1) influencing the fluxes and patterns of groundwater flow in and/or around a repository; 2) influencing the chemistry of the groundwater in and/or around the repository; and 3) influencing the nature and spatial distribution of receptors that could be impacted by any radionuclides or contaminants that are transported from the repository. Effects on the groundwater flow regime in and /or around a repository could arise from changes in the geographical distribution and rate of recharge. Changes in the flow regime could influence the transport of radionuclides and other contaminants from the repository to the locations of groundwater discharge. Changes in recharge could also lead to changes in the chemical conditions in and / or around the repository (e.g. higher recharge leading to fresh, oxidising, meteoric water penetrating to greater depth). Changes in temperature and/or the magnitude and kind of precipitation (i.e. rain or snow) could also influence the rates of erosion or sediment deposition, which could affect the depth of the repository below the surface in the long term. Changes in erosion/sedimentation and development/drying out of surface water bodies (i.e. lakes) all have the potential to influence mechanical loading of a repository.
2000 List	1.3.02
References	[Ref. 52], [Ref. 53], [Ref. 198], [Ref. 199]

- **FEP 1.3.3: Sea-level change**

Description	The changes in sea level which may occur as a result of global climatic change and regional geological change, e.g. isostatic movements. The component of sea level change involving the interchange of water between land ice and the sea is referred to as eustatic change. As ice sheets melt so the ocean volume increases and sea levels rise. Sea level at a given location will also be affected by vertical movement of the land mass, e.g. depression and rebound due to glacial loading and unloading, referred to as isostatic change.
Category	Event, Process
Relevance to Performance and Safety	Sea-level change could impact upon the performance and safety of a repository that is sufficiently close to the coast by: 1) influencing the fluxes and patterns of groundwater flow in and/or around a repository; 2) influencing the chemistry of the groundwater in and/or around the repository; and 3) influencing the nature and spatial distribution of receptors that could be impacted by any radionuclides or contaminants that are transported from the repository. The first influence arises because sea level change could affect the groundwater flow regime around a repository, which could influence the transport of radionuclides and other contaminants from a repository to the locations of groundwater discharge. Sea-level change could also influence the rates and spatial distribution of erosion or sediment deposition, which could affect the depth of the repository below the surface in the long term. These erosion/sedimentation processes and the presence/absence of a column of seawater above a repository have the potential to influence mechanical loading of the repository.
2000 List	1.3.03
References	[Ref. 52]

- **FEP 1.3.4: Periglacial effects**

Description	The physical processes and associated landforms in cold but ice-sheet-free environments within the region/locality of the repository. A key feature of such environments is the formation of large volumes of permanently frozen subsurface soils and rock, called permafrost.
Category	Feature, Process
Relevance to Performance and Safety	Periglacial effects could impact upon the performance and safety of a repository by: 1) influencing the fluxes and patterns of groundwater flow in and/or around a repository; 2) influencing the chemistry of the groundwater; and 3) influencing the natures and spatial distributions of receptors that could be impacted by any radionuclides or contaminants that are transported from the repository. Frozen ground could restrict groundwater recharge and hence fluxes of groundwater through a repository. The spatial distribution of permafrost could also influence the locations of groundwater recharge and discharge zones. Partial freezing may result in the development of higher salinity residual groundwater. High salinity water may be produced at the base of the permafrost freezing zone. Ground may be locally unfrozen leading to the development of isolated water bodies (taliks) with concentrated contaminant release. Freeze-thaw processes, including frost heave, thermo-karst processes and solifluction may lead to the development of distinctive land-forms. The spatial distribution of permafrost will change to reflect advances and retreats of adjacent glaciers and ice sheets. These processes will cause changes in drainage and watershed systems, which will affect near-surface groundwater flow, and changes in the plant, animal and human communities, which will affect potential exposure pathways.
2000 List	1.3.04
References	[Ref. 51], [Ref. 52]

- **FEP 1.3.5: Glacial and ice-sheet effects**

Description	The effects of glaciers and ice sheets within the region/locality of the repository, e.g. changes in the geomorphology, erosion, meltwater, mechanical and hydraulic effects.
Category	Feature, Process
Relevance to Performance and Safety	Glacial and ice sheet effects may influence repository performance and safety by: 1) influencing the groundwater flow regime in and/or around the repository; 2) influencing the chemistry of groundwater in and around the repository; 3) influencing the stresses on the repository system and surrounding rocks; 5) reducing the thickness of the geological barrier; 6) if sufficient erosion occurs, impacting on the physical integrity of the EBS and 7) influencing the natures and spatial distributions of receptors that could be impacted by any radionuclides or contaminants that are transported from the repository. The presence or absence of ice will influence the water recharge to groundwater beneath the glacier or ice sheet. Beneath so-called "cold-bottomed" glaciers or ice sheets water recharge may be prevented. Conversely, beneath so-called "warm-bottomed" glaciers or ice sheets water recharge may be enhanced by the weight of overlying ice that leads to high groundwater heads. Head gradients may develop beneath the glacier or ice sheet due to heterogeneous ice loading and heterogeneous distribution of recharge. Such gradients will tend to be greatest near the margins of the glacier or ice sheet. Ice sheets will also influence the geothermal gradient in the rocks beneath them, owing to the thermal insulating effect of the ice. Loading/unloading of the repository and surrounding rock during glaciation/deglaciation may change the characteristics of potential groundwater flow pathways (e.g. fracture dilation during unloading, fracture contraction during loading). The weight of large ice sheets may lead to isostatic depression of the land surface. The depressed surface will rebound following retreat of the ice sheet. These

	isostatic effects can result in changes in local sea level in the vicinity of a repository. Water recharged beneath a glacier or ice sheet will be fresh and oxidising. Such water could be detrimental with respect to certain engineered barriers should it reach the repository (e.g. bentonite buffer erosion being promoted by low salinity) and or with respect to transport of radionuclides or other contaminants (e.g. U being transported in an oxidised form). The advance and retreat of glaciers and ice sheets will influence erosion and sedimentation and have a major effect on topography. Erosional processes (abrasion, over-deepening) associated with glacial action, especially advancing glaciers and ice sheets, and with glacial meltwaters beneath the ice mass and at the margins, can lead to morphological changes in the environment e.g. U-shaped valleys, hanging valleys, fjords and drumlins. Depositional features associated with glaciers and ice sheets include moraines and eskers. These erosional and depositional processes could, in the long-term, influence the thickness of overburden above a repository.
2000 List	1.3.05
References	[Ref. 52], [Ref. 54], [Ref. 55], [Ref. 56], [Ref. 201]

- **FEP 1.3.6: Warm climate effects (tropical and desert)**

Description	The effects of warm tropical and desert climates, including seasonal, meteorological and geomorphological effects specific to these climates within the region/locality of the repository. These effects may include extreme weather patterns (e.g. monsoons, hurricanes under tropical climates, infrequent heavy rainfall events in desert climates) that could result in flooding, storm surges and high winds with implications for erosion. These effects also include desertification, which could lead to deforestation and loss of grassland.
Category	Feature, Process
Relevance to Performance and Safety	Warm climate effects may influence repository performance and safety by: 1) influencing the groundwater flow regime in and/or around the repository; 2) influencing the chemistry of groundwater in and/or around the repository; 3) influencing the separation of the repository from the biosphere; and 4) influencing the natures and spatial distributions of receptors that could be impacted by any radionuclides or contaminants that are transported from the repository. Warm climate effects may be sudden and of short duration (e.g. typhoons) or more prolonged (e.g. desertification). Sudden warm climate effects that could affect the environment of a repository include floods and landslips. Warm climate effects that would influence recharge of groundwater include variations in rainfall, evapotranspiration and influences on nature of soils. Under tropical climate conditions there will be high levels of evapotranspiration compared to desert regions. In desert regions, total rainfall, erosion and recharge may be dominated by infrequent storm events. Warm climate effects could exert a profound control on the depth of the water table. In tropical regions the water table may be near the ground surface, but in arid regions the water table could be at a considerable depth (maybe hundreds of metres). A lowered water table would affect natural biota, and might also lead to the use of deep water-supply wells to support local agriculture (or to use of distant water supplies). Warm climate controls on recharge would influence groundwater fluxes. Weathering and erosion could be influenced strongly by warm climate effects. Tropical weathering could potentially extend much deeper than desert weathering. Similarly, transport and sedimentation of material removed by erosion could be influenced strongly by warm climate effects. In turn, weathering and erosion or sedimentation could affect the thickness of overburden above a repository. Weathering processes would also influence the chemistry of the groundwater system. In tropical climates weathering would be important to greater depth than in arid regions. In arid climates evaporation of surface water bodies (which may be ephemeral) could generate hypersaline and potentially hyperalkaline lakes, which could influence the chemistry of underlying groundwater. Desertification caused by extended drought could lead to deforestation and loss of grassland; dust storms might become a common feature causing

	soil erosion; alkali flats might form causing the accumulation of salts and contaminants at the soil surface.
2000 List	1.3.06
References	[Ref. 51]

- **FEP 1.3.7: Hydrological/hydrogeological response to climate change**

Description	The changes in hydrology and hydrogeology, e.g. recharge, sediment load and seasonality, in response to climate change within the region/locality of the repository. Potential effects include climate-induced evolution of surface-water bodies, such as the formation of lakes and rivers, or their loss by sedimentation and infilling, river-course meander and long-lasting flooding or drying of low-lying areas.
Category	Event, Process
Relevance to Performance and Safety	Hydrological and hydrogeological responses to climate change could influence the performance and safety of a repository by: 1) influencing the groundwater flow regime in and/or around the repository; 2) influencing the chemistry of groundwater in and/or around the repository; 3) influencing the separation of the repository from the biosphere; 4) influencing the processes by which radionuclides or other contaminants are concentrated or dispersed within the biosphere; and 5) influencing the nature and spatial distribution of receptors that could be impacted by any radionuclides or other contaminants that are transported from the repository. Changes in the amount of precipitation and evaporation, seasonal ice and snow cover will change the recharge to groundwater. These processes could also result in changes in groundwater chemistry, such as freshwater penetrating to greater depth in times of greater recharge. Additionally, there could be modifications to the quantities and patterns of runoff and the existence / spatial distributions of surface water bodies. In turn, these factors would influence the patterns and rates of erosion, sediment transport and deposition. A consequence of these processes could be changes in the thickness of overburden above and/or near a repository (increasing if sedimentation occurs, decreasing if erosion occurs). A possible result of the hydrological responses to climate change is that topography is modified. Modified flows (quantities and directions) of surface water and groundwater, and associated changes in erosion and sedimentation, accompanied by ecosystem changes, could affect the concentration or dispersion of radionuclides or other contaminants. Hydrological responses to climate change could also cause changes in the character / spatial distributions of ecosystems that could be impacted by any radionuclides or other contaminants that might leave a repository.
2000 List	1.3.07
References	[Ref. 52], [Ref. 56]

- **FEP 1.3.8: Ecological response to climate change**

Description	The changes in ecology, e.g. vegetation, animal and plant populations, in response to climate change within the region/locality of the repository.
Category	Event, Process
Comments	Ecological responses to climate change (this FEP 1.3.8) may reflect the Hydrological / hydrogeological responses to climate change that are covered by FEP 1.3.7.

Relevance to Performance and Safety	Ecological responses to climate change are relevant for repository performance and safety because they affect the nature of the biosphere that could be impacted by any radionuclides or other contaminants that might leave a repository in the future. Climate change will influence the relative importance of aquatic and terrestrial ecosystems among the potential receptors that need to be considered by a safety assessment. Within aquatic and terrestrial ecosystems the nature and proportions of different plants and animals will depend strongly upon climatic factors. Changes in ecosystems due to climate change will also impact upon biological processes by which radionuclides or other contaminants that originate in a repository could be concentrated or dispersed. Interactions between humans and natural ecosystems will also be affected by climate change, with a consequent influence on the potential for humans to be exposed to radionuclides or other contaminants that might leave a repository. For example, the potential for agriculture to occur near a repository, with associated ecosystem changes, will depend upon climatic conditions.
2000 List	1.3.08
References	[Ref. 51], [Ref. 52]

- **FEP 1.3.9: Human response to climate change**

Description	The changes in human behaviour, e.g. habits, diet, size of communities, dwelling types, agriculture and location, in response to climate change within the region/locality of the repository.
Category	Event, Process
Relevance to Performance and Safety	Human responses to climate change are relevant to repository performance and safety because they influence: 1) the likelihood for humans or other potential receptors to be exposed to radionuclides or other contaminants that might leave a repository in future; 2) the nature of the radionuclides or contaminants to which humans or other potential receptors are exposed; 3) the duration of such exposures should they occur; and 4) anthropogenic processes by which radionuclides or other contaminants could be concentrated or dispersed. Climate change will impact upon the characteristics, abundances and spatial distributions of natural resources, such as agricultural land and water resources (both surface water and groundwater). Humans will respond to such changes in ways that might affect the potential for humans or other potential receptors to be impacted by radionuclides or other contaminants originating in a repository. For example, humans may change the kind of agriculture that is undertaken, or drill to greater depths to obtain groundwater. Humans may also respond to climate changes in ways that modify the sizes and spatial distributions of human populations in the area surrounding a repository. For example, some climate change, such as desertification, may make an area uninhabitable. Conversely, improving conditions for agriculture might make an area more attractive to human populations. The daily activities of humans may change as a response to climate change and influence the potential for humans to be impacted by radionuclides or other contaminants originating in a repository. For example, under colder climatic conditions, humans might spend more time indoors than under warmer climatic conditions.
2000 List	1.3.09
References	[Ref. 51], [Ref. 52]

- **FEP 1.3.10: Geomorphological response to climate changes**

Description	The geomorphological responses to climate changes within the region/locality of the repository. This FEP covers landscape evolution as a result of changes in climatic

	conditions. In turn, these can be coupled to changes in hydrological and ecological conditions.
Category	Event, Process
Relevance to Performance and Safety	Geomorphological responses to climate changes are relevant to repository performance and safety because they may: 1) influence the fluxes and patterns of groundwater flow in and/or around a repository; 2) cause modifications in groundwater chemistry in and / or around a repository; 3) affect the separation between a repository and the biosphere; 4) influence the potential concentration or dispersal of radionuclides or other contaminants that originate in a repository; and 5) influence the natures and spatial distributions of receptors that could be impacted by any radionuclides or contaminants that are transported from the repository. Geomorphological responses to climate change may occur over a prolonged time, for example reflecting long-term changes in annual precipitation. Alternatively, these responses may occur rapidly, such as when landslips are caused by storm events. Geomorphological responses to climate changes may cause the characteristics and spatial distributions of surface water bodies, rivers and coastlines to change. There would be consequent influences on the spatial distributions of groundwater recharge and discharge zones. These geomorphological responses will also impact upon the rates of groundwater recharge, for example by influencing the vegetation and the nature of the soils that occur at a given locality. Therefore, geomorphological responses impact upon the fluxes and directions of groundwater flow through and around a repository and the potential distances over which radionuclides and / or other contaminants may be transported between a repository and the biosphere. There will be a corresponding influence on the chemical conditions in and around a repository since these are coupled to groundwater fluxes, flow directions and flow path lengths. For example, groundwater that flows from the recharge zone to a repository very slowly and over a great distance will be more likely to be reducing by the time it reaches the repository than groundwater that flows from the recharge zone to the repository rapidly over a short distance. Landscape evolution will be accompanied by erosion, sediment transport and deposition that may change the thickness of overburden above a repository and hence the spatial separation between the repository and the biosphere. Another consequence of landscape evolution will be changing patterns of drainage and sediment transport. These processes, accompanied by changes in ecosystems, will impact upon the concentration or dispersion of any radionuclides or other contaminants that originate in a repository. The characteristics of the biosphere will be markedly impacted by changes in geomorphology. Flora and fauna will be affected by factors such as altitude and proximity to surface water bodies, rivers or coastlines.
2000 List	Not explicitly mentioned
References	[Ref. 51] [Ref. 52]

- **FEP 1.4: Future human actions**

Description	The factors related to human actions in the future, following closure that potentially change the disposal system to the extent that this affects its performance and safety.
Category	FEP Subgroup
2000 List	1.4
References	[Ref. 51], [Ref. 16], [Ref. 17], [Ref. 173], [Ref. 174]

- **FEP 1.4.1: Human influences on climate**

Description	The human activities that could affect the change of climate either globally or in a region. This FEP covers global warming due to man-made emissions of "greenhouse gases" such as CO_2 and CH_4. It also covers more local variations, for example micro-climates due to urban development.
Category	Event, Process
Relevance to Performance and Safety	Human influences on climate could impact upon repository performance and safety by: 1) influencing the fluxes and patterns of groundwater flow in and/or around a repository; 2) influencing the chemistry of the groundwater in and/or around the repository; 3) influencing the processes by which radionuclides or other contaminants that originate in a repository may be concentrated or dispersed in near-surface environments; and 4) influencing the nature and spatial distribution of receptors that could be impacted by any radionuclides or contaminants that are transported from the repository. Human influences on climate could operate either globally, as in the case of global warming due to emissions of greenhouse gases (principally CO_2 and CH_4) or locally (e.g. in the case of micro-climates being developed around large cities). Over the timescale of a typical performance assessment, anthropogenic effects could result in changes to air temperatures and the quantity and nature of precipitation (i.e. whether rain or snow). The human influences on climate would be superimposed on natural climatic influences, resulting in modified temporal changes in conditions throughout the timeframe of a safety assessment. The groundwater flow regime in and /or around a repository could be modified by changes in the geographical distribution and rate of recharge, caused in turn by anthropogenic climatic effects. Changes in the flow regime could influence the transport of radionuclides and other contaminants from the repository to the locations of groundwater discharge. Modifications to recharge could also lead to variations in the chemical conditions in and / or around the repository (e.g. higher recharge leading to fresh, oxidising, meteoric water penetrating to greater depth). Changes in temperature and/or the magnitude and kind of precipitation (i.e. rain or snow) and / or deglaciation or glaciation could also influence the rates of erosion or sediment deposition. These processes could in turn affect the depth of the repository below the surface in the long term. Changes in erosion/sedimentation and development/drying out of surface water bodies (i.e. lakes) all have the potential to influence mechanical loading of a repository. Climatic effects caused by human activity could include changes to processes that might influence the concentration or dispersion of radionuclides and other contaminants in near-surface environments, such as drainage patterns and erosion rates.
2000 List	1.4.01
References	[Ref. 51], [Ref. 52]

- **FEP 1.4.2: Social and institutional developments**

Description	The changes in social patterns and institutions that impact upon a repository, including those involved in government, planning and regulation.
Category	Event, Process
Relevance to Performance and Safety	Social and institutional developments are relevant to repository performance and safety because they could: 1) influence the measures that are taken to monitor and manage a repository post-closure; 2) influence the characteristics and spatial distributions of the human populations that could be impacted should any radionuclides or other contaminants travel from the repository to the near-surface; 3) influence the likelihood that future populations might intrude into the repository, or into a plume of radionuclides or other contaminants that have already been released from the repository but not yet reached the biosphere; and 4) influence the characteristics and spatial distributions of

	non-human biota that could be impacted should any radionuclides or other contaminants travel from the repository to the near-surface. Planning controls and environmental legislation could change in the future and cause modifications to the monitoring and management measures that are taken following repository closure. Demographic changes, social factors and planning controls could affect the sizes and spatial distributions of human populations in the area around a repository, and the activities of the human populations. Examples of such changes include increases and decreases in the sizes of local populations (including urbanisation / de-urbanisation), changes to the living environment of humans (e.g. whether living in high-rise buildings or low-rise buildings) and changes to lifestyles of humans (e.g. variations in the time spent indoors and outdoors). These factors would affect the likelihood that human populations could be impacted by radionuclides or other contaminants originating in a repository, and the nature of the impacts. The changed land uses in the area around a repository that could be caused by demographic changes, social factors and planning controls will cause the non-human biota to be modified. For example, such factors could change the proportions of forestry and arable farming in an area, with consequent changes in ecosystems. The likelihood that non-human biota will be impacted by radionuclides or other contaminants originating in a repository, and the nature of the impacts, will depend on the characteristics and spatial distributions of the non-human biota. The loss or records concerning a repository and societal memory of a repository's existence, would increase the risk of inadvertent human intrusion into the repository, or into a plume of radionuclides or other contaminants that have already been released from the repository, but not yet reached the biosphere.
2000 List	1.4.08
References	[Ref. 51], [Ref. 58], [Ref. 59], [Ref. 202], [Ref. 203]

- **FEP 1.4.3: Technological developments**

Description	Future developments in human technology and changes in the capacity and motivation to implement technologies.
Category	Event, Process
Relevance to Performance and Safety	Technological developments are relevant to repository performance and safety because they will affect: 1) the likelihood that human actions could compromise the integrity of the repository, or transport radionuclides or other contaminants that have already been released from the repository, from the deep subsurface to the biosphere; 2) the ability of humans to mitigate any impacts of radionuclides or other contaminants that might originate in the repository; 3) the actual impacts on receptors of any radionuclides or other contaminants that might originate in the repository. Generally, improved levels of technology in future compared to the present would presumably decrease the likelihood that humans might inadvertently intrude into a repository, or into a deep plume of radionuclides or other contaminants that have already been released from the repository, even if knowledge of the repository had been lost (because the existence of a repository would be recognised by non-intrusive techniques even more readily than using present technology). Improved technology would also increase the likelihood of humans being able to mitigate the impacts of radionuclides or other contaminants that might be released from a repository. An example would be improved treatments for cancers that might be caused by exposure to radionuclides or improved remediation techniques. Conversely, decreased levels of technology in future compared to the present might increase the likelihood of inadvertent intrusion and decrease the likelihood that impacts from any releases of radionuclides or other contaminants could be mitigated. Irrespective of whether humans could mitigate the impacts of radionuclides or other contaminants that might be released from a repository, the magnitude and nature of these impacts could in part be determined by technological developments. For example, technologies for producing food will impact upon the likelihood that food sources for humans could be contaminated by radionuclides and the routes by which humans could be exposed in

	the event of such contamination. The increasing use of insulation in homes is an example of a recent technological development that has tended to increase risks from natural radon releases from the sub-surface in some regions of the world.
2000 List	1.4.09
References	[Ref. 60], [Ref. 61], [Ref. 204], [Ref. 205]

- **FEP 1.4.4: Knowledge and motivational issues [repository]**

Description	The degree of knowledge of the existence, location and/or nature of the repository, including reasons (motivation) for deliberate interference with, or intrusion into, a repository after closure with complete or incomplete knowledge.
Category	Event, Process
Relevance to Performance and Safety	Knowledge and motivational issues are relevant to repository performance and safety because they affect the future responses of humans to the existence of the repository. Future knowledge of the existence, location and nature of a repository will always be subject to some uncertainty. Consequently, there is always some potential for accidental human intrusion to occur, either into the repository itself, or into a plume of radionuclides or other contaminants that may have been released from the repository, but not yet transported to the biosphere. However, if there is a high degree of knowledge about the existence, location and nature of the repository, any human intrusion will probably be deliberate. In contrast, where there is little such knowledge, any human intrusion will probably be accidental. No knowledge at all about the repository implies that any human intrusion would certainly be accidental. Compared to accidental intrusion, deliberate intrusion is more likely to be accompanied by measures that would prevent and / or mitigate adverse environmental impacts from radionuclides or other contaminants. Higher levels of knowledge about the existence, location and nature of a repository are likely to result in more appropriate / effective mitigation measures being available than in cases where there is less knowledge. For intrusion to occur, whether deliberately or accidentally, there will also need to be a motivation, such as seeking resources. Deliberate intrusion could possibly be motivated by an attempt to mitigate the effects of radionuclide releases or other contaminant releases (e.g. an attempt may be made to retrieve certain wastes).
2000 List	1.4.02
References	[Ref. 35], [Ref. 46], [Ref. 47], [Ref. 194], [Ref. 203]

- **FEP 1.4.5: Drilling activities**

Description	Any type of drilling activity in the vicinity of or within the repository.
Category	Event, Process
Comments	Drilling activities may be undertaken with or without knowledge of the repository (FEP 1.4.4).
Relevance to Performance and Safety	Drilling activities are relevant to the performance and safety of a repository because they will disturb the geosphere around the repository and/or engineered barriers to some degree. The boreholes themselves may provide pathways by which radionuclides and/or other contaminants may be transported to the biosphere, either directly from the repository (if the borehole connects the biosphere to the repository) or from a plume of radionuclides and / or other contaminants that has already been released from the repository, but not reached the biosphere (if the borehole connects the biosphere to such

	a plume). The borehole could behave as a pathway either during drilling or sometime thereafter (in the event that the borehole is improperly sealed). If a borehole produced by drilling was to penetrate waste containers (e.g. in the event of accidental intrusion) then radionuclides and other contaminants could be released from the wastes. A borehole could also form part of a pathway for radionuclides and/or other contaminants to migrate from the repository to the biosphere, such as when a short investigation borehole that is drilled underground connects the repository to a naturally transmissive fracture zone that extends to the biosphere. Drilling activities may perturb the chemistry of the rock-groundwater system, which may in turn impact upon the transport or radionuclides or other contaminants. For example, borehole drilling may involve the use of organic fluids which could form mobile complexes with certain radionuclides. Some materials used in borehole drilling could react adversely with certain barrier materials. For example, cement is often used in boreholes and could interact with any bentonite barrier with which it comes into contact. Borehole drilling may also involve pumping water, which could lead to a disturbance of the groundwater system surrounding the borehole. One effect of pumping water from a borehole could be to cause radionuclides or other contaminants to be drawn towards the borehole and thereafter transported to the biosphere. If, on the other hand, fluids are pumped into the borehole during drilling groundwater pressures and water chemistry could be perturbed.
2000 List	1.4.04
References	[Ref. 59], [Ref. 62], [Ref. 203]

- **FEP 1.4.6: Mining and other underground activities**

Description	Any type of mining or excavation activity carried out in the vicinity of the repository. These activities include conventional blasting and excavation practices, strip mining and solution mining.
Category	Event, Process
Comments	Mining may be undertaken with or without knowledge of the repository (FEP 1.4.4).
Relevance to Performance and Safety	Mining and other underground activities are relevant to repository performance and safety because, depending upon the distance between these activities and the repository, they will perturb the geosphere around the repository and the repository itself. There may be a combination of mechanical, hydrogeological and chemical perturbations. If sufficiently close to the repository, the integrity of the repository could be compromised; in the most extreme case mining or other underground activities could intrude into the repository, either accidentally or deliberately. Excavated openings could potentially form pathways by which radionuclides or other contaminants originating in a repository could migrate all or part of the way from the repository to the biosphere. The latter situation would arise if the openings connect other kinds of pathway, as when an excavation connects a repository to a naturally transmissive fracture zone. The openings could act as pathways during their excavation or when operations are undertaken in them, or at some time afterwards if they are imperfectly sealed. Potentially, the stresses in the rocks surrounding a repository and in the repository itself could be affected by mining and other underground activities. Consequences could include the creation of fractures, or the dilation or contraction of existing fractures. These fractures could form pathways for the migration of radionuclides or other contaminants. Roof collapses in underground excavations could produce collapse columns that might become pathways by which radionuclides and / or other contaminants could be transported. Mining and other underground activities may involve introducing and / or removing water or other fluid from the subsurface (e.g. groundwater may be extracted during mine drainage operations, or gas that has been previously stored in salt caverns may be removed). These activities could influence groundwater heads and hence groundwater flow rates and directions in and / or around a repository. Groundwater chemistry could also be

	influenced, with possible impacts on the migration or retardation of radionuclides and / or other contaminants that might originate in a repository. For example, underground redox conditions may be influenced by mining, with consequent impacts on the evolution of barriers.
2000 List	1.4.05
References	[Ref. 59], [Ref. 63], [Ref. 203]

- **FEP 1.4.7: Un-intrusive site investigation**

Description	Any airborne, surface or other remote investigations of a repository site after repository closure, which does not involve disturbing the sub-surface environment (except for the transient, limited extent resulting from seismic techniques).
Category	Event, Process
Comments	This FEP excludes all intrusive site investigation activities such as drilling and mining, which are covered by FEP 1.4.5 and FEP 1.4.6, respectively.
Relevance to Performance and Safety	Un-intrusive site investigations would yield information about the sub-surface in the area around a repository that could influence whether intrusive activities are undertaken to the detriment of repository performance and safety. The information obtained from un-intrusive site investigations could provide a motivation to undertake invasive activities (see also FEP 1.4.4), or alternatively provide a reason for not undertaking such activities. For example, if it is revealed that an ore deposit occurs near the repository there could be a motivation to proceed with invasive site investigations leading potentially to mining. Conversely, if the un-intrusive site investigations identified a repository about which knowledge and / or records had been lost, then a decision might be taken not to proceed with invasive activities. If there is a motivation to proceed with invasive activities, decisions about the kinds of invasive activities to undertake could be based on information from un-intrusive site investigations. Information obtained by the un-intrusive site investigations will affect the likelihood that these invasive activities will compromise the integrity of the repository or provide pathways for the transport of radionuclides and / or other contaminants from the sub-surface to the biosphere.
2000 List	1.4.03
References	[Ref. 59]

- **FEP 1.4.8: Surface activities**

Description	Any human activities that may be carried out in the surface environment, other than water management, which potentially change the disposal system to the extent that this affects its performance and safety. Examples include: changes in land use; quarrying and trenching; excavation for industrial purposes such as construction of a building; excavation for archaeological purposes; residential and road construction; and major earthmoving projects, such as construction of dikes and dams.
Category	Event, Process
Comments	FEPs related to water management, such as following dam construction, are excluded; they are covered by FEP 1.4.9.

Relevance to Performance and Safety	Surface activities are relevant to repository performance and safety because they could: 1) influence the locations of groundwater recharge and discharge and the recharge rates (which could in turn influence the groundwater flow regime in and around a repository); 2) influence the chemistry of water that recharges the groundwater system (which could in turn influence the chemistry of groundwater in and around a repository); 3) influence mechanical loading on the ground around a repository (e.g. if large buildings are constructed or quarries are excavated); 4) influence patterns of surface drainage, erosion and sedimentation, with consequent influences on topography; 5) influence the pathways by which receptors could be exposed to radionuclides or other contaminants originating in a repository; and 6) influence the nature of receptors that could be impacted by radionuclides or other contaminants originating in a repository. Many surface activities will influence groundwater recharge by changing the permeability of near-surface media (e.g. construction of buildings will reduce recharge) and distribution of soils and vegetation (which will affect water storage and evapotranspiration). Similarly, many surface activities have the potential to affect the chemistry of recharged waters, for example waste disposal in landfill, application of fertilizer during agriculture, or spillages of chemicals during industrial activities. Mechanical loads exerted by some surface activities, such as construction of large buildings or dams / reservoirs, could be considerable. In extreme cases seismicity could result (e.g. a M6.7 earthquake is thought to have been triggered by a dam at Koyna, India in 1967). Hydrological systems could be affected by surface activities such as land drainage or dam construction. Rates of erosion could be influenced by changing land use and by construction of structures. Some surface activities are intended to limit or modify erosion, for example rock bolting and shotcreting steep slopes to prevent landslips. These activities could collectively modify patterns of erosion and sedimentation thereby influencing future landforms. The ecosystems that could be impacted by radionuclides and / or other contaminants originating in a repository could reflect in part the surface activities that have been undertaken in an area; ecosystems in agricultural areas and urban areas will be very different. The effects of surface activities on hydrology, recharge, erosion and sedimentation, landforms, sediment types / rock types and ecosystems could potentially influence retardation and dispersion of radionuclides and other contaminants at the earth's surface / near-surface. These effects could also influence the pathways by which organisms could be exposed to radionuclides or other contaminants.
2000 List	1.4.06
References	[Ref. 59]

- **FEP 1.4.9: Water management (groundwater and surface water)**

Description	Groundwater and surface water management including water extraction, artificial recharge and underground water storage, reservoirs, dams, sewage water treatment and river management.
Category	Event, Process
Comments	Water management (this FEP 1.4.9) covers pumping of water from boreholes or the injection of water to boreholes for the purposes of managing groundwater resources, but does not cover the actual drilling of water wells. Drilling of water wells is considered under Drilling activities (FEP 1.4.5).
Relevance to Performance and Safety	Water management has the potential to influence the performance and safety of a repository by: 1) affecting the flow of groundwater in and/or around a repository; 2) affecting the chemistry of the groundwater in and/or around a repository; 3) providing a pathway for organisms to be exposed to radionuclides and/or other contaminants originating in a repository; 4) affecting erosion and sedimentation (with a consequent impact on landforms); 5) affecting the processes by which radionuclides and/or other contaminants originating in a repository could be retarded or dispersed; and 5) affecting

	the nature of organisms and ecosystems that could be impacted by radionuclides and/or other contaminants originating in a repository. Groundwater abstraction could transport contaminated water from a repository or its environs to the biosphere. Even if contaminated water is not abstracted, groundwater heads could be drawn down, thereby affecting groundwater fluxes in and around a repository. Groundwater management may involve artificial recharge, which could introduce fresh, oxidising water to depth near a repository. Such recharge could also affect groundwater head gradients and ground fluxes in and around a repository. Surface water management could include the construction of reservoirs and water courses, both to provide water resources and to prevent or mitigate the chances for flooding. Vegetation and land uses in catchments might be managed to control storage and runoff rates in the near-surface. The changes in hydrology that could accompany management of surface water could influence erosion and sedimentation. These processes, combined with certain water management measures themselves (e.g. straightening of meandering rivers, construction of reservoirs) have the potential to change landforms. Ecosystems could be influenced by the measures taken to manage water resources. For example, construction of a reservoir may lead to the development of wetland habitats where none existed previously. Thus, water management could affect the nature of organisms that could be impacted by radionuclides and / or other contaminants. The processes by which radionuclides and / or other contaminants could be retarded or dispersed in the near surface will be affected by potential changes in water drainage patterns/volumes, landforms, the nature of soils / sediments, exposures of rock and ecosystems.
2000 List	1.4.07
References	[Ref. 64], [Ref. 206]

- **FEP 1.4.10: Explosions and crashes**

Description	Deliberate or accidental explosions and crashes that might have an impact on a closed repository.
Category	Event
Relevance to Performance and Safety	Explosions and crashes could affect the performance of the repository in a variety of ways, such as changes to the integrity of the host rock and failure of seals. Depending upon their sizes and where they are located, explosions and crashes could potentially compromise the natural and / or engineered barriers of a repository. Explosions and crashes also have the potential to transport radionuclides and other contaminants to the biosphere. During such transport, the contaminants would be dispersed to some degree. If they were to occur after other processes had compromised the integrity of the repository and transported contaminants to the biosphere, explosions and crashes may also have the potential to further disperse the contaminants within the biospheres. The kinds of human responses to an explosion or crash would influence the likely exposure of humans and other organisms to radionuclides and / or other contaminants.
2000 List	1.4.11
References	[Ref. 59], [Ref. 207]

- **FEP 1.4.11: Remedial actions**

Description	The actions that might be taken following repository closure to remedy problems with a repository arising from its sub-standard performance, disruption by some natural event or process, or inadvertent or deliberate damaged by human actions.
Category	Process

Relevance to Performance and Safety	Remedial actions will influence the impacts of any (assumed or real) impaired repository performance. If the remedial actions are successful, then impacts of impaired performance will be reduced or eliminated. However, if inappropriate remedial actions are taken, then the impacts could be made worse. In an extreme case where repository performance is incorrectly believed to be impaired, unnecessary remedial actions could cause impairment. For example, if the integrity of a repository is incorrectly believed to be compromised, an unnecessary decision might be taken to retrieve the waste, with consequent adverse environmental impacts. Certain remedial actions, whether necessary or not, could generate waste that needs to be managed appropriately.
2000 List	1.4.10
References	[Ref. 65], [Ref. 66]

- **FEP 1.4.12: Deliberate human intrusion**

Description	The reasons for and the nature and consequences of deliberate intrusion into a repository after closure with complete or incomplete knowledge of the repository.
Category	Event, Process
Relevance to Performance and Safety	Deliberate human intrusion is relevant to repository performance and safety because it involves penetrating the repository, which will compromise the barrier system. Depending upon the nature of the human intrusion, it might transport materials contaminated by radionuclides and / or other contaminants from the repository to the biosphere. The potential consequences for repository performance and safety will depend upon the level of technology possessed by the people carrying out the intrusion, the level of knowledge they have about the repository, and the reasons for the intrusion. Intrusion that uses high levels of technology may decrease the likelihood of adverse environmental impacts compared to intrusion that uses low levels of technology. Consequences may include the long-term impacts of disrupting the barrier system and / or the effects or moving material from the repository to the biosphere. Similarly, compared to lower levels of knowledge about the repository, greater levels of knowledge will, for a given level of technological capability, imply a lower likelihood of adverse environmental impacts. Intrusion that is undertaken to remove material, for example waste retrieval, could result in greater impacts to the biosphere than intrusion that is intended purely for exploratory purposes, for example to establish the characteristics of the wastes. Intrusion that is authorised is more likely to observe the requirements of a robust regulatory framework than intrusion that is unauthorised. It follows that unauthorised intrusion is, all other factors being equal, more likely to result in adverse environmental impacts than authorised intrusion.
2000 List	1.4.02
References	[Ref. 59], [Ref. 62], [Ref. 70], [Ref. 203]

FEP 1.5: Other external factors

Description	Any other external scenario-generating factors not accommodated in FEP categories 1.1 to 1.4.
Category	FEP Subgroup
2000 List	1.5
References	[Ref. 18], [Ref. 172], [Ref. 179], [Ref. 183]

- **FEP 1.5.1: Meteorites and human space debris**

Description	The possibility of a large meteorite or human space debris impact occurring at or close to the repository site and related consequences.
Category	Event
Relevance to Performance and Safety	A large meteorite or human space debris impacting at or close to a repository site could impact on repository and safety by: 1) impairing the performance of the engineered and/or natural barriers; 2) transporting radionuclides and other contaminants from the repository to the biosphere and dispersing them there; 3) dispersing radionuclides and other contaminants that have already been released by the repository owing to other processes; 4) changing the topography, with consequent impacts on drainage; 5) affecting the nature of ecosystems that could be impacted by radionuclides and / or other contaminants that might reach the biosphere from the repository. Very large meteor impacts could cause faults and fractures to form and / or existing faults and fractures to be reactivated and to dilate and/or seal. There could be related influences on groundwater fluxes and chemistry. Large impacts may result in metamorphism of the rocks and dispersion of ejecta, which may be contaminated by radionuclides and/or other contaminants. Effects on surface topography could include cratering, damming of rivers or breaching of topographical barriers such as ranges of hills. These processes could alter the surface drainage and the spatial distributions of water bodies. For example lakes could form in impact craters. These changes could be accompanied by local changes in ecosystems and hence the natures of organisms that could be impacted by any radionuclides or other contaminants originating in a repository. In very extreme meteor impact events there could be a global effect on organisms, possibly including mass extinctions, which could be followed by evolutionary radiation. Some effects of impacts of meteorites or human space debris would occur immediately, such as the breaching of a repository. Other effects could be very long-lasting, such as the topographical changes and related effects that could be caused by the impact of a large meteorite.
2000 List	1.5.01
References	[Ref. 67], [Ref. 68], [Ref. 208], [Ref. 209]

- **FEP 1.5.2: Evolution of biota**

Description	The biological evolution of humans, other animal or plant species, by both natural selection and selective breeding/culturing.
Category	Process
Relevance to Performance and Safety	The evolution of organisms will affect how ecosystems might respond to being exposed to radionuclides and / or other contaminants that originate in a repository. This evolution could be natural, caused by deliberate human actions (e.g. selection for agricultural purposes) or could be an indirect consequence of human actions, such as a response to pollution. Potentially, some organisms could evolve because of exposure to contaminants from a repository. Evolution could influence how organisms can concentrate or disperse these contaminants, as well as the physiological effects of the contaminants on the organisms themselves. Not all organisms in an ecosystem will evolve at the same rate. Microorganisms may evolve much more quickly than higher organisms such as humans. This may be especially relevant for evolved microorganisms that are brought into the repository by intrusive measures and that may subsequently alter the properties of safety barriers. Human actions could speed up the evolution of organisms by either selection or genetic manipulation. Potentially, such anthropogenically caused evolution could produce organisms that are resistant to radionuclides or other contaminants. Alternatively, evolution caused by humans could produce organisms that are more vulnerable if exposed to radionuclides or other

	contaminants from a repository. The evolution of even a single organism within an ecosystem could potentially affect the entire ecosystem significantly.
2000 List	1.5.02
References	[Ref. 69], [Ref. 210]

▪ FEP 2: Waste package factors

Description	The factors related to waste packages (i.e. waste forms and any associated packaging) and the associated release and migration of contaminants from them.
Category	FEP Group
2000 List	2.1, 3.1, 3.2
References	[Ref. 4], [Ref. 28]

o FEP 2.1: Waste form

Description	The waste at the time of emplacement in the repository, following any pre-disposal treatment and/or conditioning.
Category	FEP Subgroup
2000 List	2.1.02
References	[Ref. 4], [Ref. 161], [Ref. 175], [Ref. 176]

▪ FEP 2.1.1: Contaminant inventory

Description	The content of radioactive and non-radioactive contaminants in the various waste forms disposed of in the repository.
Category	Feature
Relevance to Performance and Safety	The contaminant inventory is relevant to performance and safety because it describes the identities and quantities of radioactive and non-radioactive waste constituents that potentially could be harmful should environmental receptors be exposed to them. The physical and chemical properties of each contaminant (e.g. whether it can exist in different oxidation states, whether it is sorbing or non-sorbing, whether it partitions into liquid water or a gaseous phase, the rate of decay) are important controls on the mechanisms by which it may be released from the waste form and transported through engineered and natural barriers, potentially to the biosphere. The abundance and properties of each radioactive and non-radioactive contaminant in the waste form, in combination, will influence the potential environmental consequences, as considered in a safety assessment.
2000 List	2.1.01
References	[Ref. 71], [Ref. 72], [Ref. 211], [Ref. 212]

- ***FEP 2.1.1.1: Radionuclide content***

Description	The inventory of radioactive isotopes (radionuclides) of all elements in the various waste forms disposed of in the repository. Included are the identities and quantities of radioactive isotopes that are present in the waste initially and those that might form subsequently by processes such as radioactive decay, activation.
Category	Feature
Relevance to Performance and Safety	The radionuclide content is relevant to performance and safety because it describes the identities and quantities of radioactive waste constituents that potentially could be harmful should environmental receptors be exposed to them. The physical and chemical properties of each radionuclide (e.g. whether it can exist in different oxidation states, whether it is sorbing or non-sorbing, whether it partitions into liquid water or a gaseous phase, the rate of decay) are important controls on the mechanisms by which it may be released from the waste form and transported through engineered and natural barriers, potentially to the biosphere. The abundance and properties of each radionuclide in the waste form, in combination, will influence strongly the dose that an environmental receptor could receive, as calculated in a safety assessment. The natures and quantities of radionuclides will evolve over time as a result of processes such as radioactive decay and activation. The potential for mobilisation and the activities of radionuclides that are ingrown by these processes need to be taken into account by safety assessment.
2000 List	2.1.01
References	[Ref. 72], [Ref. 73], [Ref. 213]

- ***FEP 2.1.1.2: Chemical content***

Description	The inventory of non-radioactive (chemotoxic) contaminants in the various waste forms disposed of in the repository.
Category	Feature
Relevance to Performance and Safety	The content of non-radioactive contaminants describes the identities and quantities of non-radioactive waste constituents that potentially could be harmful should environmental receptors be exposed to them. The physical and chemical properties of each contaminant (e.g. whether it can exist in different oxidation states, whether it is sorbing or non-sorbing, whether it partitions into liquid water or a gaseous phase, rate of degradation) are important controls on the mechanisms by which it may be released from the waste form and transported through engineered and natural barriers, potentially to the biosphere. The abundance and properties of each non-radioactive contaminant in the waste form, in combination, will influence strongly the environmental consequences, as calculated in a safety assessment.
2000 List	2.1.01
References	[Ref. 72], [Ref. 73]

- **FEP 2.1.2: Waste form characteristics and properties**

Description	The physical, chemical and biological characteristics and properties of the waste forms at the time of emplacement in the repository. This includes the mass and volume of each waste form type, as well as information on the associated thermal, hydraulic, chemical and mechanical characteristics. The phase characteristics (solid, gas or liquid) is also covered by this FEP.

Category	Feature
Relevance to Performance and Safety	The physical and chemical characteristics of the waste form control the release rates of radioactive and non-radioactive contaminants, and the physical and chemical forms in which they are released from the waste form. Waste forms may be metallic, organic or non-metallic and inorganic in nature. Some waste forms may also be in liquid or gas phase. The physical and chemical characteristics and properties will also influence how the different components of the waste form interact with each other and with the waste container. Depending upon the physical and chemical characteristics of the waste form, these latter interactions may influence the integrity of the containers. For example, the alkaline environment maintained by cementitious waste forms may help to decrease the corrosion rate of an iron or steel container. On the other hand, the possibility that bituminous waste forms may expand due to radiolysis, thereby impacting upon the container, may need to be considered by a safety assessment.
2000 List	2.1.02
References	[Ref. 74], [Ref. 75], [Ref. 212], [Ref. 214]

- ***FEP 2.1.2.1: Metals***

Description	The characteristics and properties of metallic waste forms that may be disposed of in a repository.
Category	Feature
Relevance to Performance and Safety	The physical and chemical characteristics of metallic waste forms control the release rates of radioactive and non-radioactive contaminants from the metals, and the physical and chemical forms in which these contaminants are released. The physical and chemical characteristics and properties will also influence how the waste form interacts with any other waste forms (e.g. organic materials or inorganic, non-metallic waste forms) in the same waste container, and with the waste container itself. Depending upon the physical and chemical characteristics of the metal in the waste form, these latter interactions may accelerate the rate at which containers degrade following an initial breach allowing water ingress. For example, a safety assessment may need to consider whether, following an initial breach, corrosion of the metals in the waste form may release hydrogen gas which then leads to pressurisation of the waste container. Corrosion of metals may be accompanied by volume changes that could impact upon the integrity of surrounding barriers (e.g. expansion causing stressing of containers). Corrosion products may take up radionuclides or other contaminants, by sorption or accommodation within crystal structures.
2000 List	3.1.03
References	[Ref. 66], [Ref. 75]

- ***FEP 2.1.2.2: Organics***

Description	The characteristics and properties of organic waste forms that may be disposed of in a repository.
Category	Feature
Relevance to Performance and Safety	The physical and chemical characteristics of organic waste forms control the release rates of radioactive and non-radioactive contaminants from the organic materials, and the physical and chemical forms in which they are released. Examples of these waste forms include paper, cotton, rubber, plastics and resins. Degradation products of organic

	waste forms may form mobile aqueous complexes with radionuclides. The physical and chemical characteristics and properties of the organic materials will also influence how the waste form interacts with any other waste forms (e.g. metals or non-metallic inorganic wastes) in the same waste container, and with the waste container itself and influence the overall chemical environment within the waste (e.g. pH and Eh). Depending upon the physical and chemical characteristics of the organic matter in the waste form, these latter interactions may help to accelerate the rate at which containers degrade. For example, a safety assessment may need to consider whether evolution of gas caused by degradation of organic wastes could potentially pressurise an unvented container and promote its failure.
2000 List	3.1.05
References	[Ref. 75], [Ref. 76]

- ***FEP 2.1.2.3: Non-metals, inorganics***

Description	The characteristics and properties of non-metallic, inorganic waste forms that may be disposed of in a repository.
Category	Feature
Relevance to Performance and Safety	The physical and chemical characteristics of non-metallic inorganic waste forms control the release rates of radioactive and non-radioactive contaminants from these waste forms, and the physical and chemical forms in which they are released. Examples of such waste forms include spent fuel (as UO_2 rather than as a metallic form), concrete and ash. The physical and chemical characteristics and properties of the non-metallic, inorganic materials will also influence how the waste form interacts with any other waste forms (e.g. organics) in the same waste container, and with the waste container itself. Depending upon the physical and chemical characteristics of the non-metallic inorganic waste forms, these latter interactions may influence the rate at which containers degrade. For example, cementitious waste forms may help to buffer conditions within an iron or steel container at high values, thereby minimising the rate of container corrosion.
2000 List	3.1.03
References	[Ref. 75], [Ref. 215]

- ***FEP 2.1.2.4: Immobilisation matrix***

Description	The characteristics and properties of the waste immobilisation matrix/matrices at the time of emplacement in the repository.
Category	Feature
Relevance to Performance and Safety	An immobilisation matrix minimises the rate of release of contaminants from a breached or vented waste package. Another purpose may be to minimise free space within a waste container, thereby helping to provide structural integrity (e.g. so that a waste container can withstand the weight of other containers stacked on top of it). The physical and chemical characteristics of the immobilisation matrix govern how contaminant release is limited. For example, a borosilicate glass matrix may immobilise radionuclides principally owing to being chemically stable and impermeable. In contrast, a cementitious matrix may immobilise contaminants because of its chemical reactivity, by buffering pH at alkaline values, under which conditions many contaminants are poorly soluble. The physical and chemical characteristics of the immobilisation matrix will also influence the form in which any radionuclides or other contaminants might be released from a waste form and subsequently transported from a waste container following

	container breach. For example, reactions between water, CO_2 and a cementitious matrix may prevent C-14 from being transported from encapsulated activated metals in the form of gaseous CO_2. The physical and chemical characteristics and properties of an immobilisation matrix will influence how it interacts with other waste form components (whether metallic, organic or non-metallic and inorganic) and with the waste container. Depending upon the physical and chemical characteristics of the immobilisation matrix, these latter interactions may influence the integrity of the containers. For example, the alkaline environment maintained by a cementitious matrix may decrease the corrosion rate of an iron or steel container. On the other hand, the possibility that a bituminous immobilisation matrix may expand due to radiolysis, thereby impacting upon the container, may need to be considered by a safety assessment.
2000 List	2.1.02
References	[Ref. 77], [Ref. 78], [Ref. 79]

○ FEP 2.2: Waste packaging characteristics and properties

Description	The physical, chemical and biological characteristics and properties of the waste packaging (i.e. the waste package excluding the waste form) at the time of emplacement in the repository.
Category	FEP Subgroup
2000 List	2.1.03
References	[Ref. 4], [Ref. 161], [Ref. 175], [Ref. 176], [Ref. 212]

▪ FEP 2.2.1: Container characteristics and properties

Description	The physical, chemical, and biological characteristics and properties of the containers at the time of emplacement in the repository.
Category	Feature
Relevance to Performance and Safety	The relevance of container characteristics and properties to repository performance and safety will depend upon the disposal concept being evaluated. Some concepts require a container to have a long-term containment function (e.g. in some disposal concepts for spent fuel), but other concepts do not need long-term containment (e.g. in many disposal concepts for low-level waste [LLW]). The characteristics and properties of a waste container will determine whether it completely prevents the migration of radionuclides and other contaminants from the waste form immediately after repository closure. If there is complete containment initially, the container's physical, chemical and biological characteristics and properties will determine whether containment is lost subsequently during the assessment period and if so, when this occurs. An assessment will need to assess the significance for safety and performance of mechanical and chemical interactions between different container components (e.g. internal structures such as iron inserts that are placed within copper canisters for spent fuel in some disposal concepts) and between the container, the waste form and barriers that surround the container. The chemical and biological characteristics and properties of the container will also affect the chemical environment of the waste form and surrounding barriers, which may in turn influence the release of radionuclides and other contaminants from the waste form and their subsequent mobility and/or retardation. The mechanical strength of a container may be relevant to repository performance and safety; for example if it is necessary to maintain the integrity of the containers as they are loaded by other containers being stacked on them.

2000 List	2.1.03
References	[Ref. 80], [Ref. 81]

- **FEP 2.2.2: Overpack characteristics and properties**

Description	The physical, chemical, and biological characteristics and properties of any overpack at the time of emplacement in the repository. An overpack is a container that is used to secure or shield one or more inner containers and in some disposal concepts is used for disposal (as well as transport and storage).
Category	Feature
Relevance to Performance and Safety	Overpack characteristics and properties are relevant to the performance and safety of repositories that contain waste packages with overpacks; not all repository concepts include such waste packages. The overpack, if present, protects an inner container and contributes to containment of radionuclides and other contaminants within a waste package. The physical, chemical and biological characteristics and properties of an overpack will determine its evolution during the post-closure period, whether its integrity is lost during this period, and if so when the integrity loss occurs. The characteristics and properties of the overpack also control how it interacts with the container inside it and with the barriers (whether engineered or natural) that surround the overpack. The overpack will contribute to the mechanical strength of the overall waste package. The chemical and biological characteristics and properties of the overpack will also determine its ability to buffer the chemical conditions of the environment within and around a waste package. For example, corrosion of an iron overpack may contribute to maintaining reducing conditions. This ability to buffer conditions may help to influence the mobility of radionuclides and other contaminants after any breach in the waste package. As they are released from a breached waste package, certain radionuclides and other contaminants may be retarded by sorption on, or co-precipitation with, alteration products of the overpack (e.g. iron oxides). A safety / performance assessment needs to consider the potential for an overpack to react with surrounding barriers in ways that influence the performance of these barriers. For example, iron released from an iron-containing overpack may react with smectite in a surrounding bentonite buffer, thereby influencing its swelling pressure.
2000 List	Not explicitly mentioned but covered by 2.1.03
References	[Ref. 80], [Ref. 81]

FEP 2.3: Waste package processes

Description	The events and processes occurring within the waste packages, or on the external surfaces of the waste packages, resulting in their evolution in the repository.
Category	FEP Subgroup
2000 List	2.1
References	[Ref. 4], [Ref. 19], [Ref. 175], [Ref. 176]

- **FEP 2.3.1: Thermal processes [waste package]**

Description	The internal thermal processes that affect the waste packages.

Category	Process
Comments	External thermal processes (i.e. from the repository and surrounding geosphere) are considered under separate FEPs 3.2.1 and 4.2.1.
Relevance to Performance and Safety	Heat production, consumption and transport within a waste package may influence the evolution of the waste package's physical, chemical and biological properties. Relevant thermal processes are the production of heat by radioactive decay, the production and consumption of heat by chemical reactions and the transport of heat by conduction and convection of any fluid present through any gaps within the waste package. Thermal processes will influence the temperature evolution of the waste package and the rates of chemical and biological processes within it. Heat generated within the waste package may also influence the physical, chemical and biological properties of the barriers that surround the waste package (whether natural or engineered). The effects of temperature and associated gradients could include the thermal expansion and consequent generation of stresses in the waste packages (that could cause cracks to form) and changes in fluid densities and viscosities, which in turn could affect the movement of fluids through the waste packages.
2000 List	2.1.11
References	[Ref. 82], [Ref. 83], [Ref. 84]

- ***FEP 2.3.1.1: Radiogenic heat production and transfer***

Description	The production and transfer of heat originating from radioactive decay in the waste packages. Heat generation from radiation attenuation is a function of the decay rate and the nature of the waste and its packaging.
Category	Process
Relevance to Performance and Safety	Radioactive materials are heated directly by the decaying radionuclides. Radiation that is emitted from these materials heats other substances (whether radioactive or non-radioactive) as it passes through them and is attenuated. Once generated within a material, the radiogenic heat will be transferred within the waste package by a combination of conduction and convection. The heating will affect the physical, chemical, and biological properties of the heated materials. The rates of chemical and biological processes will depend upon the temperatures attained. Physical properties of the waste form and packaging, such as volumes and mechanical strength will also be influenced by the temperature evolution. Should the integrity of a waste package fail, the rate at which radionuclides and other contaminants are released from the package, and the forms in which they are released, will depend on variations in these physical, chemical, and biological properties due to radiogenic heating. The heating of the waste package due to radiogenic heat production within it, could potentially influence the chemical, physical and biological characteristics and properties of the surrounding barriers, whether engineered or natural.
2000 List	2.1.11
References	[Ref. 83], [Ref. 84]

- ***FEP 2.3.1.2: Chemical heat production and transfer***

Description	The production and transfer of heat originating from chemical processes affecting the waste packages.

Category	Process
Relevance to Performance and Safety	Chemical reactions among materials within the waste package may generate or consume heat. Once generated heat will be transferred within the waste package by a combination of conduction and convection. Heating will affect the physical, chemical, and biological properties of the heated materials. The rates of chemical and biological processes will depend upon the temperatures attained. Physical properties of the waste form and packaging, such as volumes and mechanical strength will also be influenced by the temperature evolution. Should the integrity of a waste package fail, the rate at which radionuclides and other contaminants are released from the package, and the forms in which they are released, will depend on variations in these physical, chemical, and biological properties due to chemical heat production. The heating of the waste package due to chemical heat production within it, could potentially influence the chemical, physical and biological characteristics and properties of the surrounding barriers, whether engineered or natural.
2000 List	2.1.11
References	[Ref. 83], [Ref. 84]

- ***FEP 2.3.1.3: Biological heat production and transfer***

Description	The production and transfer of heat originating from biological processes affecting the waste packages.
Category	Process
Relevance to Performance and Safety	Biologically-mediate processes within the waste package may generate heat. Once generated heat will be transferred within the waste package by a combination of conduction and convection. Heating will affect the physical, chemical, and biological properties of the heated materials. The rates of chemical and biological processes will depend upon the temperatures attained. Physical properties of the waste form and packaging, such as volumes and mechanical strength will also be influenced by the temperature evolution. Should the integrity of a waste package fail, the rate at which radionuclides and other contaminants are released from the package, and the forms in which they are released, will depend on variations in these physical, chemical, and biological properties due to biological processes that produce heat. The heating of the waste package due to biological processes within it, could potentially influence the chemical, physical and biological characteristics and properties of the surrounding barriers, whether engineered or natural.
2000 List	2.1.11
References	[Ref. 83]

- **FEP 2.3.2: Hydraulic processes [waste package]**

Description	The hydraulic processes that affect the waste packages.
Category	Process
Relevance to Performance and Safety	The presence and movement of water within a waste package will influence the rates at which radionuclides and other contaminants are released from the waste form and transported from the waste package, should there be a lack of package integrity. The presence and movement of water will also influence the physical, chemical, and biological evolution of materials within the waste package, including any immobilisation matrix and the waste container. If water is present within a non-vented waste container,

	the evolution of container materials by hydraulic processes may result in loss of waste package integrity.
2000 List	2.1.08
References	[Ref. 78]

- ***FEP 2.3.2.1: Saturation/desaturation***

Description	The saturation or desaturation of the waste package.
Category	Process
Relevance to Performance and Safety	The saturation / desaturation of the waste package by water governs the availability of water within the waste package to dissolve and transport radionuclides and other contaminants. The presence and movement of water will also influence the physical, chemical, and biological evolution of materials within the waste package, including any immobilisation matrix and the waste container.
2000 List	2.1.08
References	[Ref. 78]

- ***FEP 2.3.2.2: Thermal effects***

Description	The impact of thermal effects on hydraulic processes influencing the waste package.
Category	Process
Comments	The evolution of the waste package's temperature over time (FEP 2.3.1) can influence the associated hydraulic conditions (for example temperatures in excess of boiling point will result in waste packages remaining unsaturated).
Relevance to Performance and Safety	Thermal effects will influence the form of water within a waste package (i.e. whether present as chemically bound water, free liquid water, or steam) and the possible movement of this water (e.g. through change of viscosity). Temperature gradients within the waste package will drive convection of a free water phase. Pressure gradients and consequent movement of free water could also be caused by temperature-related changes in the form of water (i.e. steam generation). These thermal effects can also influence the degree to which a waste package will saturate with free water sourced from outside the package, should the package lack integrity. Thermal effects may therefore influence the degree to which materials within the waste package are water-saturated, the ability of water to mobilise radionuclides and other contaminants, and the ability of water to participate in reactions with any other materials present, including any immobilisation matrix and the waste container.
2000 List	2.1.11
References	[Ref. 83], [Ref. 84]

- ***FEP 2.3.2.3: Mechanical effects***

Description	The impact of mechanical effects on hydraulic processes influencing the waste package.
Category	Process

Comments	The evolution of the waste package's mechanical condition over time (FEP 2.3.3) can influence the associated hydraulic conditions (for example material volume changes resulting in changes in hydraulic properties).
Relevance to Performance and Safety	Mechanical effects may influence the volume and connectivity of pore space within a waste package and the pressures to which free water within the pore space is subjected. Pressures will affect the distribution of water between bound (to solid phases) and free forms and the form of free water (whether liquid or steam). Pressure gradients could cause free water to move. These mechanical effects can also influence the degree to which a waste package will saturate with free water sourced from outside the package, should the package lack integrity. Mechanical effects may therefore influence the degree to which materials within the waste package are water-saturated, the ability of water to mobilise radionuclides and other contaminants, and the ability of water to participate in reactions with any other materials present, including any immobilisation matrix and the waste container.
2000 List	2.1.07
References	[Ref. 83]

- ***FEP 2.3.2.4: Chemical effects***

Description	The impact of chemical effects on hydraulic processes influencing the waste package.
Category	Process
Comments	The evolution of the waste package's chemistry over time (FEP 2.3.4) can influence the associated hydraulic conditions (for example alteration of waste packages will result in changes in hydraulic properties).
Relevance to Performance and Safety	Chemical effects will influence the volume and connectivity of pore space within a waste package and the evolution and consumption of free water within the waste package. These chemical processes could influence pressure gradients and hence affect the movement of free water. Chemical effects can also influence the degree to which a waste package will saturate with free water sourced from outside the package, should the package lack integrity. Chemical effects may therefore influence the degree to which materials within the waste package are water-saturated, the ability of water to mobilise radionuclides and other contaminants, and the ability of water to participate in reactions with any other materials present, including any immobilisation matrix and the waste container.
2000 List	2.1.09
References	[Ref. 4], [Ref. 78]

- ***FEP 2.3.2.5: Gas effects***

Description	The impact of repository-generated gas effects on hydraulic processes influencing the waste package.
Category	Process
Comments	The generation, consumption and migration of gases in the waste packages due to chemical (FEP 2.3.4), biological (FEP 2.3.5) and radiological (FEP 2.3.6) processes can affect the associated hydraulic conditions (for example the generation of gas can slow the saturation of waste packages).

Relevance to Performance and Safety	The generation, consumption, and migration of gases in the waste packages, due to a combination of chemical, biological, and radiological processes, can influence pressure gradients in the waste package. Pressures attained will affect the distribution of water between bound (to solid phases) and free forms and the form of free water (whether liquid or steam). Hence, gas effects can impact upon the generation and movement of free water. These gas effects can also influence the degree to which a waste package will saturate with free water sourced from outside the package, should the package lack integrity. Depending upon the gas pressures attained, gas effects may therefore influence the degree to which materials within the waste package are water-saturated, the ability of water to mobilise radionuclides and other contaminants, and the ability of water to participate in reactions with any other materials present, including any immobilisation matrix and the waste container.
2000 List	2.1.12
References	[Ref. 85], [Ref. 86], [Ref. 216]

- **FEP 2.3.3: Mechanical processes [waste package]**

Description	The internal and external mechanical processes that affect the waste packages. This includes mechanical loads imposed on the waste package by adjacent waste packages, other repository components and the surrounding geosphere.
Category	Event, Process
Comments	Mechanical processes (this FEP, 2.3.3) concerns the effects of mechanical loads other than those due to Thermal processes (e.g. expansion, FEP 2.3.1).
Relevance to Performance and Safety	Thermal, hydraulic and mechanical loads imposed on the waste package, whether generated internally or imposed by external processes, may cause deformation of a waste package and/or waste form. If these loads are of sufficient magnitude and applied for sufficiently long times, then the integrity of the package could be affected. A package that initially contains openings (e.g. a vented container) may have larger openings produced within it. A package that initially offers complete containment may lose its integrity. If the loads affect a package that lacks integrity, then they could promote the migration of radionuclides and other contaminants from the package, by reducing the volume of any voids present within the package and producing a pressure gradient. Mechanical processes operating within and upon a waste package may also influence the performance of engineered and natural barriers that surround the package. For example, a reduction in the volume of a package, due to mechanical processes within it, could potentially lead to cracking or displacement of any surrounding backfill that might be present. Mechanical processes may operate over time periods that are very short compared to the assessment period (e.g. loading caused by seismic shearing) or over time periods that are very long compared with the assessment period (e.g. loading by creep of the surrounding geosphere).
2000 List	2.1.07, 2.1.12
References	[Ref. 4]

- ***FEP 2.3.3.1: Deformation***

Description	The deformation of the waste package due to large loads and pressures imposed on it from both internal and external sources.
Category	Event, Process

Relevance to Performance and Safety	Deformation of a waste package, whether generated by internal or external processes, if of sufficient magnitude, could affect the integrity of the package. A package that initially contains openings (e.g. a vented container) may have larger openings produced within it. A package that initially offers complete containment may lose its integrity. If the deformation affects a package that does not offer containment, then it could produce fracture pathways for the migration of radionuclides and other contaminants from the package. Deformation may also lead to the decreases in the volume of any voids present and the development of pressure gradients. These processes could promote the migration of radionuclides and other contaminants from the waste package. Deformation of a waste package may also influence the performance of engineered and natural barriers that surround the package. For example, a volume reduction of the package could potentially allow cracking of any surrounding cementitious backfill that might be present. Deformation may occur over time periods that are very short compared to the assessment period (e.g. shearing due to fracture movement during a seismic event) or over longer time periods (e.g. loading by creep of the surrounding geosphere).
2000 List	2.1.07, 2.1.12
References	[Ref. 87], [Ref. 95]

- ***FEP 2.3.3.2: Material volume changes [waste package]***

Description	The effects of volume changes in materials used in the waste package.
Category	Event, Process
Comments	Material volume changes (this FEP, 2.3.3.2) covers the actual volume change, rather than its cause. Thermal processes (FEP 2.3.1), Hydraulic processes (FEP 2.3.2) and Chemical processes (FEP 2.3.4) may all cause changes in material volume.
Relevance to Performance and Safety	Material volume changes within a waste package, if of sufficient magnitude, could affect the integrity of the package. Existing openings in a vented container may be enlarged, or new openings may form. A package that initially offers complete containment may lose its integrity. If the material volume changes occur within a package that does not offer complete containment, then the potential for radionuclides and other contaminants to migrate from the package could be affected. Material volume reduction within a package could produce pathways for such migration, such as fractures or inter-connected matrix pores. Material volume increase may lead to such pathways sealing, which may tend to diminish the potential for such migration. However, at the same time pressures within the package may be increased, thereby tending to enhance the potential for migration. Material volume changes within a waste package may also influence the performance of engineered and natural barriers that surround the package. For example, an increase in the volume of a package due to corrosion could lead to cracking of any surrounding cementitious backfill that might be present. Material volume changes may occur over time periods that are very short compared to the assessment period (e.g. due to microbially-mediated gas generation within certain organic LLW or over time periods that are very long compared with the assessment period (e.g. corrosion of copper canisters for spent fuel).
2000 List	2.1.07
References	[Ref. 88]

- ***FEP 2.3.3.3: Movement***

Description	The movement of the waste package in the repository. Included are movements from mechanical stresses on the waste package caused by, for example, package deformation

	or mass redistribution in the repository. Also included are movements resulting from seismic events.
Category	Event, Process
Relevance to Performance and Safety	Movement of waste packages could affect the performance and safety of a repository by changing the spatial dispositions of the packages (and hence the wastes), any surrounding engineered barriers, the natural barriers and residual voidage. Potentially a redistribution of waste packages, barriers and voidage could influence the rates at which radionuclides and other contaminants are released from the repository. For example, were a package to move within a surrounding backfill, the thickness of backfill between the package and the rock could be changed; where the thickness is decreased, the backfill would offer less resistance to the migration of radionuclides and other contaminants. Any spatial redistribution of voidage would affect the volume and connectivity of pathways through which groundwater could enter the repository and through which gas, radionuclides and other contaminants could leave the repository. Potentially the movement of waste packages could be short-term (e.g. movement caused by a seismic event) or long-term (e.g. movement caused by rock creep).
2000 List	2.1.07
References	[Ref. 66], [Ref. 89]

- ***FEP 2.3.3.4: Stress corrosion cracking***

Description	The conjoint action of stress and a corrosive environment which leads to the formation of a crack in the waste packaging that would not have developed by the action of the stress or environment alone.
Category	Process
Relevance to Performance and Safety	Stress corrosion cracking may mechanically weaken metal components within a waste package. This process may result in failure of the waste package component and, potentially, could produce one or more pathways via which water could enter the waste package and/or radionuclides or other contaminants could leave the package.
2000 List	2.1.07
References	[Ref. 90], [Ref. 91]

- ***FEP 2.3.3.5: Gas explosion [waste package]***

Description	An explosion resulting from the ignition of a flammable gas mixture in the waste package. Included are explosions resulting from gases produced from the corrosion and degradation of waste packages.
Category	Event
Relevance to Performance and Safety	An explosion involving a gas mixture within a waste package could potentially damage the package, possibly resulting in a loss of containment (where the package is initially sealed) or decreasing the ability of a package to retard movement of radionuclides or other contaminants (where the package initially does not provide complete containment (e.g. because it is vented), or where package integrity has already been lost). The explosion could also alter the characteristics of the waste form, thereby influencing its ability to release radionuclides or other contaminants (e.g. by fragmenting the waste form thereby increasing the surface area from which radionuclides could be released). An explosion may also provide a short-term force that drives radionuclides and other

	contaminants from the package. An explosion within a waste package could impact upon the functioning of surrounding engineered and / or natural barriers. For example, cementitious barriers may be fractured by the force of such an explosion.
2000 List	2.1.12
References	[Ref. 66]

- **FEP 2.3.4: Chemical processes [waste package]**

Description	The chemical/geochemical processes that affect the waste packages. Included are the effects of chemical/geochemical influences on the waste package by adjacent waste packages, other repository components and the surrounding geosphere.
Category	Event, Process
Relevance to Performance and Safety	Chemical processes acting within and / or upon a waste package may alter the chemical and/or physical forms of the waste package components. There may be consequent influences on the integrity of the waste package and the potential for radionuclides or other contaminants to be released from it. Chemical processes may cause a package that offers containment initially to lose its integrity. Alternatively, where a package does not offer complete containment initially (e.g. because the package is vented), the ability of the package to resist migration of radionuclides or other contaminants may be affected. Where a waste package does not provide containment, the forms in which radionuclides and other contaminants are released and migrate from it will be influenced by chemical processes within the waste package. In such a case, the ability of the waste package components to retard the migration of radionuclides and other contaminants (e.g. by sorption) will also be affected by chemical processes. Chemical processes within the waste package may be coupled to chemical processes outside the waste package, where the package lacks integrity. Chemical processes at the outer surface of a waste package will be coupled to chemical processes in the surrounding natural and / or engineered barriers. These couplings may cause the chemical processes that affect the waste package to also influence the functions of the surrounding barriers.
2000 List	2.1.09, 2.1.12
References	[Ref. 92], [Ref. 217], [Ref. 218]

- ***FEP 2.3.4.1: Evolution of pH conditions [waste package]***

Description	The temporal evolution of the waste package's pH from its initial state. Included is the pH evolution of the water within the waste package due to water exchange between the waste package and its surroundings (assuming that such exchange can occur), mixing between water from different sources, and solid-water, gas-water and non-aqueous liquid-water reactions. The evolution of pH (generation or consumption of H^+) is a characteristic of many chemical processes that may occur within a waste package or at the outer surface of the waste package. The rates of many chemical processes are dependent upon pH. Additionally, microbial processes may influence (and be influenced by) pH. The overall evolution of pH will reflect the couplings between these processes and may be heterogeneous within the waste package.
Category	Event, Process
Relevance to Performance and Safety	The evolution of pH will influence/reflect the evolution pathways and evolution rates of waste package components. Consequently, the integrity of the waste package and the potential for radionuclides or other contaminants to be released from it may be affected. pH-dependent processes may cause a package that initially offers containment to lose its

	integrity. Alternatively, where a package does not offer full containment initially (e.g. because the package is vented), the ability of the package to resist migration of radionuclides or other contaminants may be affected. Where a waste package does not provide containment, the forms in which radionuclides and other contaminants are released and migrate from it will be influenced by pH within the waste package. In such a case, the ability of the waste package components to retard the migration of radionuclides and other contaminants (e.g. by sorption) may also be affected by pH. pH within the waste package may be coupled to chemical processes outside the waste package, where the package lacks integrity. pH at the outer surface of a waste package will be coupled to chemical processes in the surrounding natural and / or engineered barriers. These couplings may cause the pH at the outer surface of the waste package and possibly within the waste package (if the waste package lacks integrity) to also influence the chemical evolution of the surrounding barriers.
2000 List	2.1.09
References	[Ref. 89], [Ref. 93], [Ref. 219]

- ***FEP 2.3.4.2: Evolution of redox conditions [waste package]***

Description	The temporal evolution of the waste package's redox state (as represented by parameters such as redox potential relative to the standard hydrogen electrode, Eh) from its initial state. This evolution depends on a number of factors, including the Eh conditions of the surrounding water and the consumption rate of any available oxygen. Oxygen-deficient (anaerobic) conditions promote the formation of lower, and often less soluble, oxidation states of elements, promote relatively slow corrosion and microbial processes, and minimise the rate of gas generation.
Category	Event, Process
Relevance to Performance and Safety	The evolution of redox conditions (as represented by a redox potential relative to the standard hydrogen electrode, Eh) may be affected by many chemical processes within a waste package, or at its outer surface, that involve chemical species in differing oxidation states (e.g. oxidation of metals, reduction of Fe-oxides). The overall evolution of Eh will reflect the couplings between these processes and will probably be heterogeneous within the waste package. The evolution of redox conditions will influence/reflect the evolution pathways and evolution rates of waste package components. Consequently, the integrity of the waste package and the potential for radionuclides or other contaminants to be released from it may be affected. Redox-dependent processes may cause a package that initially offers containment to lose its integrity (e.g. corrosion of steel canisters). Alternatively, where a package does not offer full containment initially (e.g. because the package is vented), the ability of the package to resist migration of radionuclides or other contaminants may be affected. Where a waste package does not provide containment, the oxidation state in which radionuclides and other contaminants are released and migrate from it will be influenced by Eh within the waste package. In such a case, the ability of the waste package components to retard the migration of radionuclides and other contaminants may be affected (e.g. radionuclides in different oxidation states may sorb to different extents). Redox conditions within the waste package may be coupled to chemical processes outside the waste package, where the package lacks integrity. Redox conditions at the outer surface of a waste package will be coupled to chemical processes in the surrounding natural and / or engineered barriers. These couplings may cause the redox conditions at the outer surface of the waste package and possibly within the waste package (if the waste package lacks integrity) to also influence the chemical evolution of the surrounding barriers.

2000 List	2.1.09
References	[Ref. 89], [Ref. 217]

- ***FEP 2.3.4.3: Migration of chemical species [waste package]***

Description	The migration of reactants into and reaction products from the waste package.
Category	Event, Process
Relevance to Performance and Safety	Migration of chemical species to/from the outer surface of a waste package, within a waste package, and to/from its interior (where the package lacks integrity) will influence the pathways by which a package's components evolve and the rates at which they do so. The presence of certain species, such as chloride, sulphide and sulphate, can promote the corrosion of metals (e.g. high chloride concentrations for steel) and the degradation of cement (high sulphate concentrations). Where a package offers containment initially, the nature of chemical species that migrate to / from the package's outer surface and the rates at which they do so may determine whether the package loses its containment function within the assessment time frame and if so, when this containment loss occurs. Where a package does not offer containment, the natures of chemical species that migrate into the waste package, and the rates at which they do so, will influence the rates at which radionuclides and other contaminants are released and the chemical forms in which this release occurs. Chemical species that may migrate from such a waste package include chemical species of radionuclides and other contaminants.
2000 List	2.1.09
References	[Ref. 89], [Ref. 216], [Ref. 217]

- ***FEP 2.3.4.4: Corrosion [waste package]***

Description	The degradation of the metallic component(s) of the waste package by interaction with its environment, specifically, by reactions involving water in liquid or vapour form and / or gases (e.g. oxygen in the air), and/or by reaction with solutes within the water. Corrosion of the waste package can occur by a number of processes such as generalised (or uniform), localised and galvanic corrosion. Metals are subject to uniform corrosion at rates that are dependent on the chemical and physical (and possibly biological) environment, while localised formation of cavities in a metal surface is caused by non-uniform corrosion. Galvanic corrosion occurs when two different metals are in electric contact. Metal corrosion will result in the generation of hydrogen gas under anaerobic conditions.
Category	Event, Process
Relevance to Performance and Safety	Corrosion of the metal components of a waste package may influence: their mechanical properties; any capability to contain radionuclides or other contaminants; any capability to retard migration of radionuclides or other contaminants. Any corrosion of metallic waste forms will influence the release of radionuclides and other contaminants from these waste forms. Where a waste package offers containment initially, corrosion may lead to containment being lost. Where a waste package does not offer full containment initially (e.g. because it is vented), corrosion could decrease the resistance offered by the package to the migration of radionuclides or other contaminants. The ability of corroded metal components to retard the migration of radionuclides or other contaminants will depend upon the corrosion products (e.g. aerobic corrosion of steel may produce Fe-oxides onto which radionuclides can sorb). Corrosion may produce gas (e.g. hydrogen produced by anaerobic steel corrosion) or consume gas (e.g. oxygen consumption by aerobic steel corrosion). These processes may influence the redox conditions within and

	around the waste package (which may in turn impact release rates of radionuclides and other contaminants and the forms in which they are released). Gas production or consumption may also influence the pressures within and around the waste package.
2000 List	2.1.09
References	[Ref. 90], [Ref. 91], [Ref. 94]

- ***FEP 2.3.4.5: Alteration [waste package]***

Description	The alteration of the waste package by chemical processes such as dissolution, leaching, chloride and sulphate attack, carbonation and polymer degradation.
Category	Event, Process
Relevance to Performance and Safety	"Alteration" is a change in the chemical or physical form(s) of one or more solid materials within a waste package. Many alteration processes will impact upon the functions of waste package components, such as their ability to provide containment (e.g. corrosion of a steel waste container) their ability to provide mechanical support (e.g. corrosion of iron inserts in copper containers for spent fuel) or their ability to provide chemical buffering (e.g. carbonation of a cementitious encapsulant). Waste form alteration (e.g. degradation of organic waste forms) may be accompanied by the release of radionuclides and other contaminants. Alteration of solid materials may involve the consumption or production of gases (including water vapour), liquid water or organic liquids. These processes could impact upon the mobilisation of radionuclides and other contaminants because the evolved or consumed phase may be able to transport these contaminants and / or because these processes will tend to cause pressure gradients. Alteration processes may also cause the volumes of waste package components to change. There could be consequent pressure changes, which may impact upon the migration of radionuclides and other contaminants. A net change in the volume of a waste package may result from alteration processes, potentially impacting upon the surrounding engineered and / or natural barriers. For example, expansive corrosion might result in cracking of a surrounding cementitious backfill. Leaching can result in the reduction of pH in concrete in the long-term. Chloride attack can increase concrete porosity by increasing the leaching of portlandite and reduce concrete strength. Sulphate attack depletes the reservoir of alkalinity (calcium hydroxide) in the concrete and can also result in a reduction in concrete strength. Whilst carbonation reduces the ability of concrete to impose high pH conditions on water by reacting with calcium hydroxide, it heals cracks, sealing them to ingress by water through the production of calcium carbonate, which has low solubility. Thus, carbonation can counter the effects of leaching and chloride/sulphate attack. Polymer degradation can lead to the generation of gases (e.g. carbon dioxide and methane) and the loss of the integrity of polymeric packaging material. Volatile compounds can be formed with the rate being controlled by changes in pressure, temperature and concentration of volatiles in the waste package.
2000 List	2.1.09
References	[Ref. 89], [Ref. 217]

- ***FEP 2.3.4.6: Precipitation [waste package]***

Description	The precipitation of an element from the aqueous phase to the solid phase in the waste package, which depends on chemical conditions in the waste package (particularly pH, Eh and the concentration of complexing ions).

Category	Event, Process
Relevance to Performance and Safety	Precipitation of radionuclides or other contaminants within solid phases that might form within the waste package will prevent the precipitated radionuclides or other contaminants from being later transported from the waste package by a mobile fluid phase (water, gas, or organic liquid) should conditions change. The aqueous concentration of a radionuclide or other contaminant at the time of precipitation could be an upper limit under the specific conditions prevailing; the radionuclide or other contaminant would be 'solubility limited'. Precipitation of solid phases may also impact upon the barrier function of materials within the waste package. For example, the performance of a cement encapsulant, if one is present within the waste package, may be affected by precipitation of calcium carbonate. In such a case, the calcium carbonate may occlude porosity within the cement, affecting its mass transport properties and potentially influencing the ability of the cement to buffer the pH of water present.
2000 List	2.1.09
References	[Ref. 96]

- ***FEP 2.3.4.7: Complexation [waste package]***

Description	The formation in the waste package of a molecular entity by loose association involving two or more component molecular entities (ionic or uncharged), or the corresponding chemical species. Complexation is promoted through the presence of complexing agents (organics, inorganic ligands and microbes). Sources of these agents include organics in the waste package and inflowing water.
Category	Process
Relevance to Performance and Safety	The formation of complexes between radionuclides or other contaminants and ligands such as Cl^- or HCO_3^- will influence the partitioning of the radionuclides or other contaminants between immobile solid phases and any coexisting potentially mobile fluid phase. Generally, the aqueous solubilities of radionuclides or other contaminants will be increased if the aqueous phase contains ligands with which these components form aqueous complexes, compared to the solubilities in the absence of ligands. More generally, the formation of chemical complexes has the potential to influence the chemical conditions (e.g. pH, Eh) in the waste package.
2000 List	3.2.05
References	[Ref. 96], [Ref. 97]

- ***FEP 2.3.4.8: Colloid formation [waste package]***

Description	The formation of very fine particles (with at least one dimension in the 1 µm to 1 nm range) that can affect the migration of contaminants in the repository. Particles of clay minerals, silica, iron oxy-hydroxides, other minerals, organic and bio-organic macromolecules, and contaminants themselves (e.g. Pu(IV)) may form the colloid phase. Sources can include materials in the waste package itself (e.g. cementitious materials, organic wastes), other repository components (e.g. bentonite and cementitious materials) and inflowing groundwater. Colloid formation may be promoted by steep chemical gradients, such as at an interface where the Eh or pH changes abruptly because of chemical or biological activity. The thermodynamic stability of colloids depends upon factors such as the chemistry and surface charge of the colloid and the chemistry of the dispersion medium. Colloid stability generally decreases as ionic strength (salinity) increases.

Category	Process
Relevance to Performance and Safety	Many radionuclides and other contaminants are able to form complexes with colloidal particles and thereafter be transported with the particles. If the colloids are mobile and the radionuclide/contaminant-colloid complexes are strong, then once the waste package is breached, radionuclide/contaminant release from the waste package may be enhanced compared to a case where colloids do not form. On the other hand, under certain circumstances colloids may be less mobile than free complexes in the mobile phase (e.g. aqueous complexes of a radionuclide and bicarbonate). For example, colloids would tend to be even less mobile through compacted bentonite than aqueous complexes which could diffuse.
2000 List	3.2.04
References	[Ref. 98], [Ref. 99], [Ref. 220]

- **FEP 2.3.5: Biological processes [waste package]**

Description	The biological/biochemical processes that affect the waste packages.
Category	Event, Process
Relevance to Performance and Safety	Potentially, biological/biochemical processes could impact upon all aspects of a waste package's chemical evolution and consequently the physical characteristics of waste package components (since chemical and physical processes are coupled). Formation of biofilms could also affect the mass transport properties of materials composing a waste package. Biological / biochemical processes may therefore influence the release rates of radionuclides or other contaminants from the waste form. The chemical and physical forms in which such releases occur may be affected by the biological/biochemical processes. Biological / biochemical processes may also influence the nature of the phases that are present within the waste package at any time. For example, the rates of gas generation, and the gas composition, could be controlled by biological processes. Thus, the pressure evolution, and the pressures attained within the waste package, could also be influenced by biological / biochemical processes. This pressure evolution potentially may influence the integrity of the waste package. If the waste package does not offer full containment (either because it is vented or because it has been breached), the pressure evolution could affect the transport of radionuclides and other contaminants from the waste package. These biological / biochemical processes may affect the characteristics of engineered components, and potentially their performance. For example, microbes may influence corrosion of metals ('microbially-influenced corrosion').
2000 List	2.1.10, 2.1.12
References	[Ref. 100], [Ref. 221]

- ***FEP 2.3.5.1: Microbial growth and decline [waste package]***

Description	The processes affecting the growth and decline of microbes in the waste package. Microbes can be present in waste packages, especially those containing organic waste. Their growth requires the presence of suitable nutrients, such as cellulosic wastes, simple organic molecules containing oxygen, nitrogen and/or sulphur, and small amounts of putrescible materials. The loss of such nutrients can result in the decline of microbial populations, as can microbial poisoning. Microbial processes may decline as a result of high temperature, as a result of pH changing to a value at which the microbial

	population ceases to function, and due to the presence of high concentration of heavy metals or other contaminants.
Category	Event, Process
Relevance to Performance and Safety	The growth and decline of microbial populations within a waste package, or on its outer surface, will determine the potential for biological/biochemical processes to impact a waste package's chemical evolution and consequently the physical characteristics of waste package components (since chemical and physical processes are coupled). Formation or decay of biofilms could also affect the mass transport properties of waste package materials. Different kinds of microbe within a population may grow or decline at different rates as conditions (e.g. temperature) evolve within a waste package. The make-up of the microbial population, and hence its influence on the evolution of the waste package, may therefore also change temporally. The growth and decline of microbial populations may influence the release rates of radionuclides or other contaminants from the waste form. This growth and decline may also impact the chemical and physical forms of any such releases. The abundance and compositions of different phases that are present within the waste package at any time may be affected by whether microbial populations are growing or declining. For example, the rates of gas generation, and the gas composition, could be controlled by the proportions of different microbes in a population. These proportions will depend in turn on how the growth and decline of each kind of microbe present is affected by the evolving environment. Thus, the pressure evolution, and the pressure values attained within the waste package, could also be influenced by microbial growth and decline. This pressure evolution potentially may influence the integrity of the waste package. If the waste package does not offer full containment (either because it is vented or because it has been breached), the pressure evolution could affect the transport of radionuclides and other contaminants from the waste package. The growth and decline of microbial populations may affect the characteristics of engineered components, and potentially their performance. For example, microbes may influence corrosion of metals ('microbially-influenced corrosion').
2000 List	2.1.10, 2.1.12
References	[Ref. 101], [Ref. 221]

- ***FEP 2.3.5.2: Microbially/biologically mediated processes [waste package]***

Description	The biological processes affecting the waste package such as degradation of organics, nitrate ions and sulphate ions, biofilm growth and volatilisation.
Category	Event, Process
Relevance to Performance and Safety	Microbially/biologically mediated processes may affect the release of radionuclides and other contaminants from the waste and the potential mobility of these contaminants within the waste package. Microbially/biologically mediated processes may also impact upon the safety functions of waste package components. For example, microbial processes can lead to the formation of acidic and oxidising species that can participate in corrosion of the metals and generation of reducing conditions. Such microbially influenced corrosion may affect the ability of a steel container to contain the waste and / or its ability to resist mechanical deformation. Microbially/biologically mediated processes may generate or consume fluids (gas, non-aqueous phase liquids [NAPLs] and water) and may change the specific volume of solid materials. These processes may thus change the pressures within a waste package and thereby the forces that could drive radionuclides or other contaminants from the waste package, should it be vented or become breached. Pressure changes may also lead to mechanical deformation, and potentially affect the integrity of, waste package components. Biofilms may form on or around the waste package and may act to concentrate radionuclides or other

	contaminants. Biofilms may also decrease the permeability of materials within the waste package.
2000 List	3.1.04, 3.2.06
References	[Ref. 101], [Ref. 221]

- **FEP 2.3.6: Radiological processes [waste package]**

Description	The effects of radiation emitted from the waste forms in the waste packages, and the overall radiogenic evolution of the waste packages.
Category	Event, Process
Relevance to Performance and Safety	Radiation emitted from the wastes in the waste packages may influence the chemical and physical properties of the materials composing the waste package. The changes in these properties because of radiation could influence the rates at which radionuclides and other contaminants are released from the waste and the chemical and physical forms in which these releases occur. Radiological processes may also influence the barrier function of waste package components. For example, radiolysis of water may generate oxidising conditions that cause enhanced rates of steel container corrosion.
2000 List	2.1.13
References	[Ref. 4]

- ***FEP 2.3.6.1: Radioactive decay and ingrowth [waste package]***

Description	The spontaneous disintegration or de-excitation of an atomic nucleus, resulting in the emission of sub-atomic particles and energy and the formation of a new progeny (or “daughter”) nucleus in the waste package.
Category	Process
Relevance to Performance and Safety	Radionuclide decay and ingrowth will affect: 1. the radioactivity at any location within the waste package; 2. the rates at which radionuclides and other contaminants are released from solid matrices in the waste package; and 3. the chemical and physical forms in which the releases occur. In the long-term, radioactive decay reduces the total activity of the radionuclides in the waste package, but at the same time changes the proportions of radionuclides present, until and unless secular or transient equilibrium is achieved between parent and daughter radionuclides. Where a precursor radionuclide decays to a progeny radionuclide, this causes the ingrowth of progeny in the waste package. The chemical and physical properties of a daughter nuclide may differ from its parent. A daughter isotope may have a different mobility to its parent (e.g. Ra-226 is more soluble in water than its parent, Th-230). Radiation damage to a solid material in which a daughter isotope is formed may make the daughter more likely to be released from the solid than its parent. Recoil (movement of a relatively high-energy daughter isotope) may enhance release of the daughter isotope. In post-closure assessment, radioactive decay chains are often simplified, e.g. by assuming that the shorter-lived radionuclides decay instantaneously in release and migration calculations but adding any dose-contribution to longer-lived parent radionuclides.
2000 List	3.1.01
References	[Ref. 4], [Ref. 222]

- ***FEP 2.3.6.2: Radiolysis [waste package]***

Description	The dissociation of molecules by ionizing radiation in the waste package. The radiolysis of water within a waste package can produce molecular species such as hydrogen, oxygen, and hydrogen peroxide. The actual composition and amount of the radiolysis products that will be formed is controlled by the radiation dose rate and by the composition and amount of the air and water mixture contained in the waste package.
Category	Process
Relevance to Performance and Safety	Radiolysis is the dissociation of molecules by ionizing radiation in the waste package. Therefore, radiolysis may affect the rates at which radionuclides and other contaminants are released from solid matrices in the waste package, and the chemical and physical forms in which the releases occur. Radiolysis may impact the quantities and compositions of different fluids (water, gas, organic liquids) present within a waste package. For example, radiolysis of water will generate O_2 and H_2, while decreasing the quantity of water present. These effects may influence the evolution of pressure within a waste package. Radiolysis may directly affect the physical properties of solid materials present in the waste package. For example, if present, a bitumen encapsulant might degrade owing to radiolysis. The impact of radiolysis on chemical conditions may also indirectly affect the physical properties of the solid materials present. An example is the generation of O_2 by radiolysis of water causing enhanced corrosion of a steel container.
2000 List	2.1.13
References	[Ref. 102]

- ***FEP 2.3.6.3: Helium production***

Description	The production of helium gas from alpha decay of radionuclides in the waste package.
Category	Process
Relevance to Performance and Safety	Helium production from alpha-decay of radionuclides in the waste package may influence the release rate of radionuclides from certain kinds of waste. The produced helium will accumulate at defects in the structures of the waste materials and contribute to structural modification of the waste form. For example, within spent fuel, helium produced by alpha-decay may form bubbles and contribute to the physical expansion of the fuel. Helium generation will also result in an increase in gas pressurisation. Release of radionuclides will be influenced by the changes in the physical characteristics of the waste form and the pressure evolution.
2000 List	3.1.06
References	[Ref. 103], [Ref. 104]

- ***FEP 2.3.6.4: Radon production [waste package]***

Description	The production of radon gas from the decay of uranium, thorium and radium in the waste package. The main radon isotope considered in assessments is Rn-222 (the longest-lived isotope at 3.82 days).
Category	Process

Relevance to Performance and Safety	Radon is a radioactive noble gas, which hence is relatively mobile. All except 5 of the 17 isotopes of radon are alpha-emitters. These alpha-emitters include the longest-lived isotope, Rn-222 (half-life 3.82 days). Radon is produced by the decay of uranium, thorium and radium in the waste package and would contribute directly to radiological risk if there is an exposure pathway between the waste and a receptor. However, the very short half-life means that in practice the exposure pathway would need to be very short and / or transport of radon along the pathway would need to be very rapid.
2000 List	3.1.06
References	[Ref. 105]

- ***FEP 2.3.6.5: Radiation damage [waste package]***

Description	The damage caused to the waste package by radiation.
Category	Process
Relevance to Performance and Safety	'Radiation damage' refers to changes in the structure of a material due to the action of particles produced by either fission, or radioactive decay, or by recoil of atoms within the structure that undergo decay. The most important structural changes occur due to the loss of energy by particles produced by decay or fission during elastic collisions with atoms in the material, and by recoil of atoms produced by decay. Electronic excitation of atoms by beta particles and alpha particles, and formation of new elements by radioactive decay (transmutation) may also cause radiation damage. This damage can change the macro-physical properties of the material (e.g. embrittlement). The damage can also influence the mass transport properties of the materials. The rate at which radionuclides are released from a waste form will depend partly upon the degree of radiation damage to the waste form.
2000 List	2.1.13
References	[Ref. 106]

- ***FEP 2.3.6.6: Criticality [waste package]***

Description	The possibility and effects of spontaneous nuclear fission chain reactions within the waste package. Criticality requires a sufficient concentration and localised mass (critical mass) of fissile isotopes (e.g. U-235, Pu-239) and is more likely to occur in the presence of neutron moderating materials, such as water, in a suitable geometry; a chain reaction is less likely to occur in the presence of neutron absorbing isotopes (e.g. Pu-240).
Category	Event, Process
Relevance to Performance and Safety	Spontaneous nuclear fission chain reactions within the waste package would produce a wide range of fission products, and ultimately their daughter isotopes, which would need to be taken into account in any assessment of post-closure criticality scenarios. Criticality would generate power and in an increase in temperature. Such power and temperature excursions may affect the chemical and physical properties of the waste form, any other materials in the waste package, such as encapsulant, and the container itself. These changes may impact the rate at which radionuclides and other contaminants might be released from the waste package, which may be damaged by the criticality event. However, criticality will continue until negative feedback mechanisms, such as a decrease in moderator density associated with heating or depletion of the fissile material, cause it to shut down.

2000 List	2.1.14
References	[Ref. 107], [Ref. 223]

FEP 2.4: Contaminant release [waste form]

Description	The processes that directly affect the release of contaminants from the waste forms once the waste package has been emplaced in the repository.
Category	FEP Subgroup
2000 List	3.2
References	[Ref. 6], [Ref. 161], [Ref. 175], [Ref. 176]

FEP 2.4.1: Liquid-mediated release

Description	The processes resulting in the release of contaminants in a liquid phase from the waste form. Included is the release of contaminants in the aqueous phase from liquid waste forms and release of contaminants in non-aqueous phase liquids.
Category	Process
Relevance to Performance and Safety	Liquid in contact with the waste form may release radionuclides or other contaminants from the waste form, by dissolving the waste form or causing the contaminants to desorb from the waste form's solid surfaces. Some waste forms may undergo reactions that evolve a liquid phase, into which radionuclides or other contaminants may partition. Radionuclides and other contaminants that are released in/by a liquid phase will have the potential to be transported from the waste package with the liquid, should the waste package be vented or breach later in the post-closure period. The rate of liquid-mediated release depends upon the degree to which the liquid is unsaturated with respect to the radionuclide or other contaminant (a function of temperature, pressure and liquid composition) and the rate at which the liquid moves to / from the surface of the waste form. The nature of the liquid phase will also influence the partitioning of radionuclides and other contaminants between the liquid phase in which release occurs, other liquid or gaseous phases that might be present, and solid phases.
2000 List	3.2.07
References	[Ref. 6]

FEP 2.4.1.1: Dissolution [waste form]

Description	The dissolving of contaminants from the waste form into a solution on contact with water. For some waste forms (e.g. glass), this process can be very slow and result in the slow congruent release of contaminants contained within the waste form. For others, such as those with surface contamination or those that are readily soluble on contact with water, this process can be very rapid and result in the instantaneous release of contaminants contained within the waste form.
Category	Process
Relevance to Performance and Safety	Dissolution of a solid waste form by a coexisting liquid phase will release radionuclides or other contaminants from the waste form. The radionuclides or other contaminants will thereby be rendered potentially mobile. Such a liquid phase would be able to migrate

	into the surrounding engineered or natural barriers should the waste package be vented initially or be breached later in the post-closure period. The solubility of a radionuclide or other contaminant will govern its maximum concentration in the liquid phase (FEP 2.4.1.3). The solubility will also govern the rate at which a radionuclide or other contaminant dissolves in the coexisting liquid phase under any given set of conditions (temperature, pressure, liquid composition) prior to this maximum concentration being attained.
2000 List	3.2.01
References	[Ref. 66], [Ref. 108]

- ***FEP 2.4.1.2: Diffusion [waste form]***

Description	The diffusion of contaminants from the waste form in a fluid phase. This phase may be liquid water but may alternatively be non-aqueous liquid or a gas. Diffusion results in the net flux of contaminants from a region of higher concentration to one of lower concentration. The rate of diffusion is a function of temperature, viscosity of the fluid and the size (mass) of the associated molecules.
Category	Event, Process
Relevance to Performance and Safety	Given sufficient time, and in the absence of advection, diffusion will tend to remove radionuclides or other contaminants from the surface of a solid waste form, once these constituents have entered a fluid phase. In the absence of significant bulk movement of the fluid (i.e. advection / convection), the rate of diffusion will control the overall rate at which the radionuclides or other contaminants are released from the waste form. In this case, the steeper the chemical potential gradient (approximated by a concentration gradient) from the surface of the waste form into the coexisting fluid, the greater will be the rate at which the radionuclides or other contaminants are released. The degree to which the concentrations of radionuclides or other contaminants are heterogeneous within any fluid phase will depend upon the rates at which these constituents are added to / removed from the liquid phase, the concentration gradients that develop and the diffusion coefficients of the constituents. Typically the fluid phase of concern will be liquid water, with contaminants, including radionuclides, diffusing through it as aqueous species. If the waste package is vented, or is breached later in the post-closure period, then water may enter the package. Then, diffusion in the aqueous phase will be the dominant transport mechanism if pressure / head gradients are sufficiently small that no significant advection occurs. Contaminants, including radionuclides, that are present in other fluids, such as non-aqueous liquids or gases, may also be able to diffuse if chemical potential gradients exist in these phases.
2000 List	3.2.07
References	[Ref. 6], [Ref. 66]

- ***FEP 2.4.1.3: Speciation and solubility [waste form]***

Description	The chemical speciation and solubility processes affecting the release of contaminants from the waste form under repository conditions. "Chemical speciation" refers the form of elements within an aqueous solution or non-aqueous solution, for example as simple ions or in combination with other elements, forming complexes that may be neutral or negatively charged or positively charged. "Solubility" refers to the limiting quantity of a solid phase that may dissolve in a fluid phase. Factors such as temperature, gas partial pressure, ionic strength, the presence of complexing agents and pH and Eh conditions affect solubility.

Category	Process
Relevance to Performance and Safety	Chemical speciation and solubility will influence the potential for a radionuclide or other contaminant to be released from the waste form and then transported in a coexisting liquid phase. The solubility of a contaminant is its equilibrium concentration in a liquid phase that contacts the waste form. Chemical speciation will influence how solubility changes as a function of pressure, temperature and chemical conditions (e.g. pH, redox, salinity). Chemical speciation will influence the rate of contaminant release from the waste form under any given set of non-equilibrium conditions. The chemical speciation of the radionuclides or other contaminants will also influence their partitioning between the liquid and any gaseous phase that might be present.
2000 List	3.2.02, 3.2.05
References	[Ref. 109], [Ref. 110], [Ref. 224]

- ***FEP 2.4.1.4: Sorption and desorption [waste form]***

Description	The sorption/desorption processes affecting the release of contaminants from the waste form under repository conditions. Sorption describes the physico-chemical interaction where dissolved species adhere to a solid phase. Desorption is the opposite. Two sorption-desorption processes are commonly considered: ion-exchange processes involving an electrostatic or ionic attraction between charged dissolved species and oppositely charged surfaces; and chemisorption involving the formation of a chemical bond. Neutral species and (usually) anions are generally not strongly sorbed.
Category	Process
Relevance to Performance and Safety	Sorption and desorption will influence the partitioning of radionuclides and other contaminants between a solid waste form and any coexisting liquid. Consequently, sorption and desorption influence the potential mobility of radionuclides and other contaminants. Sorption and desorption are typically rapid processes in comparison to dissolution and (especially) precipitation reactions. The fractions of the radionuclides that are sorbed on solid waste form surfaces may be important contributors to the instant release fraction (IRF), the fraction of the inventory that may be rapidly released from the waste when exposed to groundwater.
2000 List	3.2.03
References	[Ref. 97], [Ref. 225]

- **FEP 2.4.2: Gas-mediated release**

Description	The release of contaminants in gas or vapour phase or as fine particulate or aerosol in gas or vapour from the waste form. This FEP includes the mobilisation of C-14 by incorporation into carbon dioxide or methane, incorporation of I-129 into iodine gas or methyl iodide, and incorporation of tritium (H-3) in hydrogen gas or water vapour. Gas-mediated release can also include the direct release of gases from gaseous waste forms (e.g. Kr isotopes).
Category	Event, Process
Comments	Gas-mediated release can arise from various gas production processes such as radon production (FEP 2.3.6.4), biochemical processes resulting in volatilisation (e.g. FEPs 2.3.4.5 and 2.3.5.2) and radiolysis resulting in hydrogen production (FEP 2.3.6.2).

Relevance to Performance and Safety	Radionuclides or other contaminants released from a waste form directly in gaseous form (e.g. Rn or Kr isotopes), or into a gaseous phase that contacts the waste form (e.g. isotope exchange of C-14 with C-12 and C-13 present in coexisting CO_2), will have the potential to be mobile. The mobility will depend partly upon the degree to which the gaseous phase is miscible with / soluble in any liquid phase that might also be present, and the relative densities of the gaseous and liquid phases (which will control the buoyancy of the gaseous phase). Radionuclides or other contaminants that are released into or as a gas phase may be mobilised by bulk gas movement (if there is a pressure gradient) or by gas diffusion (if there is no significant pressure gradient). If diffusion is the dominant mechanism, then the rate of release from the waste form will depend upon the concentration gradient that exists from the surface of the waste form into the gaseous phase. Sorption / desorption of the gaseous phase may influence the partitioning of radionuclides or other contaminants between the solid and gaseous phases. Gas generation processes may lead to pressurisation of the waste form, which in turn might also influence the rate of release of radionuclides and other contaminants, and the chemical / physical forms in which these releases occur.
2000 List	3.1.04, 3.1.06, 3.2.09
References	[Ref. 21], [Ref. 111], [Ref. 112], [Ref. 216], [Ref. 226]

- **FEP 2.4.3: Solid-mediated release**

Description	The release of contaminants in solid phase from the waste form.
Category	Event, Process
Comments	This might result from processes such as the fluvial erosion of the repository (FEPs 1.2.8), the glacial erosion of the repository (FEP 1.3.5) or magmatic/volcanic activity affecting the repository (FEP 1.2.5).
Relevance to Performance and Safety	The release of radionuclides and other contaminants in solid form implies physical disruption of the waste form by processes such as fluvial, marine or glacial erosion. The physical nature of the solids (grain size, shape, hardness, density etc.) and the characteristics of the environment into which the release occurs (e.g. whether a sub-aqueous environment or a subaerial environment), will determine the area over which the solids bearing radionuclides and other contaminants are dispersed and the rate at which the dispersion occurs. The chemical and physical characteristics of the waste form will together determine how the radionuclides and other contaminants partition into any coexisting liquid or gaseous phases and their bioavailability.
2000 List	3.2.04, 3.2.08
References	[Ref. 21]

- **FEP 2.4.4: Human-action-mediated release**

Description	The release of contaminants from the waste form as a direct result of human actions.
Category	Event, Process
Comments	Human-action-mediated release (this FEP, 2.4.4) covers the release process once humans have gained access to the waste. Such access may result from processes such as drilling into or excavation of the waste form (FEPs 1.4.5 and 1.4.6).

Relevance to Performance and Safety	Human actions that result in releases of radionuclides or other contaminants from the waste form will affect the rates of release and the chemical / physical forms in which releases occur. For example, direct drilling into a waste form may result in a sudden release of radionuclides in solid form. On the other hand, groundwater abstraction near a repository may result in more rapid fluxes of groundwater through the repository, leading to more rapid release of radionuclides dissolved in water.
2000 List	3.2.12
References	[Ref. 59], [Ref. 62], [Ref. 203]

○ FEP 2.5: Contaminant migration [waste package]

Description	The processes that directly affect the migration of contaminants through the waste package once they have been released from the waste form.
Category	FEP Subgroup
2000 List	3.2
References	[Ref. 6], [Ref. 161], [Ref. 175], [Ref. 176]

▪ FEP 2.5.1: Water-mediated migration [waste package]

Description	The processes related to the migration of contaminants through the waste package in the aqueous phase (including dissolved gases).
Category	Event, Process
Relevance to Performance and Safety	Radionuclides and other contaminants that are present within the waste package in a liquid phase will have the potential to migrate throughout the waste package. The nature of this migration will determine the degree to which the concentrations of radionuclides and other contaminants in the liquid phase are homogenised at any given time. For example, bulk movement of liquid due to temperature gradients (convection) may result in the concentrations of radionuclides and other contaminants becoming homogenised more rapidly than if liquid movement occurs only by diffusion. If liquid-mediated migration does not homogenise concentrations of radionuclides or other contaminants within the waste package, then potentially rates at which these contaminants are released from a vented or breached waste package will depend upon the location of the vent or breach. If there is more than one immiscible liquid phase within the waste package, liquid-mediated migration could cause spatial separation of different contaminants / radionuclides. Such a situation might arise if an aqueous phase and an immiscible non-aqueous phase liquid of different density coexist and different radionuclides or other contaminants partition differently between the two phases. The nature of the liquid phase(s) will also influence the partitioning of radionuclides and other contaminants between the liquid phase(s), coexisting solid phases and any coexisting gases present.
2000 List	3.2.07
References	[Ref. 66], [Ref. 113]

▪ *FEP 2.5.1.1: Advection [waste package]*

Description	The migration of dissolved contaminants by the bulk flow of the water through the waste package.

Category	Event, Process
Relevance to Performance and Safety	The bulk movement of liquid through a waste package has the potential to transport radionuclides and other contaminants from the waste form itself to the inner surfaces of the container. This bulk movement of liquid will influence the degree to which concentrations of radionuclides or other contaminants present in the liquid are homogenised. Under liquid-saturated conditions, the more rapid the advection the more rapidly will concentrations of radionuclides or other contaminants homogenise. Under partially liquid saturated conditions advection of a liquid phase will tend to transport radionuclides and other contaminants downwards within the waste package. If more than one immiscible liquid phase occurs, then the phases may move relative to one another under the influence of buoyancy. In such a case, partitioning of radionuclides or other contaminants between the liquid phases may cause contaminant concentrations to vary spatially within the waste package. If advection produces spatially heterogeneous concentrations of radionuclides or other contaminants within the waste package, the rates at which contaminants are released from a vented or breached waste package will depend upon the location of the vent or breach.
2000 List	3.2.07
References	[Ref. 66], [Ref. 227]

- ***FEP 2.5.1.2: Dispersion [waste package]***

Description	The spread in the spatial distribution of contaminants with time in the waste package because of differential rates of and pathways for advective transport through the waste package. Dispersion can occur in the direction of flow (longitudinal dispersion) and perpendicular to the direction of flow (transverse dispersion).
Category	Event, Process
Relevance to Performance and Safety	Dispersion within the waste package will influence the degree to which concentrations of radionuclides and other contaminants are homogenised within the fluid phases present at any time. Dispersion will influence the rate at which homogenisation occurs. Any spatial heterogeneity in these concentrations will mean that releases of these contaminants from a vented or breached waste package at any time will depend upon the location of the vent or breach.
2000 List	3.2.07
References	[Ref. 66], [Ref. 227]

- ***FEP 2.5.1.3: Diffusion [waste package]***

Description	The diffusion of contaminants through the waste package. Diffusive migration is driven by chemical potential gradients, and can be affected by thermal gradients, and can thus be in any direction.
Category	Event, Process
Relevance to Performance and Safety	Diffusion within the waste package will influence the degree to which concentrations of radionuclides and other contaminants are homogenised within the fluid phases present at any time. Diffusion will influence the rate at which homogenisation occurs and will depend upon the concentration gradients that exist at any time. Any spatial heterogeneity in the concentrations or radionuclides or other contaminants will mean that releases of

	these contaminants from a vented or breached waste package at any time will depend upon the location of the vent or breach.
2000 List	3.2.07
References	[Ref. 66], [Ref. 227]

- ***FEP 2.5.1.4: Dissolution, precipitation, and crystallisation [waste package]***

Description	The dissolution, precipitation and crystallisation of contaminants in the waste package under repository conditions. Dissolution is the process by which constituents of a solid or gas dissolve into solution. Dissolution is controlled by changes in pressure, temperature and gas partial pressures. Precipitation and crystallisation are processes by which solids are formed out of liquids and are controlled by changes in pressure, temperature and concentrations of chemical species. Precipitation occurs when chemical species in solution react to produce a solid. Crystallisation is the process of producing pure crystals of an element, molecule or mineral from a fluid or solution undergoing a cooling process.
Category	Event, Process
Relevance to Performance and Safety	Dissolution, precipitation and crystallisation influence the partitioning of radionuclides and other contaminants between solid and fluid phases within a waste package. These processes therefore influence the potential mobility of the radionuclides and other contaminants. These processes may also influence the form of a contaminant within any phase. For example, a radionuclide may exist within more than one crystal form of a solid phase with a particular chemistry. The form of a radionuclide or other contaminant within a solid phase will influence the likelihood that the contaminant could be re-mobilised by a fluid phase should conditions change.
2000 List	3.2.01
References	[Ref. 114]

- ***FEP 2.5.1.5: Speciation and solubility [waste package]***

Description	The chemical speciation and solubility processes affecting contaminant migration through the waste package under repository conditions. The concentration of an element in aqueous solution (at equilibrium) reflects the solubility of the solid compounds which contain the element. Factors such as temperature, gas partial pressure, ionic strength, the presence of complexing agents and pH and Eh conditions affect solubility. These factors affect the chemical form and speciation of the element. Thus different solids of the same element may have different solubilities in a particular solution.
Category	Feature
Relevance to Performance and Safety	The solubility and chemical speciation of a radionuclide or other contaminant will influence its partitioning between solid and liquid phases within the waste package and thereby affect the concentration of the contaminant in the fluid phase and hence its potential mobility. Solubility and chemical speciation of any contaminant are related. The solubility of a contaminant will tend to be increased if it forms chemical complexes with ligands in the liquid phase. Chemical speciation will also influence the rates at which solid precipitation and dissolution reactions occur (i.e. the rate at which solubility equilibrium is attained). Hence, chemical speciation has the potential to influence the rates at which radionuclides or other contaminants are released from the waste. If the chemical system within the waste package achieves equilibrium, then the solubility of a solid phase that contains a radionuclide or other contaminant will control the

	concentration of the contaminant in the liquid phase. The chemical speciation of a radionuclide or other contaminant in a fluid phase will not only influence the solubility of the contaminant, but also its ability to sorb to the surfaces of solid phases within the waste package and to diffuse through these solid phases.
2000 List	3.2.02, 3.2.05
References	[Ref. 109], [Ref. 110]

- ***FEP 2.5.1.6: Sorption and desorption [waste package]***

Description	The sorption/desorption processes contaminants in the waste packages under repository conditions. Sorption describes the physico-chemical interaction where dissolved species adhere to a solid phase. Desorption is the opposite. Two sorption-desorption processes are commonly considered: ion-exchange processes involving an electrostatic or ionic attraction between charged dissolved species and oppositely charged surfaces; and chemisorption involving the formation of a chemical bond. Neutral species and (usually) anions are generally not strongly sorbed.
Category	Event, Process
Relevance to Performance and Safety	Sorption and desorption of a radionuclide or other contaminant will influence its partitioning between solid and fluid phases within the waste package, and thereby affect the concentration of the contaminant in the fluid phase and hence its potential mobility. Generally, compared to solid-phase dissolution and precipitation, the rates of sorption and desorption tend to be rapid. Hence, these processes influence the rate at which radionuclides or other contaminants are released from solid phases within the waste package.
2000 List	3.2.03
References	[Ref. 97]

- ***FEP 2.5.1.7: Colloid transport [waste package]***

Description	The transport of colloids and interaction of contaminants with colloids migrating through the waste package under repository conditions. Colloids are particles with a maximum dimension typically less than 10 µm and are usually considered to have at least one dimension in the range 1 nm to 1 µm. Colloids are particles that can exist within a liquid without settling out.
Category	Event, Process
Relevance to Performance and Safety	The potential mobility of radionuclides and other contaminants within a waste package will be influenced by their partitioning between colloids and chemical species in solution, and between colloids and solid phases. Radionuclides or other contaminants may themselves form colloids (e.g. Pu(IV)), be incorporated chemically into the structures of colloids, or may sorb to the surfaces of colloids. In all these cases, the contaminants are transported with the colloids. If the colloids themselves are mobile, then migration of the associated radionuclides or other contaminants will be enhanced. Alternatively, if mobility of the colloids is restricted, for example by filtration as water passes through other materials in the waste package, then migration of the associated radionuclides or other contaminants will be diminished.
2000 List	3.2.04

References	[Ref. 98], [Ref. 99], [Ref. 220]

- **FEP 2.5.2: Gas-mediated migration [waste package]**

Description	The migration of contaminants in gas or vapour phase or as fine particulate or aerosol in gas or vapour through the waste packages.
Category	Event, Process
Comments	Gas-mediated migration [waste package] (this FEP 2.5.2) does not cover the movement of contaminated water due to pressurisation by gas or decreasing pressurisation by consumption of gas. Instead, this process is covered by Advection [waste package] (FEP 2.5.1.1).
Relevance to Performance and Safety	Certain radionuclides and other contaminants may be transported directly as gases (e.g. Rn or C-14 in the form of CO_2), or may be transported together with non-radioactive gases (e.g. H-3 in a small component of water vapour that is transported with migrating CH_4). Aerosols or particulates may be transported along with non-radioactive gases. Contaminants, including radionuclides, may be expelled from the waste package in the event that it is vented or becomes breached in the post-closure period.
2000 List	3.1.04,3.1.06, 3.2.09
References	[Ref. 111], [Ref. 112]

- ## FEP 3: Repository factors

Description	The factors related to the repository (including the excavation damaged and disturbed zones, and site investigation/monitoring boreholes but excluding the waste packages) and the associated migration of contaminants.
Category	FEP Group
2000 List	2.1
References	[Ref. 6], [Ref. 7]

- ### FEP 3.1: Repository characteristics and properties

Description	The physical, chemical and biological characteristics and properties of the repository components (excluding the waste packages) at repository closure.
Category	FEP Subgroup
2000 List	2.1
References	[Ref. 20], [Ref. 21], [Ref. 161], [Ref. 162], [Ref. 163], [Ref. 164], [Ref. 165], [Ref. 175], [Ref. 176]

- #### FEP 3.1.1: Buffer/backfill

Description	The physical, chemical and biological characteristics and properties of the buffer/backfill at the time of waste emplacement in the repository.
Category	Feature
Comments	Buffer and backfill are sometimes used synonymously. In some high-level waste (HLW)/spent fuel concepts, the term buffer is used to mean material immediately surrounding a waste package and having some chemical and/or mechanical buffering role, whereas backfill is used to mean material used to fill other underground openings. However, in some intermediate-level waste (ILW)/low-level waste (LLW) concepts the term backfill is used to describe the material placed between waste packages which may have a chemical and/or mechanical role. Buffer/backfill materials may include clays, cement and mixtures of cement with aggregates, e.g. of crushed rock.
Relevance to Performance and Safety	A buffer / backfill, if present, will affect the rate and nature of waste package evolution. The buffer/backfill may therefore influence whether waste package integrity is lost and if so the time following repository closure at which this occurs. Depending upon its design, a buffer / backfill will influence to some degree the mechanical forces upon a waste package, the rate of fluid flow around the waste package (such as liquid water, non-aqueous phase liquids and gas), and the biological /chemical environment of the waste package. These factors will affect the potential for the waste package to undergo mechanical deformation and to evolve chemically (e.g. corrode, in the case of metallic overpacks, or leach, in the case of cementitious containers). Should release from waste packages occur, the rate at which radionuclides and other contaminants are able to leave a repository will depend upon the physical, chemical and biological characteristics of any buffer or backfill that is present. The chemical characteristics of the buffer / backfill will influence the chemical and physical forms in which radionuclides or other contaminants migrate (e.g. chemical speciation, partitioning between aqueous and gaseous forms).

	The porosity and permeability of the buffer / backfill will influence the pressures that are attained within the repository post closure, should gas be generated by the wastes and / or engineered barrier components. The pressure evolution could in turn impact the integrity and effectiveness of repository seals. The presence and mechanical characteristics of a buffer / backfill will influence post-closure deformation of the surrounding geosphere and possibly evolution of potential pathways for fluid flow within it. For example, backfill with swelling properties may exert a pressure on the wall rocks of sealed tunnels that tends to decrease apertures of fractures in the excavation disturbed zone.
2000 List	1.1.07
References	[Ref. 6], [Ref. 21], [Ref. 155], [Ref. 163], [Ref. 234]

- **FEP 3.1.2: Room/tunnel seals**

Description	The physical, chemical and biological characteristics and properties of the seals in the waste emplacement rooms and access tunnels at repository closure. Sealing materials may include clay bricks, cement bricks and cement plugs.
Category	Feature
Relevance to Performance and Safety	The characteristics of room / tunnel seals will impact the potential for radionuclides and other contaminants to migrate through / from the rooms and tunnels, should they be released from the waste packages. These room / tunnel seals may also influence the rate at which fluids (such as liquid water, non-aqueous liquids or gases) may enter or leave the repository in the post-closure period. The room / tunnel seals may therefore affect the rate at which the repository re-saturates following closure. Should the wastes and / or engineered barrier components evolve to produce gas, the permeability of the seals may influence the pressures that are attained. The ability of the room / tunnel seals to affect fluid movement to the repository, including the resaturation rate, may impact upon the evolution of other engineered barrier components. Depending upon the chemical and biological characteristics of these seals, their volumes and their locations relative to the waste packages, they may impact upon the biology and chemistry of the environment around the waste packages.
2000 List	2.1.05
References	[Ref. 21], [Ref. 38], [Ref. 155], [Ref. 235]

- **FEP 3.1.3: Shaft/ramp seals**

Description	The physical, chemical and biological characteristics and properties of the shaft/ramp seals at repository closure.
Category	Feature
Relevance to Performance and Safety	The characteristics of shaft/ramp seals will impact upon the potential for radionuclides and other contaminants to migrate through / from the repository, should the waste packages and any other engineered barriers have pathways through them from the disposal tunnels / rooms. The shafts / ramps provide a connection between the repository and the surface. Hence, impairment of these seals could potentially provide pathways from the repository to the biosphere. These shaft / ramp seals may also influence the rate at which fluids (such as liquid water, non-aqueous liquids or gases) may enter or leave the repository in the post-closure period. The shaft / ramp seals may therefore affect the rate at which the repository re-saturates following closure. Impairment of the shaft / ramp seals may, depending upon the natural hydraulic gradients, result in cross-flow of

	groundwater or other fluids (e.g. hydrocarbon liquids or gases) between different rock formations or structures in the rock sequence above the repository. Should the wastes and / or engineered barrier components evolve to produce gas, the permeability of the shaft / ramp seals may influence the pressures that are attained. The potential ability of the shaft / ramp seals to affect fluid flow to / from repository means that they could potentially influence the chemical and biological conditions within the repository. The presence and nature of shaft / ramp seals may also impact upon the likelihood of future human intrusion into the repository, by influencing how easy it is to gain access to the facility.
2000 List	2.1.05
References	[Ref. 21], [Ref. 38], [Ref. 155], [Ref. 235]

- **FEP 3.1.4: Borehole seals**

Description	The physical, chemical and biological characteristics and properties of any site investigation/ monitoring boreholes at the time of sealing.
Category	Feature
Relevance to Performance and Safety	If radionuclides and other contaminants are able to leave the repository via the EBS, their potential to migrate through the surrounding geosphere will be impacted by the characteristics of seals in any boreholes there. The borehole seals may influence the rate at which fluids (such as liquid water, non-aqueous liquids or gases) may enter or leave the repository in the post-closure period. This in turn may affect the chemical and biological conditions within the repository. Boreholes may connect the surface to the deeper geosphere, and potentially the repository itself. The effectiveness of its seals will determine whether a borehole may form a pathway to the biosphere for radionuclides or other contaminants that can leave the repository via the EBS. Boreholes that do not penetrate from the surface to the repository may connect different permeable rock formations or structures (e.g. transmissive faults) that are naturally separated by impermeable rock formations or structures. Impairment of borehole seals may, depending upon the natural hydraulic gradients, result in cross-flow of groundwater or other fluids (e.g. hydrocarbon liquids or gases) between different rock formations or structures in the rock sequence above the repository.
2000 List	2.1.05
References	[Ref. 156]

- **FEP 3.1.5: Other engineered features**

Description	The physical, chemical and biological characteristics and properties of the engineered features (other than waste packages, buffer/backfill, and seals) at the time of repository closure. Such features can include rock bolts, shotcrete, tunnel and shaft liners, silo walls, any service components and equipment not removed before closure.
Category	Feature

Relevance to Performance and Safety	Other engineered features have the potential to influence the physical, chemical and biological conditions in and around the repository. These influences may impact upon the stability of EBS components and upon the chemical forms and mobility of radionuclides and other contaminants that are can leave the repository by the EBS. They may also contribute to gas generation. Engineered features such as rock bolts and tunnel lining that affect the mechanical responses of the geosphere, could influence the potential for migration pathways to develop through the geosphere for radionuclides and other contaminants. Engineered features that affect chemical conditions could impact upon the stability of EBS components and the chemical forms and mobility of radionuclides and other contaminants. For example, an alkaline plume could develop from shotcrete and might dissolve mineral phases in nearby bentonite barriers. Cement might react with bicarbonate in the groundwater, thereby reducing its concentration and the ability of certain radionuclides to complex with carbonate. Certain engineered features, such as shotcrete or rock bolts, could provide surfaces for sorption of radionuclides or other contaminants that might be able to leave the repository via the EBS. Emplacement of engineered features might introduce micro-organisms to the sub-surface, thereby influencing microbially-mediated reactions that might occur. These reactions might in turn impact upon the stability of engineered materials and the mobility and chemical forms of radionuclides and other contaminants that leave the repository.
2000 List	2.1.06
References	[Ref. 20], [Ref. 205]

- **FEP 3.1.6: Excavation damaged and disturbed zones**

Description	An "excavation disturbed zone" is the zone of rock around caverns, tunnels, shafts or other underground opening that is mechanically damaged (fractured), hydraulically disturbed (e.g. dewatered) or chemically perturbed. An "excavation damaged zone" is the part of an "excavated disturbed zone" characterised by mechanical damage. Mechanical damage and hydraulic or chemical disturbances may extend for different distances in the rock, so that an "excavation damaged zone" and "disturbed zone" may be extend for different distances. The extent and properties depend on factors such as the nature of the host rock, the excavation method, and the location and effectiveness of seals and grouts around the rooms and tunnels. The extent of damage will decrease with increasing distance from the excavation wall and generally there will be a transition from the excavation damaged zone to the excavation disturbed zone to the undisturbed host rock. The zones are likely to have different properties to the undisturbed host rock, e.g. opening of fractures or change of hydraulic properties due to stress relief.
Category	Feature
Comments	FEPs affecting the undisturbed host rock are considered under Geosphere Factors (FEP 4). While a desaturated state can be a characteristic of the excavation damaged and disturbed zone (this FEP 3.1.6) the process of desaturation is covered by FEP 3.2.2.1.
Relevance to Performance and Safety	The physical, chemical and biological properties of excavation damaged and disturbed zones will influence their potential to provide migration pathways for radionuclides and other contaminants, should these leave the repository via EBS. The porosity and permeability of the excavation damaged and disturbed zones will influence their ability to conduct fluids (such as liquid water, non-aqueous liquids or gases) to and from the repository. Initially, at the time of closure, the excavation damaged and disturbed zone will be at least partly desaturated and will provide a

	pathway via which resaturation of the repository and EBS could occur. This in turn may influence the rates at which certain engineered barriers attain their long-term design properties (e.g. swelling pressure of a bentonite buffer). The potential ability of the excavation damaged and disturbed zones to affect fluid flow to / from repository also means that they could potentially influence the chemical and biological conditions within the repository. The chemical and biological properties of the excavation damaged and disturbed zones may influence the chemical forms, and consequently mobilities, of any radionuclides and other contaminants that might be conducted along them.
2000 List	2.2.01
References	[Ref. 112], [Ref. 157], [Ref. 158], [Ref. 159]

FEP 3.2: Repository processes

Description	The processes occurring within the repository resulting in its evolution (excluding the waste packages).
Category	FEP Subgroup
2000 List	2.1
References	[Ref. 21], [Ref. 161], [Ref. 162], [Ref. 163], [Ref. 164], [Ref. 175], [Ref. 176]

FEP 3.2.1: Thermal processes [repository]

Description	The internal and external thermal processes that affect the buffer/backfill, seals and other engineered features, and the overall thermal evolution of the repository. The thermal evolution of the repository will be affected by heat transfer due to gradients in temperature caused by heat conduction or convective flow which will be affected by the thermal characteristics (thermal conductivity, heat capacity) of the engineered features and the surrounding geosphere. Thermal processes include thermal expansion and contraction and consequent changes in densities of materials in the repository.
Category	Event, Process
Comments	Internal thermal processes are those that arise from the waste packages (FEP 2.3.1) and other components of the repository. They are distinct from external thermal processes that arise from the surrounding geosphere and are covered by FEP 4.2.1 (Thermal processes [geosphere]).
Relevance to Performance and Safety	Thermal processes that affect the repository could impact upon: the effectiveness of the EBS; processes by which radionuclides and other contaminants are released, should this be possible via the EBS; the rates at which such released radionuclides and other contaminants are transported; the forms (chemical species and phases) within which these released radionuclides and other contaminants are transported; and processes by which released radionuclides and other contaminants are retarded. Thermal processes will affect the temperature evolution of the repository, which may in turn impact upon the mechanical properties of EBS components and the geosphere. There might be a consequent influence on responses to the stress regime, and the rheological properties of solids, for example whether they are brittle (potentially leading to migration pathways developing for radionuclides and other contaminants) or undergo plastic deformation.

	The temperature evolution will also impact upon the rates and characteristics of biological and chemical processes within the repository and surrounding geosphere. These processes might influence the rates and characteristics of evolution shown by engineered barrier components. Temperature-related variations in these biological and chemical processes will also impact upon the releases of radionuclides and other contaminants from the waste packages, should there be pathways through the EBS. For example, the solubilities of solid phases that contain these contaminants will be temperature-dependent. Temperature gradients that develop within a repository and in the surrounding geosphere might help to drive the movement of fluids (such as liquid water, non-aqueous liquids and gases) and any radionuclides or other contaminants that they contain. For example, convection of groundwater might transport heat away from heat-generating waste packages.
2000 List	2.1.11
References	[Ref. 82], [Ref. 84]

- **FEP 3.2.2: Hydraulic processes [repository]**

Description	The hydraulic processes that affect the seals and other engineered repository features, and the overall hydraulic/hydrogeological evolution of the repository. This includes the effects of hydraulic/hydrogeological influences on the repository components by the waste packages and the surrounding geosphere.
Category	Event, Process
Relevance to Performance and Safety	Hydraulic/hydrogeological processes may influence the physical, chemical and biological evolution of the EBS and the mobility of radionuclides and other contaminants, should these be released from the waste packages and should there be pathways through the other EBS components. Flowing water may transport micro-organisms and solutes to / from engineered barriers. The water and solutes may participate in chemical reactions, which, depending upon the conditions, may be microbiologically mediated. These reactions may influence the effectiveness of the engineered barriers. The rates of chemical reactions will depend partly upon the rate at which flowing water is able to supply reactants and remove reaction products. The rate at which water flows through the repository will influence the rates at which radionuclides and other contaminants are transported, should these be released from the waste packages. Flowing water may also cause other phases (non-aqueous liquids and gases) to move. There may be consequent implications for the mobility of radionuclides and other contaminants that occur in these other phases. Flowing water may also, if sufficiently rapid, cause the physical modification of certain EBS materials. For example, physical erosion of bentonite buffer may need to be considered. Flow of water will transport heat and therefore influence the temperature evolution of the repository, with consequences for the rates of chemical reactions. Some heat generated by waste packages will be transported by water that flows through the EBS.
2000 List	2.1.08
References	[Ref. 49], [Ref. 124], [Ref. 169], [Ref. 206]

- ***FEP 3.2.2.1: Desaturation/resaturation***

Description	The establishment of unsaturated conditions in the repository during the construction and operation phases, and the subsequent return to saturated conditions.
Category	Event, Process
Relevance to Performance and Safety	The degree to which the EBS and rock surrounding a repository are water-saturated will influence: 1) the chemical, physical and biological evolution of the EBS; and 2) the mobility of radionuclides and other contaminants, which may originate in the wastes, should there be breaches in the waste packages. Changes in water saturation (desaturation and resaturation) may cause changes in the chemical reactions that occur in the EBS and rock of the excavation disturbed zone and affect their physical properties. Water is necessary for many chemical reactions that may affect the EBS and the rock immediately surrounding the repository. Flowing water may supply dissolved reactants and remove reaction products. Microbes, which may mediate many chemical reactions, may be supplied by water, while water is necessary for the metabolism of microbes; the presence of water-saturated or unsaturated conditions will influence the kinds and abundances of microbes that occur. Cracking and fracture dilation may accompany desaturation. Swelling and fracture sealing may occur as clay-rich (smectite-bearing) rocks and EBS components (e.g. bentonite buffer, backfill) resaturate. The air in the desaturated rock around excavated cavities (tunnels, waste emplacement rooms, waste emplacement holes etc.) at the time of closure may cause oxidation of reduced minerals in the rock. Under initially under-saturated conditions, air will also be present in many of the EBS components (e.g. bentonite, backfill), with the potential for oxidation of reduced solid phases present. When the excavation disturbed zone and/or EBS components are unsaturated with water, their effective permeabilities with respect to non-aqueous liquids and gases will be higher than those in the presence of liquid water.
2000 List	2.1.08

- ***FEP 3.2.2.2: Piping/hydraulic erosion***

Description	The hydraulic erosion of the buffer/backfill due to water flowing through the repository, for example through intersecting hydraulically active fractures. If the rate of throughflow exceeds the rate of uptake by the buffer/backfill, then active flow channels or 'pipes' may develop in the buffer/backfill.
Category	Event, Process
Relevance to Performance and Safety	The density of buffer or backfill would be reduced by piping or hydraulic erosion, were it to occur. The loss of density may impair the buffer's function. In this case, there could be enhanced transport of solutes to / from the waste container, potentially leading to its degradation and ultimately loss of its containment function. Were this to occur, transport of radionuclides and other contaminants from the waste container might occur through the buffer. Loss of buffer density could also impair its ability to insulate the waste container from the effects of rock movements. Loss of backfill density by piping / hydraulic erosion could potentially lead to pathways forming for the transport of radionuclides and other contaminants, should there be release pathways to the backfill through the other engineered barriers. Were it to proceed sufficiently, piping / hydraulic erosion of the backfill could potentially lead to any mechanical support function of the backfill being impaired.
2000 List	2.1.08

- **FEP 3.2.3: Mechanical processes [repository]**

Description	The mechanical processes that affect the seals and other engineered repository features, and the overall mechanical evolution of the repository. Included are the effects of mechanical loads imposed on repository components by adjacent repository components, the waste packages and the surrounding geosphere.
Category	Event, Process
Comments	There is some overlap between the scope of FEP 3.2.3 (this FEP, Mechanical processes [repository] and FEP 3.2.1 (Thermal processes) 3.2.2 (Hydraulic processes), FEP 3.2.4 (Chemical processes), FEP 3.2.5 (Biological processes) and FEP 3.2.6 (Radiological processes). FEPs 3.2.1-3.2.6 may all result in variations in mechanical loads on materials within the repository. Mechanical processes (this FEP, 3.2.3) covers the mechanical effects of the loads that are caused by the processes covered by these other FEPs.
Relevance to Performance and Safety	Mechanical processes may influence the effectiveness of the engineered barriers and any barrier function ascribed to the rock immediately surrounding the repository. These processes may produce or seal pathways through the barriers through which fluids (such as liquid water, non-aqueous liquids and gases) may potentially migrate. Mechanical processes may also produce forces that drive these fluids. Hence mechanical processes could influence the likelihood that radionuclides and other contaminants are released from the waste packages, and if release occurs, the subsequent migration of the radionuclides and other contaminants through the barrier system. Mechanical processes may also affect retardation of radionuclides and other contaminants (sorption and matrix diffusion) along pathways through the barriers. Changes in the surface areas of solid phases that contact advecting fluid may affect sorption. Changes in the connectivity between fracture porosity and matrix porosity may influence the potential for retardation of radionuclides and other contaminants by matrix diffusion. Depending upon the magnitude and orientation of the stresses affecting the barriers, brittle deformation could result in the formation of fractures through the barriers, or widening of existing fractures. Alternatively, existing fractures may close. Plastic deformation could cause the re-distribution of barrier materials, with consequences for barrier performance. For example, bentonite within a buffer may be re-distributed, leading to changes in its thickness. Mechanical processes may also impact upon the stability of openings. These processes may influence the requirement for, and nature of, seals, linings and other engineered structures/ materials within the repository. This may have further implications for safety.
2000 List	2.1.07, 2.1.12
References	[Ref. 160], [Ref. 184]

- ***FEP 3.2.3.1: Material volume changes [repository]***

Description	The effects of volume changes in materials used in the repository. Examples include the shrinkage/expansion of concrete, expansion of metallic components due to corrosion, the swelling of bentonite and thermal expansion / contraction.
Category	Event, Process
Comments	This FEP (3.2.3.1) concerns explicitly the changes in volume that materials within the repository may undergo, rather than the causes of these changes, which are covered by

	FEP 3.2.1 (Thermal processes), FEP 3.2.2 (Hydraulic processes), FEP 3.2.4 (Chemical processes), FEP 3.2.5 (Biological processes) and FEP 3.2.6 (Radiological processes).
Relevance to Performance and Safety	Changes in the volumes of materials used in the EBS and the rock immediately adjacent to the repository could impact upon: 1) the development and / or sealing of potential mass transport pathways through the barrier system; and 2) forces driving migration of fluids (such as liquid water, non-aqueous liquids and gases). Material volume changes could therefore affect the likelihood that radionuclides and other contaminants are released from a waste package, and if release occurs, the subsequent migration of the radionuclides and other contaminants through the barrier system. Decreases in material volumes could result in the development of connected porosity (fractures, connections between matrix pores) through the materials. Increases in material volumes could result in sealing of such pathways, or creation of pathways, depending upon the interaction between the stresses generated during volume increase and the pre-existing stress field. Changes in the volume of one material may impact upon the deformation shown by an adjacent material, and upon its mass transport properties. For example, a bentonite-bearing backfill that is emplaced dry may swell, thereby imposing a stress on the adjacent rock, leading to decreases in the apertures of fractures in the excavation disturbed zone. If material volume changes cause variations in the surface areas of pores that are accessible to fluid, there may be an impact upon the ability of the material undergoing volume change to retard radionuclide migration. Changes in surface areas that are accessible to migrating radionuclides and other contaminants, should these be released from the waste packages, will tend to impact on retardation by sorption. Retardation by matrix diffusion will be influenced by material volume changes that affect the connectivity between fractures though which fluid advection occurs and more poorly connected pores in the material's matrices.
2000 List	2.1.07

- ***FEP 3.2.3.2: Creep***

Description	The plastic movement of buffer/backfill material and surrounding rock in the EDZ under an imposed load. The buffer and backfill materials can creep or move as a result of imposed loads such as the weight of the waste packages or lithostatic pressure from and creep of the surrounding geosphere.
Category	Process
Relevance to Performance and Safety	Creep of certain components of the EBS and certain kinds of host rock near a repository could potentially impact upon: 1) the development and / or sealing of potential mass transport pathways through the barrier system; and 2) forces driving migration of fluids (water, liquid hydrocarbons and gases) by reducing void volumes. Material creep could therefore affect the likelihood that radionuclides and other contaminants are released from the waste packages, and if release occurs, the subsequent migration of radionuclides and other contaminants through the barrier system. Creep of one material may influence the mechanical behaviour of an adjacent material. For example, creep of a salt host rock in the EDZ and salt backfill surrounding a waste package may affect the stresses borne by the waste package and hence the likelihood that it might deform, releasing radionuclides and other contaminants. The thickness of a barrier might be affected by creep. For example, owing to creep a buffer might decrease in thickness in some areas, but increase in thickness in others.

	There might be consequent implications for buffer performance. Creeping of the surrounding rock restrains components of the EBS ensuring the sealing function of these components. If creep causes variations in the surface areas of pores that are accessible to fluid, there may be an impact upon the ability of the material undergoing volume change to retard radionuclide migration. Changes in surface areas that are accessible to migrating radionuclides and other contaminants, should these be released from the waste packages, will tend to impact on retardation by sorption. Retardation by matrix diffusion will be influenced by any creep that changes the connectivity between fractures though which fluid advection occurs and more poorly connected pores in the material's matrices.
2000 List	2.1.07

- ***FEP 3.2.3.3: Collapse of openings***

Description	The collapse of tunnels, shafts and boreholes, including cave-ins, roof settling, spalling and rock bursts. Collapses could occur where voids remain post-closure (e.g. because galleries or not backfilled, or because backfill emplacement is not 100% efficient, resulting in there being residual headspace).
Category	Event, Process
Relevance to Performance and Safety	The collapse of openings within a repository could potentially influence post-closure performance of the EBS and/or the surrounding geosphere barrier. Collapses of openings could damage waste packages or other components of the EBS. Collapses could also produce pathways through the surrounding geosphere for the possible migration of fluids (such as liquid water, non-aqueous liquids and gases). These fluids could transport radionuclides and other contaminants from the repository, should there be pathways through the EBS. Were collapses to occur, they could change the permeability distribution of materials in the repository, with a consequent effect on the patterns of fluid flow through / around it. While collapses could potentially produce pathways for fluid migration, they might also increase the areas of exposed fresh solid surfaces. These surfaces might contact migrating radionuclides or other contaminants, should these be released from the waste packages and move through the other EBS components. The increased surface areas might engage in increased sorption and hence retardation.
2000 List	2.1.07

- ***FEP 3.2.3.4: Gas-induced dilation [repository]***

Description	The dilation of repository materials due to gas pressure.
Category	Event, Process
Relevance to Performance and Safety	Dilation of materials in the EBS and / or the host rock immediately surrounding the repository, caused by gas pressures generated within the repository, may damage the EBS and/or natural barriers. Dilation may produce new microscopic or macroscopic pathways through the engineered or natural barriers or increase the apertures of existing pathways. Via these pathways, gas will migrate and may carry radionuclides and other contaminants with it. Depending upon the mechanical properties of the engineered and natural barriers, and the prevalent stress regime, the pathways may close if gas pressures dissipate, or they may remain open. If pathways remain open, they might subsequently conduct groundwater or non-aqueous fluids that could transport radionuclides and other contaminants, should these be released from waste packages.

2000 List	2.1.12

- ***FEP 3.2.3.5: Gas explosion [repository]***

Description	An explosion resulting from the ignition of a flammable gas mixture in the repository. Gases could be produced from the corrosion and degradation of waste packages and/or engineered repository features and/or could enter the repository from the surrounding geosphere. Some gases might be flammable or might form an explosive mixture. For instance, hydrogen and methane could mix with oxygen and explode. However, a gas explosion can only occur if a flammable gas mixture forms and there is a source of ignition or the gas mixture has the capability to auto-ignite.
Category	Event
Relevance to Performance and Safety	Were a gas explosion to occur it might damage the EBS and surrounding geological barrier. Such an explosion may also provide a force driving the movement of fluids (water, non-aqueous liquids and gas), which may carry radionuclides and other contaminants, should they be released from the waste packages. A gas explosion may also modify the chemical environment within the repository, which may then impact upon the subsequent evolution of the EBS and potentially upon the release and migration of radionuclides and other contaminants, should they be released from the waste packages.
2000 List	2.1.12

- **FEP 3.2.4: Chemical processes [repository]**

Description	The chemical/geochemical processes that affect the seals and other engineered repository features, and the overall chemical/geochemical evolution of the repository. This includes the effects of chemical/geochemical influences on repository components by the waste packages, adjacent repository components and the surrounding geosphere.
Category	Event, Process
Comments	Chemical processes [repository] (this FEP 3.2.4) concerns the chemical events / processes that impact upon the properties of repository components and on the overall chemical conditions in the repository. The influences of these FEP Subgroup 3.3 (Contaminant Migration [repository].
Relevance to Performance and Safety	Chemical processes in the repository will influence the chemical, biological and physical evolution of the EBS and the surrounding geosphere. Some chemical processes may lead to the formation or enhancement of pathways through the EBS and surrounding geosphere, through which fluids (such as liquid water, non-aqueous liquids and gases) may migrate. These fluids may transport radionuclides and other contaminants, should these be released by the waste packages. Other chemical processes may cause the complete or partial sealing of pre-existing pathways through the EBS and surrounding geosphere. Chemical processes will influence the chemical conditions (e.g. redox, pH, cation and anion concentrations) within the repository and surrounding geosphere. These conditions may in turn influence the behaviour of radionuclides and other contaminants from the wastes (should the waste packages release contaminants). For example, chemical processes may influence the solubilities and aqueous chemical speciation of these solutes, thereby influencing their mobilities.

	Chemical processes may impact upon the thermal conditions in the repository. Some chemical reactions are endothermic (consume heat), whereas others are exothermic (produce heat). Chemical processes may lead to density gradients that in the fluid phase(s) that may in turn contribute to driving advection. These gradients may develop as a result of dissolution or precipitation processes, or as a consequence of certain chemical reactions generating or consuming heat (exothermic and endothermic reactions respectively).
2000 List	2.1.09, 2.1.12
References	[Ref. 96], [Ref. 97], [Ref. 110], [Ref. 129]

- ***FEP 3.2.4.1: Evolution of pH conditions [repository]***

Description	The temporal evolution of pH within the repository.
Category	Event, Process
Relevance to Performance and Safety	The evolution of pH within the repository and surrounding geosphere will both influence and reflect the chemical and biological evolution of the EBS and the adjacent natural barrier. The evolution of pH conditions will therefore be related to the physical evolution of these barriers, which is coupled to the chemical evolution. The pH evolution may be coupled with the development or sealing of potential pathways through which fluids (such as liquid water, non-aqueous liquids or gases) may move. If mobile such fluids may in turn transport radionuclides and other contaminants, should these be released from the waste packages. pH represents the chemical activity of H^+ in the water present within the EBS and surrounding geosphere. Some chemical reactions in these barriers will consume H+ (increase pH) while others will generate H+ (decrease pH). Reactions that influence pH in one barrier component, may influence the chemical evolution of an adjacent barrier if fluid is able to move between the components. For example, a high (alkaline) pH developed in the porewater within a cement barrier may passivate the steel forming a waste container in contact with the cement, thereby reducing the rate of steel corrosion. The pH evolution will affect the chemical speciation of radionuclides and other contaminants and influence their abilities to precipitate / co-precipitate, re-dissolve, sorb and diffuse. The pH will affect the partitioning of the radionuclides and other contaminants among different potentially mobile phases (such as water, non-aqueous liquids or gases). The pH evolution within the repository will therefore influence the release rate of radionuclides and other contaminants from the waste package (should this release occur), and their subsequent migration and retardation within the EBS and surrounding geosphere.
2000 List	2.1.09

- ***FEP 3.2.4.2: Evolution of redox conditions [repository]***

Description	The temporal evolution of the repository's redox state, as represented by parameters such as the redox potential relative to the standard hydrogen electrode (Eh).
Category	Event, Process
Relevance to Performance and Safety	The redox evolution of the repository will be coupled to the physical evolution of the EBS and the surrounding geosphere barrier. For example, aerobic corrosion of a steel waste container immediately after repository closure will consume oxygen present initially in the repository and at the same time potentially decrease the mechanical strength of the container. Thus, the redox evolution may impact upon the development or

	sealing of potential pathways through which fluids (such as liquid water, non-aqueous liquids or gases) may move. If mobile, such fluids may in turn transport radionuclides and other contaminants, should these be released from the waste containers. The redox evolution is coupled to the temporal changes in the identities and proportions of solid phases and fluid phases (which may include one or more of liquid water, non-aqueous liquids and gases), and temporal changes in the chemistries of these phases. Reactions that influence redox conditions in one barrier component may influence the chemical evolution of an adjacent barrier if fluid is able to move between the components, or at the interface between the components. For example, oxidation of trace sulphide minerals in a backfill may remove dissolved oxygen from the pore fluid, which then cannot oxidise a steel barrier component with which it later comes into contact. The redox evolution will affect the chemical speciation of certain redox-sensitive radionuclides and other contaminants directly. Redox evolution may influence indirectly the chemical speciation of non-redox-sensitive radionuclides and other contaminants that may combine with redox-sensitive species. These redox-related effects may influence the abilities of radionuclides and other contaminants to precipitate / co-precipitate, re-dissolve, sorb and diffuse, and partition among different potentially mobile fluid phases (such as liquid water, non-aqueous liquids and gases).
2000 List	2.1.09

- ***FEP 3.2.4.3: Migration of chemical species [repository]***

Description	The migration of reactants into and reaction products from the repository. Chemical species can migrate into and out of the repository and its various components by advection (head/pressure gradient driven) and diffusion (chemical potential gradient driven). Where solutions with different concentrations are separated by a semi-permeable membrane there may be osmotic transport of water. Chemical concentration gradients in the repository and its various components could be caused by various factors. Migration of chemical species by advection may cause concentration gradients that drive diffusive transport. Temperature gradients may produce concentration gradients by influencing the chemical reactions that occur between fluids (e.g. liquid water, non-aqueous liquids and gases) and between solids and fluids, and the rates of these reactions. Temperature gradients may also lead to advective (convective) migration. heterogeneities in the spatial distribution of waste packages and repository materials.
Category	Event, Process
Relevance to Performance and Safety	The migration of chemical species into and out from the repository will influence the chemical evolution of the EBS and the surrounding geosphere. This migration may also influence biological processes within the repository, since nutrients and energy sources required for microbial activity may be among the migrating chemical species. The chemical evolution of the EBS and surrounding geosphere may be coupled to its physical evolution; pathways for movement of fluids (such as water, non-aqueous liquids or gases) can form, be enhanced, partially seal or fully seal due to chemical processes. The formation of chemical concentration gradients may lead to the dissolution and precipitation of chemical compounds with subsequent opening or plugging of flow paths. The presence of certain species, such as chloride, sulphide, sulphate and potassium, can affect the evolution of the repository and its seals, for example through promoting the corrosion of metals (high chloride/sulphide concentrations), the degradation of cement (high sulphate concentrations) and the illitisation of bentonite (high potassium concentrations). Among the migrating chemical species may be radionuclides and other contaminants originating in the wastes, should the waste packages release them. Migrating chemical species may include ligands that can complex with radionuclides and other contaminants, thereby influencing their mobility and retardation. The chemical

	speciation of the radionuclides and other contaminants will depend partly upon the migration of chemical species to the repository. This chemical speciation will influence the partitioning of the radionuclides and other contaminants among different solid phases and mobile phases (such as water, non-aqueous liquids and gases).
2000 List	2.1.09

- ***FEP 3.2.4.4: Corrosion [repository]***

Description	The degradation of the metallic component(s) of the repository by interaction with its environment, specifically, by reactions involving water in liquid or vapour form and / or gases (e.g. oxygen in the air), and/or by reaction with solutes within the water (e.g. sulphide). Corrosion of repository metals can occur by a number of processes such as generalised (or uniform), localised and galvanic corrosion processes. Galvanic corrosion occurs when two different metals are in electric contact. Metal corrosion may result in the consumption of oxygen, or the generation of hydrogen.
Category	Event, Process
Relevance to Performance and Safety	Corrosion may impact upon the effectiveness of the EBS, and / or upon the effectiveness of the geosphere barrier surrounding the repository. Corrosion of rebars in certain cementitious barriers may lead to these barriers losing mechanical integrity. Such corrosion may reduce the overall strength of a barrier owing to the rebars losing strength. Alternatively, corrosion may cause the metallic components to expand, thereby cracking the cementitious barrier. Corrosion of rock bolts may allow deformation of the rock surrounding excavated cavities. Possibly, there could be rock collapse if cavities remain, for example where galleries are not backfilled, or where headspace remains above backfill. Such deformation may in turn impact upon the integrity and performance of the EBS. Corrosion of metals, whether present for structural reasons, or present in equipment / facilities that are not removed on closure (e.g. ventilation ducts or rails), may influence gas pressures within the repository. Aerobic corrosion of Fe-bearing metal components will consume oxygen that has been trapped within the repository at the time of closure. Later anaerobic corrosion of Fe-bearing metal components will generate H_2 gas and consume water. The evolution of gas pressure caused by corrosion may affect the mechanical properties of the engineered and natural barriers. Potentially, existing fractures could dilate, or new fractures could form. The evolution of gas pressure due to corrosion may also impact upon the movement of fluids (such as water, non-aqueous liquids and gases) to and from the repository and within the repository. Such fluid movement may influence the transport of radionuclides and other contaminants originating in the wastes, should these be released from the waste packages. In this case, the partitioning of the radionuclides and other contaminants between immobile solid phase and mobile fluids may be affected by the evolution of redox conditions caused by corrosion (i.e. evolution from oxidising to reducing conditions caused by consumption of O_2 and generation of H_2). Radionuclides and other contaminants may sorb to, or co-precipitate with, the products of corrosion, such as Fe-oxyhydroxides. Thus, corrosion may help to retard or immobilise radionuclides and other contaminants.
2000 List	2.1.09

- ***FEP 3.2.4.5: Alteration [repository]***

Description	Alteration, including its evolution in time, of repository materials by chemical processes such as dissolution, leaching, chloride and sulphide/sulphate attack, carbonation, illitisation.
Category	Event, Process
Comments	“Dissolution” and “leaching” are closely related terms. “Dissolution” is the dissolving of a solid phase in a fluid phase, typically liquid water. “Leaching” refers to the removal of components of a solid phase by a moving fluid phase, typically liquid water. “Alteration” encompasses these terms and also the transformation of a given assemblage of solid phases to a different assemblage of solid phases. Carbonate minerals dissolving in porewater within a backfill is an example of dissolution. An example of leaching is the removal of soluble components from Ordinary Portland Cement by groundwater flowing through it, leading to a progressive reduction in the pH of cementitious pore fluids in the long-term. Conversion of the smectite in bentonite into illite (illitisation) is an example of alteration involving the transformation of a mineral assemblage.
Relevance to Performance and Safety	Alteration may influence the effectiveness of the EBS and the adjacent geosphere barrier. Alteration may change the porosity and permeability distribution of the barriers. Potentially, some alteration reactions could produce pathways through the EBS and adjacent geosphere, via which fluids (such as liquid water, non-aqueous liquids and gases) might flow. Movement of such fluids could transport radionuclides and other contaminants originating in the wastes, should these be released from the waste packages. Other alteration reactions could decrease the porosity and / or permeability of the EBS and / or the adjacent geosphere. Possibly, some alteration reactions could seal previously existing pathways via which fluids might otherwise flow. Alteration could affect the forces that could potentially drive the flow of fluids through the EBS and adjacent barriers, and possibly transport radionuclides and other contaminants. Alteration could remove solutes from solution, or add solutes to solution, thereby changing the chemical potential gradients that drive diffusion. Such alteration could also affect thermal gradients, reflecting the exothermic character of some reactions and endothermic character of other reactions. Changes in the concentrations and / or temperatures of solutions due to alteration reactions could impact upon the density gradients within fluid phases and consequently upon density-driven fluid flow. Alteration reactions that consume or generate gas and / or that change the porosity could affect gas pressures within the repository, again potentially impacting upon fluid flow. The swelling pressures exerted by certain barriers (bentonite buffers, bentonite-bearing backfill) could potentially be affected by alteration, again possibly contributing to the development of pathways for fluid flow and the forces driving such flow. Alteration could impact upon the chemical conditions within the repository (e.g. pH, Eh, concentrations of ligands). These conditions could in turn influence the mobility and retardation of radionuclides and other contaminants that originate in the waste, should they be released from the waste packages. Variations in chemical conditions related to alteration could affect the partitioning of radionuclides and other contaminants among different potentially mobile fluid phases (such as waste, non-aqueous liquids and gases) and between these phases and immobile solid phases.
2000 List	2.1.09

- ***FEP 3.2.4.6: Precipitation of solid phases [repository]***

Description	The precipitation processes, including their evolution in time, affecting repository materials.

	Precipitation can be caused by changes in chemical conditions in the repository (particularly pH, Eh and the concentration of complexing ions). These changes can be gradual, or abrupt. The latter occur especially at the interface between different repository components. Temperature gradients may cause precipitation; some solid phases will precipitate from a fluid phase as temperature decreases, whereas other phases may precipitate as temperature increases. The kinetics of precipitation reactions will be an important control on whether a solid phase that is over-saturated in a solution (i.e. expected to precipitate on thermodynamic grounds) actually precipitates. The presence of complexing ions can increase solubility, and cause elements to remain in solution under conditions when they would otherwise be expected to precipitate.
Category	Event, Process
Relevance to Performance and Safety	Precipitation of solid phases will tend to decrease the porosity of materials in the EBS and / or the adjacent geosphere. Thus, precipitation may reduce the permeability or even seal potential pathways for the movement of fluids (such as liquid water, non-aqueous liquids or gases) through the EBS or adjacent geosphere. Precipitation of solid phases could therefore decrease the potential for such fluid movements to transport any radionuclides and other contaminants that might be released from the waste packages. Potentially, radionuclides and other contaminants might be immobilised by being precipitated or co-precipitated in solid phases. Radionuclides and other contaminants might also sorb to the surfaces of precipitated solid phases. The precipitation of solid phases has the potential to change the chemical conditions (e.g. pH, Eh dissolved chemical species) in the repository. This influence on chemical conditions could in turn affect the chemical speciation of any radionuclides and other contaminants that might be present within the EBS or surrounding natural barrier. Such an influence on chemical speciation could affect the partitioning of the radionuclides and other contaminants between immobile solid phases and potentially mobile fluid phases (such as water, non-aqueous liquids and gases).
2000 List	2.1.09

- ***FEP 3.2.4.7: Complexation [repository]***

Description	The formation in the repository materials of a molecular entity by loose association involving two or more component molecular entities (ionic or uncharged), or the corresponding chemical species. Complexation is promoted through the presence of complexing agents (organics, inorganic ligands and microbes). Sources of these agents include organics in the waste package and inflowing water.
Category	Process
Relevance to Performance and Safety	The formation of chemical complexes potentially influences the mobility and retardation of radionuclides and other contaminants that originate in the wastes, should they be released from a waste package. Combination of a radionuclide or other contaminants with a ligand may influence its solubility or sorption. Complexation may also influence the partitioning of radionuclides and other contaminants between different potentially mobile fluids (such as liquid water, non-aqueous liquids and gases). Complexation of the dissolved chemical components in the water that occupies the pores pace within the EBS, or the surrounding geosphere, will affect the nature and quantities of solids that may precipitate or dissolve in these materials. Complexation of chemical components composing solid engineered barriers, or the surrounding geosphere, may cause the enhanced dissolution of these engineered barriers or the geosphere.

	Spatial variations and temporal changes in chemical complexes that occur in solution, due to processes such as changes in temperature or mixing between chemically distinct waters (e.g. between natural groundwater and cement-conditioned porewater) may cause dissolution or precipitation of solid phases within the EBS or surrounding geosphere. These dissolution and / or precipitation processes may impact upon the creation / enhancement or partial / complete sealing of pathways through the engineered and natural barriers for the possible migration of fluids (such as water, non-aqueous liquids or gases). These fluids could in turn transport radionuclides and other contaminants. The chemical complexation of aqueous solutes may influence the rates at which solid phases dissolve and precipitate. If dissolution or precipitation reactions are slow (kinetically inhibited), an aqueous solution may not be at equilibrium with coexisting solid phases, or may be supersaturated with respect to solid phases that do not occur (i.e. on thermodynamic grounds a solid phase ought to precipitate, but for kinetic reasons it does not do so). Depending upon the chemical complexation, at a given pressure and temperature, the aqueous concentration of a dissolved constituent may exceed the solubility of a solid phase that, if present and at equilibrium with the water, would control the aqueous concentration of the solute. Alternatively, the aqueous concentration of a solute may be lower than would be expected, based on the occurrence of solid phase and the assumption of solubility limitation.
2000 List	3.2.05

- ***FEP 3.2.4.8: Colloid formation [repository]***

Description	The formation of very fine particles (with at least one dimension in the 1 µm to 1 nm range) that can affect the migration of contaminants in the repository. Particles of clay minerals, silica, iron oxy-hydroxides, other minerals, organic and bio-organic macromolecules, and contaminants themselves (e.g. Pu(IV)) may form the colloid phase. Sources can include repository components (e.g. bentonite and cementitious materials) and inflowing groundwater. Colloid formation may be promoted by steep chemical gradients, such as at an interface where the Eh or pH changes abruptly because of chemical or biological activity. The thermodynamic stability of colloids depends upon factors such as the chemistry and surface charge of the colloid and the chemistry of the dispersion medium. Colloid stability generally decreases as ionic strength (salinity) increases.
Category	Event, Process
Relevance to Performance and Safety	Certain radionuclides and other contaminants can sorb to colloids. Potentially, colloids may also contain radionuclides within their structures. Movement of colloids, in water or non-aqueous fluids, may therefore impact upon the migration rates through the EBS and the surrounding geosphere, of certain radionuclides and other contaminants originating in the wastes (should release from a waste package occur). Colloids that carry radionuclides and other contaminants may be transported through the repository and possibly into the surrounding geosphere, in water or non-aqueous liquids, if there are physical pathways (e.g. open fractures or connected matrix pores) through the EBS and forces driving fluid flow. Their relatively large sizes may prevent colloids from entering pores in EBS materials and rock that may be accessed by dissolved ions and complexes, which are much smaller than colloids. Consequently, radionuclides and other contaminants that are transported with/as colloids may follow different pathways through the engineered and natural barriers to the pathways followed by dissolved radionuclides and other contaminants. Radionuclides and other contaminants that are transported with/as colloids and in solution may be retarded differently.
2000 List	3.2.04

- **FEP 3.2.5: Biological processes [repository]**

Description	The biological/biochemical processes that affect the seals and other engineered repository features, and the overall biological/biochemical evolution of the repository. This includes the effects of biological/biochemical influences on repository components by the waste packages and surrounding geosphere. In addition to the microbes that might be present prior to repository construction, a range of microbes can be expected to be introduced into the repository during its construction and operational phases. Some could be present in the waste packages, whereas others could be introduced as the emplacement rooms are excavated and infrastructure erected. Only some of the microbes present at repository closure will find the subsequent conditions suitable for their growth. Besides requiring certain types of nutrients, individual microbial populations will only operate under particular conditions of temperature, pH, Eh and salinity.
Category	Event, Process
Relevance to Performance and Safety	Biological processes may influence the physical and chemical properties of the EBS and the surrounding geosphere. For example, gas might be produced or consumed. The performance of the engineered and natural barriers may possibly be affected. Growth or loss of biomass may impact upon the permeability of EBS materials and the surrounding geosphere. For example, growth or loss of biofilms may affect the degree to which fracture porosity is interconnected. Biological processes may influence the migration rates through the engineered and natural barriers of radionuclides and other contaminants that originate in the wastes, should these be released by the waste packages. The physical and chemical forms of the radionuclides and other contaminants may be affected by biological processes. For example, whether a radionuclide is in gaseous form or dissolved within water may be influenced by biological activity. Should a radionuclide or other contaminant be dissolved in water, its chemical complexation may depend to some extent on biological processes. Organisms may directly concentrate radionuclides or other contaminants within their structures. Depending upon whether the organisms are immobile or mobile there might be a consequent influence on the migration rate through the engineered and natural barriers of the radionuclides and other contaminants.
2000 List	2.1.10, 2.1.12
References	[Ref. 101], [Ref. 221]

- ***FEP 3.2.5.1: Microbial growth and decline [repository]***

Description	The processes affecting the growth and decline of microbes in the repository. Growth requires the presence of energy sources and suitable nutrients in the repository, such as simple organic molecules containing oxygen, nitrogen and/or sulphur, and organics derived from wastes. The loss of such energy sources and / or nutrients can result in the decline of microbial populations, as can microbial poisoning. Poisoning of microbial processes can occur due to changes in temperature and chemical conditions in the repository but extremophiles can survive and thrive outside the range at which most microbes flourish.
Category	Event, Process
Relevance to Performance and Safety	The growth and decline of microbes in the repository may influence the evolution of the EBS and the adjacent geosphere, and potentially the performance of the EBS and natural barrier. Growth and decline of microbes in the repository may also change the migration rates through these barriers of radionuclides and other contaminants originating in the waste, should they be released from a waste package.

	Microbial growth and decline may cause temporal and spatial variations in the chemical environment within the repository that may impact upon the transport and retardation of radionuclides and other contaminants within the repository. The changing chemical environment may result in changes in the complexation of the radionuclides and other contaminants, which could in turn affect their partitioning between immobile solid phases and potentially mobile fluid phases (such as liquid water, non-aqueous liquids and gases). For example, the changing chemical conditions might impact upon processes such as sorption and solid precipitation / co-precipitation. Microbial growth and decline may also cause changes in the nature and proportions of solid and fluid phases that are present. For example, gas may be produced or consumed during microbial growth, while microbial decay may be accompanied by precipitation of solid carbonate phases. A result of microbial growth and decline affecting the chemical conditions in the repository and the natures and proportions of solid and fluid phases present may be variations in the forces driving fluid flow. Gas pressure gradients may be affected. Chemical gradients driving diffusion may also be influenced. Growth of certain micro-organisms may concentrate radionuclides and other contaminants within their structures. Conversely, decay of such micro-organisms following their death may release these radionuclides and other contaminants to a potentially mobile fluid phase.
2000 List	2.1.10

- ***FEP 3.2.5.2: Microbially/biologically mediated processes [repository]***

Description	The biological processes affecting the repository such as degradation of organics, nitrate ions and sulphate ions, biofilm growth and volatilisation.
Category	Event, Process
Relevance to Performance and Safety	Microbially / biologically mediated processes may influence the physical and chemical properties of the EBS and the surrounding geosphere. These processes may possibly affect the performance of the engineered and natural barriers. Potential pathways for flowing fluids (such as liquid water, non-aqueous phase liquids and gases) could form or be enhanced by biological processes that cause dissolution of solid EBS and geosphere constituents. Existing potential fluid flow pathways may partially or completely seal due to different microbially / biologically mediated processes causing solids to precipitate, or else due to micro-organisms themselves occluding porosity (e.g. by forming biofilms). Microbially / biologically mediated processes may also affect forces that could potentially drive fluid flow through the repository, by consuming or generating fluids (such as water, non-aqueous liquids and gases). Microbially / biologically mediated processes may also result in chemical gradients developing within the repository materials, which could possibly affect the diffusion of dissolved species. By possibly influencing the characteristics of fluid flow pathways and/or forces driving fluid advection and/or diffusion of solutes and gases, microbially / biologically mediated processes could impact upon the migration of radionuclides and other contaminants originating in the wastes, should these be released by a waste package. The influence of microbially / biologically mediated processes upon the chemical conditions in the repository (e.g. Eh, pH, dissolved inorganic carbon content) could in turn affect partitioning of radionuclides and other contaminants between different immobile solid phases and potentially mobile fluid phases. This influence could in turn affect the retardation of migrating radionuclides and other contaminants, by processes such as sorption and precipitation/coprecipitation of solids.

	Micro-organisms could concentrate certain radionuclides and other contaminants within their structures. Potentially, micro-organisms may behave as "living colloids", which, if they are mobile in flowing fluids, could enhance the mobility of any radionuclides and other contaminants that they might contain.
2000 List	3.2.06

- **FEP 3.2.6: Radiological processes [repository]**

Description	The effects of radiation emitted from the waste in the waste packages on the seals and other repository engineered features, and the overall radiogenic evolution of the repository.
Category	Event, Process
Relevance to Performance and Safety	Radiological processes may potentially affect the physical, chemical and biological characteristics of the EBS and adjacent geosphere. These processes may influence the performance of the barriers. Potentially, radiological processes could contribute to the development or enhancement of pathways through the engineered and natural barriers, via which radionuclides and other contaminants originating in the wastes might be transported, if they are released by a waste package. The physical and chemical forms of these radionuclides and other contaminants might be influenced by radiological processes (e.g. whether in gaseous form or in aqueous solution). Radiological properties could affect the partitioning of radionuclides and other contaminants between immobile solid phases and potentially mobile fluid phases (such as water, non-aqueous liquids and gases). Radiological processes may affect the nature of the fluid phase present (e.g. nature and quantities of gas) and the complexation of dissolved chemical components. For example, radiolysis might generate gas and/or contribute to the breakdown of non-aqueous organic liquids. Radiolysis may influence the redox conditions, which would impact upon the chemical speciation of certain chemical components. Radiological processes may also influence forces driving the movement of these radionuclides and other contaminants, for example by affecting gas pressures, which might influence advection, or chemical gradients, which might influence diffusion. Radiological processes such as decay and ingrowth may cause temporal variations in the quantities and natures of radionuclides that are present within the barrier system.
2000 List	2.1.13
References	[Ref. 33], [Ref. 102]

- ***FEP 3.2.6.1: Radioactive decay and ingrowth [repository]***

Description	The spontaneous disintegration or de-excitation of an atomic nucleus, resulting in the emission of sub-atomic particles and energy and the formation of a new progeny (or "daughter") nucleus in the repository.
Category	Event, Process
Relevance to Performance and Safety	Radioactive decay and ingrowth will produce temporal changes in the identities and quantities of the radionuclides present within the EBS and the adjacent geosphere. The overall radioactivity of the radionuclides present within the EBS and adjacent geosphere will vary temporally, reflecting radioactive decay and ingrowth. The nature of the radionuclides that are produced by decay and ingrowth will influence their mobilities in any fluids (such as water, non-aqueous liquids or gases) that may be

	transported through the EBS or adjacent geosphere. The physical forms (e.g. gaseous or dissolved in aqueous solution) and chemical speciation of parent and daughter radionuclides may differ. The parent and daughter radionuclides may therefore have different mobilities, reflecting the different physical forms / chemical speciation. Radioactive decay and ingrowth may affect the partitioning of radionuclides between immobile solid phases and potentially mobile fluid phases. For example, radioactive decay of a radionuclide that is immobilised within a mineral may damage the crystal structure of the mineral, making it easier for flowing water to leach the daughter nuclide. In post-closure assessment, radioactive decay chains are often simplified, e.g. by neglecting the shorter-lived radionuclides in release and migration calculations but adding any dose-contribution to longer-lived parent radionuclides.
2000 List	3.1.01

- ***FEP 3.2.6.2: Radiolysis [repository]***

Description	The dissociation of molecules by ionising radiation in the repository surrounding the waste package. The actual composition and amount of the radiolysis products that will be formed is controlled by the radiation dose rate and by the compositions and amounts of the solid and fluid phases contained in the repository surrounding the waste package.
Category	Event, Process
Relevance to Performance and Safety	Radiolysis has the potential to change the physical, chemical and biological properties of the EBS and the adjacent geosphere. Radiolysis may change the chemical environment within the repository, for example by producing locally oxidising conditions. There may be a consequent impact upon the stability of solid components of the EBS and the adjacent geosphere, and the natures and quantities of fluid phases present. Any changes in the identities and quantities of immobile solid phases and potentially mobile fluid phases (such as water, non-aqueous liquids and gases) produced by radiolysis might affect forces driving advection. Any changes in the chemical environment caused by radiolysis may produce chemical potential gradients that could influence diffusion. There may be implications of radiolytic processes for the partitioning between immobile solid phases and potentially mobile fluid phases (such as water, liquid hydrocarbons and gases) of radionuclides and other contaminants originating in the wastes, if they are released by a waste package. As a result, radiolysis may impact upon transport rates through the repository of radionuclides and other contaminants. Radiolysis may affect the viability of microbial populations within the repository. This could then result in implications for the biological processes that might impact upon performance of the EBS and natural barriers, forces driving fluid flow and solute transport, and the mobility of radionuclides and other contaminants.
2000 List	2.1.13

- ***FEP 3.2.6.3: Radon production [repository]***

Description	The production of radon gas from the decay of uranium, thorium and radium in the repository. The main radon isotope considered in assessments is Rn-222 (the longest-lived isotope at 3.82 days). The uranium, thorium and radium may be waste-derived and/or naturally occurring.
Category	Process

Relevance to Performance and Safety	Radon, whether evolved by decay of U, Th and Ra in the repository could potentially contribute directly to the radiation doses received by organisms. However, the longest-lived isotope, Rn-222, has a half-life of only 3.82 days. Hence, a significant contribution by Rn-222 to post-closure doses received by possible biosphere receptors, implies rapid Rn-222 transport (over a time of no more than few days) from the repository to the biosphere. Radioactive daughter isotopes of Rn decay, such as Po-218 and Po-214, could also contribute to doses received by biosphere receptors, if transported to the surface / near-surface from the repository post-closure.
2000 List	3.1.06

- ***FEP 3.2.6.4: Radiation damage [repository]***

Description	The damage caused to the repository materials surrounding the waste package by radiation. Radiation damage may result from radiation emitted by the waste packages, or by radioactive decay of radionuclides within the materials of the EBS. These latter include radionuclides that have been released by waste packages (assuming that radionuclide release from the waste packages is possible), radionuclides that occur within the repository materials, or radionuclides that have been transported into the EBS from the surrounding geosphere. Radiation damage could affect the macro-scale properties of the EBS materials, or alternatively only be relevant to the micro-scale.
Category	Event, Process
Relevance to Performance and Safety	Radiation damage may affect the mass transport properties and/or mechanical properties of components of the EBS and / or the adjacent geosphere. Potentially, radiation damage may contribute to producing pathways through components of the EBS and/or adjacent geosphere, via which radionuclides and other contaminants that originate in the waste might be transported, should they be released by a waste package. Radiation damage may mechanically weaken barrier components and/or structural components, thereby allowing them to deform more readily than in the absence of radiation damage. This deformation might impact upon the effectiveness of the barriers. For example, deformation might produce pathways through the barriers, through which radionuclides and other contaminants might migrate. Radiation damage might affect the partitioning of radionuclides and other contaminants among immobile solid phases and potentially mobile fluid phases (such as liquid water, non-aqueous liquids and gases). Radionuclides and other contaminants may sorb onto new solid surfaces created by the effects of radiation. Conversely, radiation may cause structural damage to solid phases that contain radionuclides or other contaminants, thereby causing enhanced leaching of the radionuclides or other contaminants by flowing water.
2000 List	2.1.13

- ***FEP 3.2.6.5: Criticality [repository]***

Description	The possibility and effects of spontaneous nuclear fission chain reactions within the repository. Criticality requires a sufficient concentration and localised mass (critical mass) of fissile isotopes (e.g. U-235, Pu-239) and also presence of neutron moderating materials in a suitable geometry; a chain reaction is liable to be damped by the presence of neutron absorbing isotopes (e.g. Pu-240).
Category	Event, Process

Relevance to Performance and Safety	Were it to occur, criticality could impact upon the physical, chemical and biological characteristics of the EBS and the adjacent geosphere. Potentially, the performance of the engineered and natural barriers could be affected. Heat generation, radiation damage and radiolysis could all potentially contribute to chemical and physical changes in these barriers that might produce pathways through them, through which fluids (such as liquid water, non-aqueous liquids and gases) might flow. These fluids could in turn potentially transport radionuclides and other contaminants. Criticality might influence the identities and proportions of different immobile and potentially mobile fluid phase present. For example, heat generated by spontaneous fission could lead to breakdown of organic materials and the generation of gas. Such heating would also affect the densities of solid and fluid phases. Chemical conditions might be affected by criticality, as a result of this process affecting chemical reactions among chemical species present in the engineered and natural barriers. Criticality might therefore influence forces driving advection of fluids and chemical gradients driving diffusion. Due to criticality, the identities and proportions of radionuclides present in the repository would change. Criticality would produce fission products, many of which would then undergo radioactive decay to produce daughter isotopes. Thus, criticality has the potential to influence the radiation doses to which receptors in the biosphere could be exposed, should radionuclides be transported from the repository to the biosphere.
2000 List	2.1.14

○ FEP 3.3: Contaminant migration [repository]

Description	The processes that directly affect the migration of contaminants in the repository once they have been released from the waste packages.
Category	FEP Subgroup
2000 List	3.2
References	[Ref. 6], [Ref. 13], [Ref. 21], [Ref. 161], [Ref. 162], [Ref. 163], [Ref. 164], [Ref. 171], [Ref. 175]

▪ FEP 3.3.1: Water-mediated migration [repository]

Description	The processes related to migration of contaminants in the aqueous phase in the repository (including dissolved gases). This process covers transport of radionuclides and/or other contaminants in water that is present initially in the repository materials (e.g. free porewater in cement), or which enters the repository from the surrounding geosphere post-closure.
Category	Event, Process
Relevance to Performance and Safety	Water-mediated migration through the EBS and adjacent geosphere, if it occurs, has the potential to influence the fluxes of radionuclides and other contaminants out of the repository If there are also pathways through the surrounding geosphere, via which solutes could be transported from the repository to the biosphere, there could be an impact on the doses of radionuclides and other contaminants received by biosphere receptors. If water flows by advection through the EBS and adjacent geosphere, it may transport dissolved radionuclides and other contaminants. Even if there is no advection of water

	within the EBS and adjacent geosphere, radionuclides and other contaminants that are dissolved in porewater may migrate by diffusion. Concentrations of radionuclides and other contaminants that are dissolved in water may be decreased by dispersion / mixing (dilution) during migration.
2000 List	3.2.07

- ***FEP 3.3.1.1: Advection [repository]***

Description	The migration of dissolved contaminants by the bulk flow of the water through the repository. Included is fluid flow driven by temperature, chemical or electrical gradients, rather than due to hydraulic pressure gradients, called thermal, chemical or electrical osmosis depending on the driving gradient.
Category	Event, Process
Relevance to Performance and Safety	Advection of water through the EBS and adjacent geosphere, if it occurs, has the potential to influence the fluxes of radionuclides and other contaminants out of the repository. These radionuclides and other contaminants may originate in the waste, if they are released from a waste package. If there are also pathways through the surrounding geosphere, via which solutes could be transported from the repository to the biosphere, there could be an impact on the doses of radionuclides and other contaminants received by biosphere receptors.
2000 List	3.2.07

- ***FEP 3.3.1.2: Dispersion [repository]***

Description	The spread in the spatial distribution of contaminants with time in the repository because of differential rates of advective transport through the repository. Dispersion can occur in the direction of flow (longitudinal dispersion) and perpendicular to the direction of flow (transverse dispersion).
Category	Event, Process
Relevance to Performance and Safety	Dispersion has the potential to decrease the aqueous concentrations of dissolved radionuclides and other contaminants, as they are transported in water that moves by advection (should it occur) through the EBS and adjacent geosphere. Dispersion may also affect the size(s) and location(s) of the area(s) across which radionuclides and other contaminants may leave the repository. Dispersion may influence chemical gradients that are established in the repository, including gradients in the concentrations of radionuclides and other contaminants. This may in turn impact upon diffusive fluxes of these contaminants within the repository and between the repository and the surrounding geosphere. If there are also pathways through the surrounding geosphere, via which solutes could be transported from the repository to the biosphere, dispersion in the repository could impact the doses of radionuclides and other contaminants that are eventually received by biosphere receptors.
2000 List	3.2.07

- ***FEP 3.3.1.3: Diffusion [repository]***

Description	The diffusion of contaminants through the repository. Diffusive migration is driven by chemical potential gradients, can be affected by thermal gradients, and can thus be in any direction. It can occur in moving or stagnant repository water.
Category	Process
Relevance to Performance and Safety	Diffusion has the potential to transport radionuclides and other contaminants that are dissolved in water, through the EBS and adjacent geosphere. As they are transported, the concentrations of the radionuclides and other contaminants will decrease. Diffusion will lead to the "spreading" of the radionuclides and other contaminants through the water, and thereby decrease the aqueous concentrations of dissolved radionuclides and other contaminants. Diffusion may affect the size(s) and location(s) of the area(s) across which radionuclides and other contaminants may leave the repository. Diffusion will influence chemical gradients that are established in the repository, including gradients in the concentrations of radionuclides and other contaminants. This may in turn impact upon diffusive fluxes of these contaminants within the repository and between the repository and the surrounding geosphere. If there are also pathways through the surrounding geosphere, via which solutes could be transported from the repository to the biosphere, diffusion in the repository could impact the doses of radionuclides and other contaminants that are eventually received by biosphere receptors.
2000 List	3.2.07

- ***FEP 3.3.1.4: Dissolution, precipitation, and crystallisation [repository]***

Description	The dissolution, precipitation and crystallisation of contaminants in the repository under prevailing repository conditions.
Category	Event, Process
Comments	This FEP concerns only the effects of dissolution, precipitation and crystallisation on the water-mediated transport of contaminants. These events/processes are influenced by the more general chemical events / processes covered by FEP 3.2.3 (Chemical processes [Repository]. Dissolution is the process by which constituents of a solid, non-aqueous liquid or gas dissolve into liquid water. Precipitation occurs when chemical species in solution produce a solid and are thereby removed from the solution. Crystallisation is the process of producing a crystalline solid phase of an element, molecule or mineral from water. Solids that are initially precipitated from an aqueous solution may be amorphous or poorly crystalline and then subsequently become more crystalline as they age.
Relevance to Performance and Safety	Dissolution of radionuclides and other contaminants in water may allow them to be transported in the aqueous phase, via diffusion or advection, through the EBS and adjacent geosphere. These radionuclides or other contaminants may originate in the wastes, should they be released from a waste package. Precipitation of solid phases from an aqueous phase may immobilise radionuclides and other contaminants. The radionuclides or other contaminants may co-precipitate with more abundant solutes, as trace or minor constituents of a solid phase. Alternatively, the radionuclides and other contaminants may be essential constituents of a solid phase. Crystallisation of solid phases that have already precipitated (e.g. progressive crystallisation of initially poorly crystalline Fe-oxyhydroxides) may affect the solubility

	of radionuclides and other contaminants contained within their structures. That is, crystallisation may influence the likelihood that radionuclides and other contaminants may be dissolved by an aqueous phase and thereby rendered mobile. Dissolution, precipitation and crystallisation may affect the spatial distributions of radionuclides and other contaminants within the EBS and adjacent geosphere. This influence may then have implications for the subsequent mobilities of the radionuclides and other contaminants, and their resulting fluxes of out of the repository, should conditions change.
2000 List	3.2.01

- ***FEP 3.3.1.5: Speciation and solubility [repository]***

Description	The chemical speciation and solubility processes affecting contaminant migration through the repository under prevailing repository conditions. The concentration of an element in aqueous solution at equilibrium with a coexisting solid reflects the solubility of the solid. Factors such as temperature, gas partial pressure, ionic strength, the presence of complexing agents and pH and redox conditions affect solubility. These factors affect the chemical form and speciation of the element. Thus different solids of the same element may have different solubilities in a particular solution.
Category	Event, Process
Relevance to Performance and Safety	The aqueous speciation and solubility of a radionuclide or other contaminant will influence their potential mobility in the aqueous phase, within the EBS and adjacent geosphere. These radionuclides and other contaminants may originate in the wastes, should they be released from a waste package. Under a given set of temperature, pressure and chemical conditions, at chemical equilibrium the maximum aqueous concentration of a radionuclide or other contaminant contained by a coexisting solid phase is governed by the solubility of that phase. This concentration is termed a "solubility limit". The chemical speciation of the radionuclides and other contaminants in the aqueous phase will influence their solubility limits at any given temperature and pressure. However, the chemical speciation may also influence the rates at which solid phases dissolve and precipitate. If dissolution or precipitation reactions are slow (kinetically inhibited), an aqueous solution may not be at equilibrium with coexisting solid phases, or may be supersaturated with respect to solid phases that do not occur (i.e. on thermodynamic grounds a solid phase ought to precipitate, but for kinetic reasons it does not do so). Depending upon the chemical speciation, at a given pressure and temperature, the aqueous concentration of a radionuclide or other contaminant may exceed the solubility of a solid phase that, if present and at equilibrium with the water, would control the aqueous concentrations of radionuclides or other contaminants. Alternatively, the aqueous concentration of a radionuclide or other contaminant may be lower than would be expected based on the occurrence of solid phase and the assumption of solubility limitation. The chemical speciation of a radionuclide or other contaminant in an aqueous solution will also influence the effectiveness of other transport and retardation processes. Partitioning of radionuclides and other contaminants between the aqueous phase and other phases that may occur (solids, non-aqueous liquids and gases) will be influenced by the aqueous speciation of the radionuclides and other contaminants. For example, sorption will depend partly upon the electrical charges of aqueous species. Transport of aqueous species by diffusion may also be affected by chemical speciation. For example, the ability of radionuclides and other contaminants to diffuse from fractures into the surrounding solid matrices may depend partly upon the charges of the aqueous species of the radionuclides and other contaminants.

2000 List	3.2.02

- ***FEP 3.3.1.6: Sorption and desorption [repository]***

Description	The sorption/desorption processes affecting the migration of contaminants through the repository under prevailing repository conditions. Sorption describes the physico-chemical interaction where dissolved species adhere to a solid phase. Desorption is the opposite. Two sorption-desorption processes are commonly considered: ion-exchange processes involving an electrostatic or ionic attraction between charged dissolved species and oppositely charged surfaces; and chemisorption involving the formation of a chemical bond. Neutral species and (usually) anions are generally not strongly sorbed.
Category	Process
Relevance to Performance and Safety	Sorption and desorption may affect the degree to which radionuclides and other contaminants are mobilised within the EBS and adjacent geosphere, if they can leave a waste package. Sorption and desorption may influence the partitioning of radionuclides and other contaminants between the potentially mobile aqueous phase and immobile solid phases. Sorption and desorption may also influence the partitioning of radionuclides and other contaminants between aqueous species and colloids, which may also be present within the potentially mobile aqueous phase. Sorption and desorption may have an impact upon other processes that contribute to the mobilisation / retardation of radionuclides and other contaminants within the EBS and adjacent geosphere. Sorption and desorption may impact upon diffusion of the radionuclides and other contaminants. For example, sorption of these contaminants on the surfaces of solids within a fracture may limit the diffusion of the contaminants into the matrices of the materials bordering the fracture. The spatial distributions of radionuclides and other contaminants within the EBS and adjacent geosphere may be affected. This influence may then have implications for the subsequent mobilities of the radionuclides and other contaminants, and their resulting fluxes of out of the repository, should conditions change.
2000 List	3.2.03

- ***FEP 3.3.1.7: Colloid transport [repository]***

Description	The transport of colloids and interaction of contaminants with colloids migrating through the waste package under repository conditions. Colloids are particles with a maximum dimension typically less than 10 µm and are usually considered to have at least one dimension in the range 1 nm to 1 µm. Colloids are particles that can exist within a liquid without settling out.
Category	Event, Process
Relevance to Performance and Safety	The potential mobility of radionuclides and other contaminants within a waste package will be influenced by their partitioning between colloids and chemical species in solution, and between colloids and solid phases. Radionuclides or other contaminants may themselves form colloids (e.g. Pu(IV)), be incorporated chemically into the structures of colloids, or may sorb to the surfaces of colloids. In all these cases, the contaminants are transported with the colloids. If the colloids themselves are mobile, then migration of the associated radionuclides or other contaminants will be enhanced. Alternatively, if mobility of the colloids is restricted, for example by filtration as water passes through other materials in the waste package, then migration of the associated radionuclides or other contaminants will be diminished.

	Compared to radionuclides and other contaminants dissolved in water, radionuclides and other contaminants that are bound to or within the structures of the colloids may migrate more slowly or more quickly, depending upon the conditions. The concentrations of radionuclides and other contaminants in the water may exceed their solubility limits if they are bound to colloids, or located within the structures of colloids. In this case, movement of the water may result in enhanced migration of the radionuclides and other contaminants, compared to the migration rate that would be possible should these contaminants be dissolved. On the other hand, colloids are much larger than dissolved species and may be larger than the throats of pores in the repository materials. In this case, the migration rate of colloids through the repository may be retarded compared to the migration of dissolved species.
2000 List	3.2.04

- **FEP 3.3.2: Gas-mediated migration [repository]**

Description	The migration of contaminants in gas or vapour phase or as fine particulate or aerosol in gas or vapour through the repository.
Category	Event, Process
Relevance to Performance and Safety	Radionuclides and other contaminants may be transported through the EBS and adjacent geosphere due to gas movement. This transport may be either direct, the radionuclides and other contaminants being in gaseous form (e.g. C-14 labelled carbon dioxide or methane). Alternatively, the movement of gas may cause other radionuclide-bearing or contaminant-bearing phases to move by advection. For example, aerosols or solid particles to which radionuclides or other contaminants are bound may be transported with moving gas. Movement of gas may also push water, within which radionuclides or other contaminants are transported, either in solution or bound to / in colloids.
2000 List	3.1.04, 3.1.06, 3.2.09
Reference	[Ref. 85], [Ref. 86], [Ref. 111], [Ref. 112], [Ref. 216]

- **FEP 3.3.3: Solid-mediated migration [repository]**

Description	The migration of contaminants in solid phase from the repository.
Category	Event, Process
Comments	This might result from processes such as the fluvial erosion of the repository (FEP 1.2.8), the glacial erosion of the repository (FEP 1.3.5) or magmatic/volcanic activity affecting the repository (FEP 1.2.5).
Relevance to Performance and Safety	The pathways by which radionuclides and other contaminants might leave the repository, the fluxes attained, and their bioavailability could be influenced by solid-mediated transport. The solids may be particles of waste, if the waste packages are physically compromised. Alternatively, the solids may be particles of engineered barrier components that have previously been contaminated, for example by radionuclides and other contaminants that have been transported into the EBS by water or gas (assuming that this transport from a waste package is possible). Solid-mediated transport may occur in concert with some other transport mechanism. For example, small contaminated solid particles may be transported as dust within moving air, in the operational phase of a repository, or if the repository is exposed to the air in the post-closure period by uplift and erosion. Another example would be transport

	of contaminated solid particles from the repository to the surface as chippings in drilling fluids, should humans drill into the repository in future.
2000 List	3.2.08
References	[Ref. 29], [Ref. 130], [Ref. 236]

- **FEP 3.3.4: Human-action-mediated migration [repository]**

Description	The migration of contaminants from the repository as a direct result of human actions.
Category	Event, Process
Comments	This might result from processes such as drilling into or excavation of the repository (FEPs 1.4.5 and 1.4.6).
Relevance to Performance and Safety	The pathways by which radionuclides and other contaminants might leave the repository, the fluxes attained, and their bioavailability could be influenced by human-action-mediated transport. Human-action-mediated migration would operate in concert with other migration mechanisms (water-mediated migration, gas-mediated migration or solid-mediated migration). Potentially human actions might result in transport of radionuclides and other contaminants directly from the waste, if the human actions physically compromise waste packages. Alternatively, the human actions may transport solid components of the EBS, other engineered components (e.g. grouts), adjacent rock, or fluids contained within the EBS and geosphere (such as water, non-aqueous liquids or gases). If these solid and fluid phases have previously been contaminated by radionuclides or other contaminants originating in the wastes, then such human actions could also transport the contaminants.
2000 List	3.2.12
References	[Ref. 17], [Ref. 59], [Ref. 62], [Ref. 63], [Ref. 171], [Ref. 189], [Ref. 202]

- ## FEP 4: Geosphere factors

Description	The factors related to the geosphere mechanically undisturbed by the construction of the repository, the evolution of the geosphere and the associated migration of contaminants.
Category	FEP Group
2000 List	2.2, 3.1, 3.2
References	[Ref. 7], [Ref. 8], [Ref. 9]

FEP 4.1: Geosphere characteristics and properties

Description	The spatial, physical, chemical, biological characteristics and properties of the geosphere and their coupling prior to repository construction.
Category	FEP Subgroup
2000 List	2.2
References	[Ref. 7], [Ref. 8], [Ref. 9], [Ref. 22], [Ref. 23], [Ref. 170], [Ref. 185]

FEP 4.1.1: Configuration

Description	The succession and spatial extent of the rocks that form the geosphere. Typically rocks are divided into specified rock formations with similar properties and characteristics. These various geological formations help to isolate the repository from the surface environment. Consideration needs to be given to the vertical thickness and horizontal extent of each rock formation.
Category	Feature
Relevance to Performance and Safety	The succession and spatial extent of the rocks that form the geosphere will influence the geometry of any repository (e.g. the size of the repository may be limited by the vertical or lateral dimensions of the host rock formation), including access tunnels. There will also be an influence on the overall geomechanical properties of the geosphere and on whether deformation during the operational phase may cause or influence pathways for the transport of water, gas, radionuclides and other contaminants during the post-closure phase. The permeability / hydraulic conductivity distribution of the geosphere around the repository will also depend upon the succession and spatial extent of the surrounding rocks. There will be consequent effects on groundwater flows towards the repository during the operational phase, and on resaturation of the repository during the post-closure phase in those lithologies that have connected water capable of flowing. In the post-closure phase, the succession and spatial extent of the rocks around the repository will influence the geometries and transport / retardation characteristics of pathways through the geosphere, between the repository and the biosphere, through which there is flow of fluid (such as water, non-aqueous liquids or gases) and consequent transport of radionuclides may occur.
2000 List	2.2.02, 2.2.03
References	[Ref. 152], [Ref. 153], [Ref. 154], [Ref. 231], [Ref. 232], [Ref. 233]

- **FEP 4.1.2: Large-scale discontinuities**

Description	The properties and characteristics of discontinuities in and between the host rock and other geological units, including faults, ductile shear zones, intrusive dykes and interfaces between different rock types. "Large-scale" is not precisely defined but implies a length-scale comparable to the scale of the repository or larger. Depending upon the processes by which they formed, large-scale discontinuities could have any orientation. Furthermore, the orientation of a single large-scale discontinuity may change spatially. At the scale of a repository a large-scale discontinuity may be modelled as a planar feature, but in reality may be 3-dimensional, with one dimension orders of magnitude smaller than its other two dimensions. There could be considerable heterogeneity (e.g. variations in porosity and permeability) within the volume of such a large-scale discontinuity.
Category	Feature
Comments	Large-scale discontinuities (this FEP, 4.1.2) grade into small-scale discontinuities such as faults and joints, which are covered by FEP 4.1.6 (Hydraulic characteristics) and FEP 4.1.7 (Mechanical characteristics).
Relevance to Performance and Safety	Large-scale discontinuities such as unconformities, faults, ductile shear zones, and contacts at the margins of intrusive igneous bodies like dykes or larger intrusions, may influence the layout of the repository and / or the locations within it where wastes are emplaced. These discontinuities may also influence the effectiveness of the geosphere barrier in the post-closure period. Individual discontinuities may affect patterns of fluid flow (such as water, non-aqueous liquids or gases) through the geosphere. Potentially, in the post-closure period, the discontinuities may act either as pathways for the flow of these fluids, and hence for the transport of radionuclides and other contaminants that originate in the repository. Alternatively, discontinuities may act as barriers to the flow of these fluids. Certain properties of these discontinuities, such as the porosity distribution and the mineralogy of the rocks along them, will influence the retardation of radionuclides and other contaminants that might be transported along them. Some of these features might focus contaminant releases into the biosphere at discharge locations.
2000 List	2.2.04

- **FEP 4.1.3: Geological resources**

Description	The resources within the geosphere, particularly those that might encourage investigation or excavation at or near the repository site. Included are natural resources such as oil, gas, solid minerals, water and geothermal resources. Can also include the presence of suitable rocks for the storage of gases by humans for subsequent use (e.g. natural gas) or sequestration (e.g. carbon dioxide). In this case, the natural porosity within a rock formation may be considered a resource.
Category	Feature
Relevance to Performance and Safety	Geological resources near a repository may provide an incentive for people to undertake disruptive activities in or near the repository following repository closure. Such activities might include borehole drilling or mining, extraction of groundwater or other fluids (gas, liquid hydrocarbons), and storage or disposal of materials such as carbon dioxide. Potentially, these activities could compromise the effectiveness of the geosphere barrier around the repository, by creating new pathways for the migration of fluids transporting radionuclides and other contaminants that originate in the repository, or by disturbing existing pathways by which fluids (such as liquid water, non-aqueous liquids or gases) may flow.

	If the repository itself is intruded, or impacted directly by nearby activities (e.g. cyclical groundwater pressure changes due to storage and extraction of natural gas), the effectiveness of the EBS could be impacted. Certain kinds of resource, such as potable groundwater or natural gas, could directly transport radionuclides or other contaminants originating in the repository through the geosphere.
2000 List	2.2.13

- **FEP 4.1.4: Undetected features**

Description	The natural or man-made features within the geosphere that may not be detected during the site investigation (e.g. fracture zones, faults, brine pockets, old mine workings and boreholes). The nature of the geological environment will indicate the likelihood that certain types of undetected features may be present and the site investigation may be able to place bounds on the maximum size or minimum proximity to such features.
Category	Feature
Relevance to Performance and Safety	Depending upon their characteristics, undetected features could be either beneficial or detrimental with respect to long-term performance and safety in the post-closure period. Features that are undetected prior to repository construction may cause design changes to be made to the repository. Certain undetected features could act as pathways via which fluids (such as water, non-aqueous liquids or gases) could flow through the geosphere, potentially transporting radionuclides and other contaminants originating in the repository. Other kinds of undetected feature could act to prevent or retard the flow of these fluids, and radionuclides or other contaminants carried by the fluids. For example, faults and fracture zones may, depending upon their specific properties, behave either as fluid flow conduits or barriers. Depending upon their properties, those undetected features that could act as conduits for fluids may retard the migration of radionuclides and other contaminants. For example, the natures of the minerals that line undetected faults will influence the extent to which radionuclides may be retarded by sorption.
2000 List	2.2.12

- **FEP 4.1.5: Geothermal characteristics and properties**

Description	The geothermal characteristics and properties of the geosphere prior to repository construction, including the temperature at repository level, the thermal conductivity and heat capacity of the various rock formations.
Category	Feature
Relevance to Performance and Safety	Geothermal characteristics and properties of the geosphere prior to repository construction will influence the subsequent thermal evolution of the geosphere, during repository construction, operation and later, post-closure. These characteristics and properties have the potential to influence the effectiveness of both the EBS and the geosphere barrier. The thermal properties of the geosphere will affect the temperature evolution of the repository, in particular of heat dissipation during the thermal phase of heat-emitting wastes. This also affects repository design (e.g. spacing of waste packages) and also pertains to alteration rates of EBS materials (e.g. illitisation of bentonite). The temperature and thermal properties of the geosphere will influence the nature and rates of fluid-solid reactions within the EBS and geosphere. These reactions will affect the partitioning between mobile and immobile phases of radionuclides and other contaminants that originate in the repository. Rates and patterns of fluid flow from the

	repository through the geosphere will depend in part upon the temperature gradients that occur, since the density of any mobile fluid phase (such as liquid water, non-aqueous liquid or gas) will be affected by temperature. Hence, the thermal characteristics and properties of the geosphere have the potential to influence the migration patterns and migration rates of radionuclides and other contaminants that originate in a repository. The geothermal characteristics and properties of the geosphere will also influence how the temperatures of the rock-water system evolves in response to external influences such as glaciation.
2000 List	2.2.10

- **FEP 4.1.6: Hydraulic characteristics and properties**

Description	The hydraulic and hydrogeological characteristics and properties of the geosphere prior to repository construction. Included are characteristics and properties such as the hydraulic conductivity, fracture frequency and connectivity, porosity, tortuosity and pore water pressure of the various rock formations.
Category	Feature
Relevance to Performance and Safety	Hydraulic characteristics and properties of the geosphere prior to repository construction will influence the subsequent hydrogeological evolution of the geosphere during repository construction, during operation and later, post-closure. These hydraulic characteristics and properties may influence the effectiveness of both the EBS and the geosphere barrier. The rate at which groundwater flows through the EBS will depend partly upon the geosphere's hydraulic characteristics and properties. This rate of groundwater flow will influence the rate of resaturation of the repository following closure and the rate at which the properties of EBS components evolve (since this evolution depends in part on the supply of solutes and / or water). The hydraulic characteristics and properties of the geosphere influence the directions and rates of groundwater flow and hence the nature of the pathways for transportation of radionuclides and other contaminants in the aqueous phase in the post-closure period. There may also be an influence on the migration of other fluids (such as non-aqueous liquids and gases), where these are driven by movement of water. These hydraulic and hydrogeological characteristics and properties may influence the retardation of radionuclides and other contaminants originating in the repository during future transport from the repository through the geosphere. This influence may be direct in the cases of radionuclides and other contaminants that are transported in water. For example, in fractured crystalline rocks, the connectivity between fractures and matrix pores in their walls will influence the retardation by rock matrix diffusion.
2000 List	2.2.07

- **FEP 4.1.7: Mechanical characteristics and properties**

Description	The mechanical characteristics and properties of the geosphere prior to repository construction. Included are properties such as the stress regime and compressive and shear strength of the various rock formations.
Category	Feature
Relevance to Performance and Safety	Mechanical characteristics and properties of the prior to repository construction will influence the subsequent mechanical evolution of the geosphere during repository construction, during operation, and later, post-closure. These mechanical characteristics and properties may influence the effectiveness of both the engineered barrier system (EBS) and the geosphere barrier. The stress regime and mechanical characteristics

	(including, among others, uniaxial compressive strength, tensile strength, shear strength, Young's Modulus, Poisson's ratio and the anisotropy of these parameters) of the geosphere will influence the design of the repository and the ease with which it can be constructed. In the operational period, these characteristics and properties will influence the evolution of void spaces and the measures that need to be taken to ensure a safe environment within which wastes and EBS components can be emplaced. They also determine the evolution of the EDZ over time. In the post-closure period, mechanical characteristics and properties of the geosphere will influence the rate at which residual porosity in the repository is lost and the stresses on EBS components and waste containers. These factors will influence in turn whether the canisters and EBS components fail and the timing of any such failure that occurs. The mechanical characteristics and properties of the geosphere will affect the responses of the geosphere to loading (e.g. by ice sheets) and unloading (e.g. by uplift accompanied by erosion) and tectonic movements, including those due to earthquakes. These responses may include the development of forces driving the migration of fluids (such as water, non-aqueous liquids or gases) from the repository, and the development of migration pathways for these fluids and any radionuclides or other contaminants originating in the repository that these fluids may carry.
2000 List	2.2.06

- **FEP 4.1.8: Geochemical characteristics and properties**

Description	The geochemical characteristics and properties of the geosphere prior to repository construction. These characteristics and properties include rock mineral composition, ground- and porewater composition (in particular pH and redox conditions), salinity and chemical gradients.
Category	Feature
Relevance to Performance and Safety	Geochemical characteristics and properties of the geosphere prior to repository construction will influence the subsequent geochemical evolution of the geosphere, during repository construction, during operation, and later, post-closure. Geochemical characteristics and properties, including both of the fluid phase (such as liquid water, non-aqueous liquids or gases) and of rocks, may influence the effectiveness of both the EBS and the geosphere barrier. These characteristics and properties will influence the rates and nature of reactions in the EBS and in the geosphere. The chemical characteristics of groundwater also determine the solubility and speciation of dissolved contaminants. pH, Eh and concentrations of Cl- and S_2- in groundwater may affect the rate of steel corrosion. The concentrations of SO^{2-} and Cl- in groundwater may influence the degradation pathway of cementitious barriers, and the cation concentrations in groundwater may influence cation exchange reactions involving clay barriers and affect the swelling pressure of bentonite. The chemical characteristics and properties of rocks will influence the chemical evolution of the fluid phase present within them. For example, the redox buffering capacity of the rocks will influence the depth to which infiltrating oxidising water can penetrate. The chemistry of the rocks, minerals they contain and fluid phase within the pore space will influence the partitioning of solutes between the solid and fluid phases. These solutes may include radionuclides and other contaminants originating in the repository.
2000 List	2.2.08

- **FEP 4.1.9: Biological characteristics and properties**

Description	The biological characteristics and properties of the geosphere prior to repository construction. Included are biological characteristics and properties such as the extent and composition of microbe populations. Potentially, more complex organisms could occur

	in the deep sub-surface. For example, nematode worms have been found in deep (>1 km) South African gold mines.
Category	Feature
Relevance to Performance and Safety	Biological characteristics and properties of the geosphere, prior to repository construction, will influence the subsequent biological evolution of the geosphere, during repository construction, during repository operation, and later, post-closure. The biological characteristics and properties of the geosphere, including those of rocks and the fluid phase (such as water, non-aqueous liquids or gases), may influence the effectiveness of the EBS and the geosphere barrier. Chemical conditions in the geosphere may be influenced by microbially mediated chemical reactions. Examples include SO_4 reduction and methanogenesis. Potentially, certain of these reactions may impact upon the performance of some engineered barriers. For example, consideration may need to be given to the possibility that microbially mediated corrosion may occur. By influencing chemical conditions, biological characteristics and properties of the geosphere may impact upon partitioning between the solid and fluid phases of radionuclides and other contaminants that originate within the repository.
2000 List	2.2.09

FEP 4.2: Geosphere processes

Description	The processes occurring within the geosphere resulting in its evolution.
Category	FEP Subgroup
2000 List	2.2
References	[Ref. 6], [Ref. 21], [Ref. 169], [Ref. 170], [Ref. 184], [Ref. 185], [Ref. 186], [Ref. 187]

FEP 4.2.1: Thermal processes [geosphere]

Description	The thermal processes that affect the host rock and other rock units, and the overall thermal evolution of the geosphere. Included is heat transfer due to natural gradients in temperature. Thermal processes include thermal expansion and contraction and consequent changes in densities of solid and fluids in the geosphere.
Category	Event, Process
Comments	Geosphere thermal processes (this FEP 4.2.1) are those that arise from natural heat flow. They are distinct from internal thermal processes that arise from processes within the repository, such as radiogenic heat generation, which is covered by FEP 3.2.1 (Thermal processes [repository]).
Relevance to Performance and Safety	The thermal processes that affect the host rock and other rock units, and the overall thermal evolution of the geosphere will influence the temperature gradients that develop in and around the repository during operation and later, in the post-closure period. Thermal processes have the potential to influence the effectiveness of both the EBS and the geosphere barrier. The mechanical properties of the EBS and geosphere barrier depend partly on temperature. Chemical reactions that affect EBS components, the repository host rock and surrounding rocks, and the fluids present (such as liquid water, non-aqueous liquids or gases) are temperature-dependent. Thermal gradients will influence fluid density gradients and fluid viscosity, thereby affecting fluxes and flow patterns of fluid (such as water, non-aqueous liquids or gases). Fluid- and solid-phase transitions may also occur due to changing temperature. For example, as temperature changes along a flow path the proportions of water and any gaseous phase present may

	vary. Partitioning of radionuclides and other contaminants originating in the repository between mobile and immobile phases will depend partly upon temperature.
2000 List	2.2.10

- **FEP 4.2.2: Hydraulic processes [geosphere]**

Description	The hydraulic/hydrogeological processes that affect the host rock and other rock units, and the overall hydraulic/hydrogeological evolution of the geosphere. Included are groundwater flow and temporal changes in fluxes and flow patterns. Also included are temporal changes in hydraulic properties of the rock.
Category	Event, Process
Relevance to Performance and Safety	Hydraulic processes in the geosphere will influence the evolution of groundwater flow directions and fluxes through the repository and surrounding rocks during repository construction, during operation and later, post-closure. These hydraulic processes may influence the effectiveness of both the EBS and the geosphere barrier. The rate at which groundwater flows through the EBS will depend partly upon the geosphere's hydraulic characteristics and properties. This rate of groundwater flow will influence the rate of resaturation of the repository following closure and the rate at which the properties of EBS components evolve (since this evolution depends in part on the supply of water and / or solutes). Hydraulic processes may affect the nature of the pathways for transportation of radionuclides and other contaminants in the aqueous phase in the post-closure period. These hydraulic processes may also influence the retardation of radionuclides and other contaminants originating in the repository during future transport from the repository through the geosphere in the aqueous phase.
2000 List	2.2.07

- **FEP 4.2.3: Mechanical processes [geosphere]**

Description	The mechanical processes that affect the host rock and other rock units, and the overall mechanical evolution of the geosphere. Included are the effects of mechanical loads caused by, among other processes, tectonic movements, glacial loading and unloading, removal of rock by weathering and erosion, or loading by sedimentation. Also included are loads imposed by repository components on the surrounding geosphere (e.g. the effects of swelling of bentonite buffer materials on the adjacent geosphere).
Category	Event, Process
Comments	There is some overlap between the scope of FEP 4.2.3 (this FEP, Mechanical processes [geosphere] and FEP 4.2.1 (Thermal processes [geosphere]), 4.2.2 (Hydraulic processes [geosphere]), FEP 4.2.4 (Geochemical processes [geosphere]), FEP 4.2.5 (Biological processes [geosphere]) and FEP 4.2.6 (Radiological processes [geosphere]). FEPs 4.2.1 and 4.2.2, and FEPs 4.2.4 to 4.2.6 may all result in variations in mechanical loads on materials within the geosphere. Mechanical processes (this FEP, 4.2.3) covers the mechanical effects of the loads that are caused by the processes covered by these other FEPs.
Relevance to Performance and Safety	Mechanical processes in the geosphere may influence the effectiveness of both the EBS and the geosphere barrier. These processes may be of short duration, for example fault movement during an earthquake, or of long duration, such as gradual loading and unloading during cycles of glaciation and deglaciation. During construction and operation of the repository, the stresses in the geosphere and consequent deformation will influence the characteristics of the disturbed zone that develops around the

	repository, which may influence migration of radionuclides and other contaminants after repository closure (if there are pathways through the EBS). During operations and in the post-closure period, stresses in the geosphere around the repository will influence the stresses on the EBS components and potentially their deformation. Such deformation may affect the integrity of barrier materials and / or the volume and distribution of void space in the repository. The rate of repository resaturation may be affected, as might the development of gas pressures within the void space. Stresses in the geosphere will also influence the deformation of the geosphere. This may cause changes in porosity/porosity distribution and consequent changes in pressure head gradients. These effects may in turn drive movement of fluid (such as water, non-aqueous liquids or gases) through the geosphere. The change in porosity due to deformation, for example along faults, may influence the directions and characteristics of pathways along which radionuclides and other contaminants might migrate from the repository, through the geosphere. Certain mechanical processes, such as cataclasis along moving fault planes, could potentially change the ability of the rock to retard these radionuclides and other contaminants. Potentially, certain mechanical processes could lead to changes in the proportions of different fluid phases (such as water, non-aqueous liquids or gases) present. For example, in some locations sudden depressurisation, as might occur transiently in an earthquake, could lead to evolution of a separate gas phases, such as CO_2 or CH_4. Such effects could influence the partitioning of radionuclides and other contaminants among different phases.
2000 List	2.2.06

- **FEP 4.2.4: Chemical processes [geosphere]**

Description	The geochemical processes that affect the host rock and other rock units, and the overall geochemical evolution of the geosphere. Included, are changes in the chemistry of recharge water (e.g. due to glaciation / deglaciation introducing fresh meltwater into the sub-surface), chemical variations in groundwater due to mixing between chemically distinct groundwater bodies, mixing or chemical reactions between different fluid phases (e.g. between liquid water and organic gases) and chemical reactions between fluid phases, including liquid water, and minerals in the rock.
Category	Event, Process
Relevance to Performance and Safety	Geochemical processes in the geosphere may influence the effectiveness of both the EBS and the geosphere barrier. Chemical processes in the geosphere will affect the chemical conditions in and around the EBS and the evolution of the EBS components. For example, carbonation of cementitious barriers will be influenced by the dissolved carbonate content of groundwater flowing through / around the repository. Dissolution of salt rock by groundwater can reduce the host rock thickness. Chemical processes within the geosphere will affect the chemical conditions around the waste forms should there be pathways through the EBS for fluids and solutes to enter the repository from the geosphere. In this case there will be a consequent impact upon the release rates of radionuclides and other contaminants from the waste, and the chemical forms in which the release occurs. Chemical reactions between rocks and fluids that contact them (such as water, non-aqueous liquids or gases) may influence both the chemical and solid phase (mineralogical) composition of the rock, and the chemical composition of the water. These chemical reactions may also influence the proportions of different fluid phases present. Chemical reactions among different fluid phases (e.g. exsolution or dissolution of gas) may also influence the chemical composition of the fluid phase and the reactions between the fluid and EBS components or rocks (e.g. CO_2 exsolution may lead to an increase in pH of the water and precipitation of carbonate minerals). These processes will affect the partitioning of radionuclides and other contaminants between the mobile fluid phase and immobile solid phase. Chemical buffering reactions within the geosphere barrier will affect the stability of chemical conditions in the sub-surface, including the environment immediately around the repository and further afield. For example, the

	redox buffering capacity of the rocks will influence the depth to which infiltrating oxidising water can penetrate.
2000 List	2.2.08

- **FEP 4.2.5: Biological processes [geosphere]**

Description	The biological/biochemical processes that affect the host rock and other rock units, and the overall biological/biochemical evolution of the geosphere. Included are the effects of changes in conditions, e.g. on microbe populations, due to the long-term presence of the repository.
Category	Event, Process
Relevance to Performance and Safety	Biological processes in the geosphere during repository construction, during repository operation, and later, post-closure, may influence the effectiveness of the EBS and the geosphere barrier. Many of the chemical reactions that may influence chemical conditions in the geosphere, and consequently in the repository, are mediated by micro-organisms. Microbes that enter the repository (e.g. carried by inflowing groundwater) may participate in chemical reactions by which the EBS evolves (e.g. microbiologically influenced corrosion). Should the EBS system have pathways for mass transport between the repository and the geosphere, micro-organisms could potentially participate in the release of radionuclides and other contaminants from wastes and could influence the forms in which such releases occur. For example, micro-organisms could participate in breaking down organic waste forms. By influencing chemical conditions biological processes in the geosphere may impact upon partitioning of radionuclides and other contaminants between mobile fluid phases and immobile solid phases.
2000 List	2.2.09

- **FEP 4.2.6: Radiological processes [geosphere]**

Description	The effects of radiation emitted from the repository on the host rock immediately surrounding repository, and the overall radiogenic evolution of the geosphere.
Category	Event, Process
Relevance to Performance and Safety	Certain radionuclides that migrate from the repository, should there be transport pathways through the EBS, may exchange with other isotopes of the same element occurring naturally in the geosphere. Such exchange may impact upon radiological risk. For example, should U-235 that is transported in water from the repository will exchange with U-238 in the rocks, causing the overall radioactivity of mobile uranium to decrease along the transport pathway. Radionuclide decay and ingrowth of radioactive daughter isotopes within the rock may impact upon long-term safety. Radionuclides that are transported from the repository in a mobile fluid phase (such as liquid water, non-aqueous liquids or gases) may be transported into the rock matrix by diffusion and there trapped within immobile porewater or be immobilised on / in solid phases by processes such as sorption and co-precipitation. Thereafter, radioactive decay of radionuclides in the rock could lead to the ingrowth of radioactive daughter isotopes. Later, parent and daughter isotopes may be transported to the biosphere, for example if conditions change causing the isotopes to partition into a mobile fluid phase, or by uplift and erosion. The possibility that processes in the geosphere might lead to concentration of radionuclides sufficient to produce criticality may need to be considered.

	Consideration may also need to be given to natural background radiation, including the component due to natural radon gas, as a basis for comparison with the effects of radionuclides that may leave the repository. The direct effects of radiation emitted from the repository on the host rock immediately surrounding repository, such as radiolysis of porewater, are expected to be limited to the rock immediately surrounding the repository, if they occur at all.
2000 List	2.1.13

FEP 4.3: Contaminant migration [geosphere]

Description	The processes that directly affect the migration of contaminants in the geosphere.
Category	FEP Subgroup
2000 List	3.2
References	[Ref. 13], [Ref. 24], [Ref. 25], [Ref. 26], [Ref. 27], [Ref. 169]

FEP 4.3.1: Water-mediated migration [geosphere]

Description	The processes related to migration of contaminants within the geosphere in the aqueous phase (including dissolved gases).
Category	Event, Process
Relevance to Performance and Safety	Water-mediated migration may influence the rates at which radionuclides and other contaminants are transported through the geosphere from a repository and the pathways follows (if release of radionuclides and other contaminants through the EBS is possible). Such migration will affect the potential for the biosphere to be exposed to these radionuclides and other contaminants, and the doses of radionuclides and other contaminants received by biosphere receptors. The nature of the receptors and the doses will depend in part on the orientations of the migration pathways, the groundwater fluxes attained, hydrodynamic dispersion, and partitioning of radionuclides and other contaminants between the water and solid and gaseous phases.
2000 List	3.2.07

FEP 4.3.1.1: Advection [geosphere]

Description	The migration of dissolved contaminants by the bulk flow of the water through the geosphere. The rate of advection will vary depending on hydraulic, thermal and density conditions in the geosphere and repository. Fluid flow driven by temperature, chemical or electrical gradients, rather than due to hydraulic head gradients is called thermal, chemical or electrical osmosis depending on the driving gradient.
Category	Event, Process
Relevance to Performance and Safety	Bulk flow of water through the geosphere may transport radionuclides and other contaminants from the repository (if there are pathways through the engineered EBS). Advection will be accompanied by dispersion, which will act to diminish the concentrations of radionuclides and other contaminants dissolved in the water. The direction and rate of advection will influence whether radionuclides and other contaminants are transported from the repository to the biosphere within the assessment period. Should this occur, the rate of advection and the magnitude of accompanying

	dispersion will influence the temporal variation in doses received by biological receptors.
2000 List	3.2.07

- ***FEP 4.3.1.2: Dispersion [geosphere]***

Description	The spread in the spatial distribution of contaminants with time in the geosphere because of differential rates of advective transport through the geosphere. Variations in water velocity and pathways cause dispersion, i.e. the spatial spreading of solutes from advective transport. Dispersion can occur in the direction of flow (longitudinal dispersion) and perpendicular to the direction of flow (transverse dispersion).
Category	Event, Process
Relevance to Performance and Safety	Should the EBS of a repository has pathways through it through which radionuclides and other contaminants can leave the repository, dispersion will tend to decrease aqueous concentrations of released radionuclides and other contaminants along groundwater flow paths through the geosphere. Thus, dispersion in the geosphere has the potential to diminish the dose rates to biological receptors, should the flowing groundwater transport radionuclides and other contaminants from the repository to the biosphere. On the other hand, dispersion will tend to increase the volume of water that contains radionuclides and other contaminants originating in the repository.
2000 List	3.2.07

- ***FEP 4.3.1.3: Diffusion [geosphere]***

Description	The diffusion of contaminants through the geosphere. Diffusive migration is driven by chemical potential gradients, can be affected by thermal gradients, and can be in any direction. Diffusion can be the most important migration mechanism in situations where groundwater flow in the geosphere is very slow.
Category	Event, Process
Relevance to Performance and Safety	Given sufficient time, diffusion could transport radionuclides and other contaminants through all or part of the distance between the repository and the biosphere. Possibly, diffusion could transport radionuclides and other contaminants through a low-permeability host rock, into a higher-permeability overlying or adjacent rock formation, through which water is able to flow and result in radionuclide and contaminant by advection.
2000 List	3.2.07

- ***FEP 4.3.1.4: Matrix diffusion***

Description	The diffusion of contaminants between a permeable fracture and the network of microfractures and micropores within the adjacent rock matrix. Diffusion is driven by a chemical potential (approximately concentration) gradient between water in the fracture and free water in the rock matrix. Matrix diffusion can operate into / from the rock matrix depending upon the direction of the chemical gradient.
Category	Event, Process

Relevance to Performance and Safety	Diffusive transport between groundwater flowing through fractures and porewater in lower permeability wall rocks could affect the rate at which radionuclides and other contaminants migrate from the repository through the geosphere (if radionuclides and other contaminants can travel through the EBS). The migration of radionuclides and other contaminants will be retarded by their diffusion into the rock matrix from a fracture. If environmental conditions change, leading to changed chemical gradients between the water flowing in the fractures and the porewater in the rock matrix, radionuclides that have previously diffused into the rock matrix may diffuse out again and then be transported in the groundwater flowing in the fracture. Radioactive isotopes that have ingrown within the rock matrix may diffuse from the rock matrix into the flowing groundwater in the fracture. Similarly, diffusive transfers between water flowing in a fracture and porewater in the rock matrix may cause the exchange of certain isotopes originating in the repository with different naturally occurring isotopes of the same element. For example, by this mechanism U-235 originating in the repository may exchange with natural U-238 in the rock. This process would change the overall radioactivity of the U being transported in the water in the fracture.
2000 List	3.2.07

- ***FEP 4.3.1.5: Dissolution, precipitation, and crystallisation [geosphere]***

Description	The dissolution, precipitation and crystallisation of contaminants in the geosphere under prevailing geosphere conditions.
Category	Event, Process
Comments	Dissolution is the process by which constituents of a solid, non-aqueous liquid or gas dissolve into liquid water. Precipitation occurs when chemical species in solution produce a solid and are thereby removed from the solution. Changes in water chemistry, such as may occur when chemically distinct solutions mix, when a solution reacts with a solid phase assemblage, or when gases exsolve, may cause precipitation or dissolution. Temperature or pressure changes may also cause precipitation or dissolution. Crystallisation is the precipitation of a crystalline solid phase. Solids that are initially precipitated from an aqueous solution may be amorphous or poorly crystalline and then subsequently become more crystalline as they age.
Relevance to Performance and Safety	Solid phases that precipitate from water may incorporate radionuclides or other contaminants that have been transported from the repository in the water (if their transport through the EBS is possible). In this way, the radionuclides and other contaminants may be immobilised. In principle, pure phases of the contaminants may possibly precipitate if the chemical conditions are suitable. However, because the contaminants will almost certainly have very low concentrations in the water, it is more likely that they will comprise minor / trace constituents of the solid phase (i.e. co-precipitate with major constituents). Dissolution of solid phases that have previously precipitated from water carrying radionuclides and other contaminants from a repository, may release these contaminants back to water, thereby remobilising them. Dissolution of a gas phase by a coexisting aqueous phase may also change the mobility of radionuclides or other contaminants that are transported from the repository in gaseous form. For example, C-14 labelled CO_2 in a buoyant gaseous phase may dissolve in a coexisting aqueous phase, which may be less mobile owing to being less buoyant. Dissolution of a non-aqueous liquid in coexisting water may have a similar effect. Changes in the crystallinity of a solid phase may influence the partitioning of radionuclides and other contaminants between the solid phase and any coexisting fluid phase. For example, over time, poorly crystalline Fe-oxyhydroxides that precipitate from

	groundwater may transform to more crystalline Fe-oxyhydroxide phases. As this process occurs, radionuclides and other contaminants that are migrating in the aqueous phase may sorb to the Fe-oxyhydroxides less effectively.
2000 List	3.2.01

- ***FEP 4.3.1.6: Speciation and solubility [geosphere]***

Description	The chemical speciation and solubility processes affecting contaminant migration through the geosphere under the prevailing geosphere conditions. The concentration of an element in aqueous solution at equilibrium with a coexisting solid reflects the solubility of the solid. Factors such as temperature, gas partial pressure, ionic strength, the presence of complexing agents and pH and redox conditions affect solubility. These factors affect the chemical form and speciation of the element. Thus different solids of the same element may have different solubilities in a particular solution.
Category	Event, Process
Relevance to Performance and Safety	The chemical speciation and solubility of radionuclides and other contaminants that originate in a repository (if their transport through the EBS is possible), will influence their partitioning between immobile solid phases and a coexisting, potentially mobile aqueous phase. Retardation of radionuclides and other contaminants by sorption will depend upon their chemical speciation within the aqueous phase and upon the surfaces of solid phases (surface complexes). The chemical speciation of these contaminants will also affect their ability to bind to potentially mobile colloids within the aqueous phase. The nature and chemical speciation of aqueous solutes other than radionuclides and contaminants will influence the concentration of species that may form complexes with the radionuclides and other contaminants. Complexation may in turn influence the partitioning of the radionuclides and other contaminants between immobile solid phases and a coexisting, potentially mobile aqueous phases. At equilibrium, the aqueous solubility of a solid phase containing a radionuclide or other contaminant will control the maximum aqueous concentration of the radionuclide or other contaminant. The aqueous solubility of solid phases that do not necessarily contain radionuclides or other contaminants may nevertheless influence the pH and Eh, and the nature and concentrations of solutes in coexisting water. These parameters may in turn influence the chemical speciation of the radionuclides and other contaminants.
2000 List	3.2.02. 3.2.05

- ***FEP 4.3.1.7: Sorption and desorption [geosphere]***

Description	The sorption/desorption processes affecting the migration of contaminants through the geosphere under prevailing geosphere conditions. Sorption describes the physico-chemical interaction where dissolved species adhere to a solid phase. Desorption is the opposite. Two sorption-desorption processes are commonly considered: ion-exchange processes involving an electrostatic or ionic attraction between charged dissolved species and oppositely charged surfaces; and chemisorption involving the formation of a chemical bond. Neutral species and (usually) anions are generally not strongly sorbed.
Category	Event, Process
Relevance to Performance and Safety	Sorption and desorption of radionuclides and other contaminants that originate in a repository (if they are transported through the EBS), will influence their partitioning between immobile solid phases and a coexisting, potentially mobile aqueous phase. The greater the degree of sorption of radionuclides and other contaminants, the greater will

	be the degree to which their migration through the geosphere is retarded. Changing chemical conditions (pH, Eh, concentrations of ligands etc.) will influence the extent to which sorption occurs. Radionuclides or other contaminants that sorb strongly under a particular set of prevailing chemical conditions may desorb if the conditions change.
2000 List	3.2.03

- ***FEP 4.3.1.8: Colloid transport [geosphere]***

Description	The transport of colloids and interaction of contaminants with colloids migrating through the geosphere under prevailing geosphere conditions. Colloids are particles with a maximum dimension typically less than 10 µm and are usually considered to have at least one dimension in the range 1 nm to 1 µm. Colloids are particles that can exist within a liquid without settling out.
Category	Event, Process
Relevance to Performance and Safety	Colloidal transport of radionuclides and other contaminants that leave a repository (if their transport through the EBS is possible) may occur at a different rate to the transport of these contaminants in solution. Colloidal transport may also influence the pathways followed by the radionuclides and other contaminants. Colloids may be filtered by low-permeability media such as clays. Additionally, colloids may sorb to immobile solid surfaces, thus immobilising or retarding radionuclides or other contaminants that are in colloidal form or bound to colloids. If chemical conditions in the groundwater change, colloids may flocculate and sediment, thereby reducing the mobility of the radionuclides or other contaminants. Colloid transport may also influence the dispersion of radionuclides and other contaminants within flowing groundwater. The dispersivity of colloids depends not only on the pore sizes and geometries, but also on the sizes and charges of the colloids. Thus, the dispersion of radionuclides and other contaminants that are transported in colloidal form or bound to colloids will depend partly upon the sizes and size distributions of the colloids.
2000 List	3.2.04

- **FEP 4.3.2: Gas-mediated migration [geosphere]**

Description	The migration of contaminants in gas or vapour phase or as fine particulate or aerosol in gas or vapour through the geosphere.
Category	Event, Process
Relevance to Performance and Safety	Gas-mediated migration may influence the rates at which radionuclides and other contaminants are transported through the geosphere from a repository (if their transport through the EBS is possible) and the pathways followed. Gas migration may directly transport radionuclides and other contaminants occurring within the gas phase. Alternatively, gas migration may indirectly lead to the transport of radionuclides and other contaminants contained in other mobile phases the movement of which is gas-driven. Evolution of gas within the repository may cause a pressure gradient that drives radionuclides in gaseous form away from the repository, through the geosphere. Radionuclides and other contaminants that leave a repository in and aqueous phase, or in non-aqueous liquids, may subsequently partition into naturally occurring gas that is encountered along the flow path. Migration of the radionuclides and other contaminants in the gaseous phase may then be driven by pressure gradients affecting the gas.

	Density contrasts between a gas phase and other fluid phases present may affect the rates and directions of gas movement, and the consequent migration of radionuclides and other contaminants contained in the gas. The buoyancy of gas relative to water may cause radionuclides and other contaminants in gaseous form to migrate generally upwards. The effective permeability of the rock with respect to gas will depend upon the proportions of gas and other fluids (most likely groundwater, but potentially non-aqueous liquids) that coexist. Interactions between the gaseous phase and any other phases present may influence the partitioning of radionuclides and other contaminants between the gas and the other phases. For example, some gases are more soluble in water than others; under relevant conditions, CO_2 is more soluble in water than CH_4, so that C-14 in the form of CO_2 will tend to partition more into a coexisting aqueous phase than would C-14 in the form of CH_4. These interactions between gases and other phases (including the evolution of gas from other fluids or the dissolution of gas in these fluids) will depend on changes in pressure and / or temperature and / or chemical environment (e.g. pH, salinity) along a migration pathway. Gases may sorb on the surfaces of solid phases, thereby preventing or retarding the migration of radionuclides or other contaminants that are transported in gaseous form.
2000 List	3.2.09

- **FEP 4.3.3: Solid-mediated migration [geosphere]**

Description	The migration of contaminants in solid phase in the geosphere.
Category	Event, Process
Relevance to Performance and Safety	Solid-mediated migration may influence the rates at which radionuclides and other contaminants are transported through the geosphere from a repository (if there are pathways through the EBS) and the pathways followed. Such transport implies the existence of a sufficient driving force and that pathways are sufficiently large that solid particles can move through them. Solid-mediated migration might affect the dispersion of radionuclides and other contaminants. This influence will reflect the fact that different solid materials may form particles of different shapes and sizes while at the same time potentially transporting different contaminants. For example, some radionuclides may have a relatively great tendency to be incorporated into the structures of solid carbonate phases, whereas other radionuclides may have a relatively great tendency to sorb onto clay minerals. Solid carbonate particles and clay particles may show different transport behaviours. Radionuclides and other contaminants may partition between moving solid phases and other phases that are present. This partitioning will be affected by the pressure and temperature and chemical environment within which transport occurs.
2000 List	3.2.08

- **FEP 4.3.4: Human-action-mediated migration [geosphere]**

Description	The migration of contaminants from the geosphere as a direct result of human actions.
Category	Event, Process
Relevance to Performance and Safety	Human actions may lead to radionuclides and other contaminants being transported from the repository and / or from its surrounding geosphere (should the EBS have pathways through which contaminants leave the repository). The nature of the human actions will determine the pathways via which the radionuclides and other contaminants are

	transported, the rates at which this transport occurs, and the physico-chemical forms in which it occurs. For example, drilling a single exploratory borehole into a repository might transport radionuclides and other contaminants to the surface in a variety of phases (possibly a combination of solids, liquid water, non-aqueous liquids and gases). However, this transport is likely to be very localised (to the borehole and its immediate surroundings at the surface). In contrast, should the EBS have pathways through which radionuclides and other contaminants leave the repository, subsequent large-scale groundwater abstraction from multiple wells drilled near the repository, but to shallower depths, might transport predominantly contaminated groundwater to the surface over a relatively wide area. Human actions might result in changes to the partitioning of radionuclides and other contaminants among mobile and immobile phases, which might impact upon contaminant transport. For example, depressurisation of groundwater during sampling from a borehole might cause dissolved CO_2 to exsolve, with consequent partitioning of C-14 from aqueous carbonate to gaseous CO_2.
2000 List	3.2.12

• FEP 5: Biosphere factors

Description	The factors related to the biosphere (the surface environment, humans and non-human biota), the associated migration of contaminants and exposure pathways. Includes the geosphere-biosphere interface such as water abstraction wells, near-surface aquifers, and unconsolidated sediments, and groundwater discharge zones.
Category	FEP Group
2000 List	2.3, 2.4, 3.1, 3.2, 3.3
References	[Ref. 10], [Ref. 11]

○ FEP 5.1: Surface environment

Description	The features, events and processes within the surface environment and their potential future evolution.
Category	FEP Subgroup
2000 List	2.3
References	[Ref. 11], [Ref. 29], [Ref. 30], [Ref. 173], [Ref. 174], [Ref. 177], [Ref. 181]

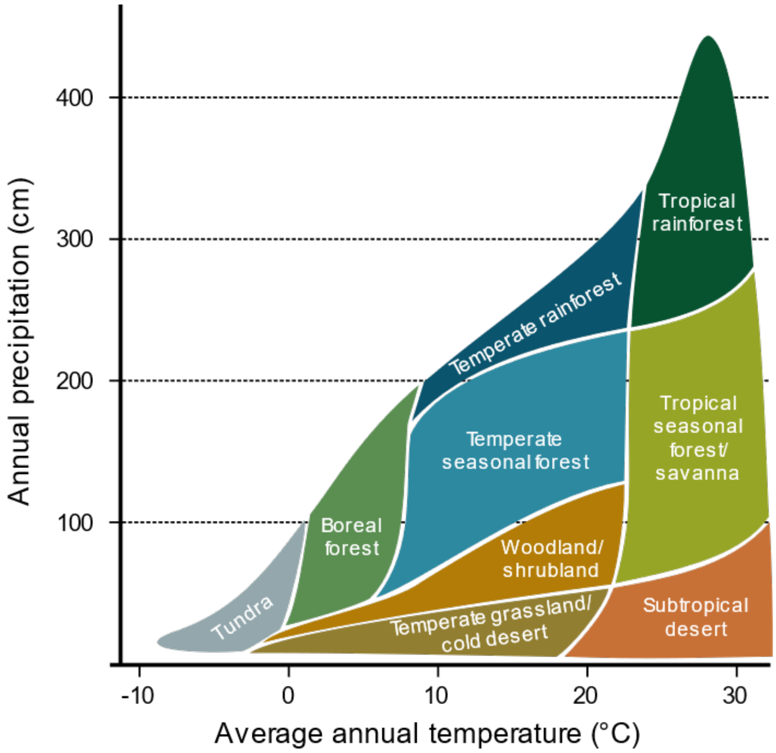
▪ FEP 5.1.1: Topography and morphology

Description	The relief and shape of the surface environment.
Category	Feature, Process
Comments	For this FEP, changes to the topography and morphology are limited to the relatively short-term, resulting from processes such as wind erosion and river meandering that could impact over a few centuries. Changes resulting from processes acting on a geological timescale, such as mountain building, are described under FEP 1.2 (Geological Factors). Other changes resulting from evolution of the climate (such as denudation and deposition from ice sheets) and human actions are discussed under FEP 1.3 (Climatic Factors) and FEP 1.4 (Future Human Actions).
Relevance to Performance and Safety	Topography and morphology will affect the surface and near-surface hydrology of the biosphere. This will impact upon the transport of contaminants that might migrate from the repository in the aqueous phase to the biosphere.
2000 List	2.3.01

▪ FEP 5.1.2: Biomes

Description	The mixed community of animals and plants (a biotic community) occupying a major geographical area (e.g. on a continental scale) and processes affecting their potential evolution. Figure 2 shows how precipitation and temperature determine the type of biome in a particular terrestrial location

Figure 2: Climate influence on terrestrial biome.



Source: Navarras.

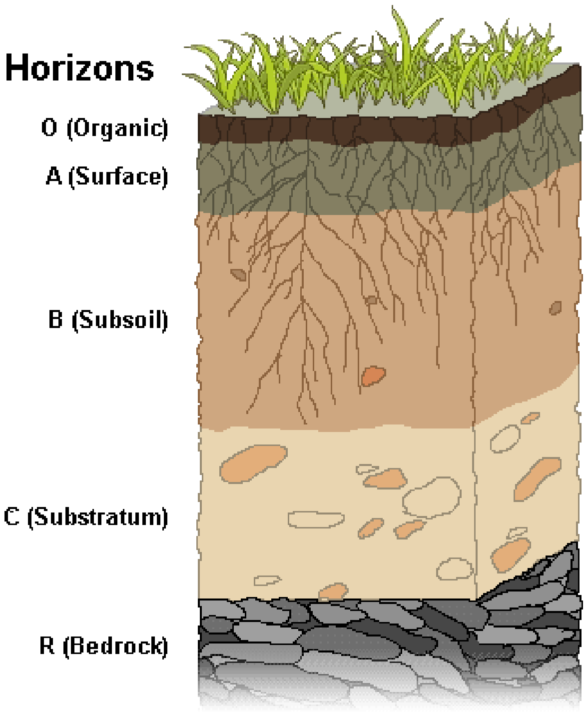
Category	Feature, Process
Comments	Each biome is characterised by similarity of vegetation structure or physiognomy rather than by similarity of species composition and is usually related to climate. Within a particular biome, the animals and plants are regarded as being well adapted to each other and to broadly similar environmental conditions, especially climate. Important factors influencing biome classification include temperature, precipitation, latitude and altitude. Anthropogenic activities may also influence the classification.
Relevance to Performance and Safety	The biome assumed will influence the habits and dietary intake of both humans and non-human biota living in that area.
2000 List	Not explicitly mentioned but related to 2.3.13
References	[Ref. 115]

- **FEP 5.1.3: Soils and sediments**

Description	The characteristics of the soils and sediments that overlie the rock of the geosphere.
Category	Feature, Process
Comments	The properties (including existence) of soils and sediments will evolve because of natural weathering processes (including hydration and dehydration, freeze-thaw cycles, dissolution and leaching, oxidation, acid hydrolysis and complexation), erosion (wind and water), and anthropogenic management practices (e.g. deforestation and dredging).

Relevance to Performance and Safety	Physical properties of soils and sediments, such as porosity and bulk density, will influence the volume of water which can pass through these environmental media. The chemical conditions in the soil and sediment will affect sorption characteristics of contaminants, and therefore affect contaminant transport and retardation. The chemical conditions will also affect the potential transformation of contaminant-bearing gases.
2000 List	2.3.02
References	[Ref. 115]

- ***FEP 5.1.3.1: Surface soils***

Description	The soils that are within a few metres of the land surface and typically underlain by unconsolidated overburden (see Figure 3) and the processes affecting their potential evolution. **Figure 3: Distinct layers of soil, formally described as "horizons"**  Source: Wilsonbiggs.
Category	Feature, Process
Comments	The soil type can be characterised by parameters such as particle-size distribution, inorganic and organic matter content. These will have different physical and chemical properties, different land management properties, and different contaminant migration properties. Microbial populations (or their absence) are an important component of soils. Typically, the top 0.2 to 0.3 m is the active surface soil region that contains the bulk of the plant roots, as well as being the region most directly affected by agricultural practices such as ploughing.

Relevance to Performance and Safety	Contaminants that might have migrated from the repository may become bound to the soil particles. Vegetation will receive a portion of their contamination via root uptake from surface soils. Both humans and non-human biota can be exposed directly to soil contamination via external exposure, and potentially inadvertent ingestion of soil, whilst spending time on top of or within the soil.
2000 List	2.3.02
References	[Ref. 115]

- ***FEP 5.1.3.2: Overburden***

Description	The unconsolidated material (e.g. sand, gravel, weathered sediments), excluding the surface soils, that overlies the rock of the geosphere and the processes affecting their potential evolution.
Category	Feature, Process
Comments	The transition from soil/sediment to overburden and from overburden to bedrock may not be abrupt. The overburden will change in time. These changes will be driven by the same processes affecting soils.
Relevance to Performance and Safety	As a surface natural rock feature, overburden is not suited to growing vegetation or animal grazing. Contaminants from the repository might migrate into the overburden. External exposure of humans and non-human biota due to time spent on the contaminated overburden is then possible.
2000 List	2.3.02
References	[Ref. 115]

- ***FEP 5.1.3.3: Aquatic sediments***

Description	The sediments formed by the deposition of particulates from surface water and the processes affecting their potential evolution.
Category	Feature, Process
Comments	Aquatic sediments are found at the bottom of surface water bodies and are generally composed of fine-grained sand, clays, gravel and organic material. They can be differentiated into upper sediments which can have higher biological activity and lower sediments that are covered by the upper sediments and are more compact. The former are subject to wave action and currents and can be eroded and reformed relatively easily. Sediments may eventually form surface soil when, for instance, a river changes its course or a lake dries up. They can be dredged for use as soil conditioners.
Relevance to Performance and Safety	Contaminants that might have migrated from the repository may become bound to aquatic sediments. Physical and chemical processes which affect the mobility of sediments, and their ability to retain contaminants, will influence the potential for exposure of aquatic biota and humans to contaminants bound to the sediments and contained in the water body overlying those sediments.
2000 List	2.3.02

- **FEP 5.1.4: Near-surface aquifers and water-bearing features**

Description	The aquifers and water-bearing features within a few tens of metres of the land surface and the processes affecting their potential evolution.
Category	Feature, Process
Comments	Aquifers are water-bearing features, geological units or near-surface deposits that yield significant amounts of water to rivers, wells or springs. The presence of aquifers and other water-bearing features will be determined by the geological, hydrological and climatic factors.
Relevance to Performance and Safety	Contaminants that might have migrated from the repository may be contained in the water in such features. The water in these contaminated features might be extracted directly and used for purposes such as crop irrigation, drinking water for humans and/or livestock, and bathing.
2000 List	2.3.03

- **FEP 5.1.5: Terrestrial surface water bodies**

Description	The characteristics of terrestrial surface water bodies, such as rivers, lakes, wetlands and springs, and the processes affecting their potential evolution.
Category	Feature, Process
Comments	Streams, rivers and lakes often act as boundaries on the hydrogeological system. They usually represent a significant source of dilution for materials (including contaminants) entering these systems, but in hot dry environments, where evaporation dominates, concentration is possible. Discharge points for groundwater are often found at the margin or base of surface-water bodies. Springs are also discharge points where the water table intersects the surface and groundwater flows out into the surface environment.
Relevance to Performance and Safety	Contaminants that might have migrated from the repository may be contained in the water in such features. The water in these contaminated features might be extracted directly and used for purposes such as crop irrigation, drinking water for humans and/or livestock, and bathing.
2000 List	2.3.04

- ***FEP 5.1.5.1: Wetlands***

Description	The land areas where the water table is at or near the surface and the processes affecting their potential evolution.
Category	Feature, Process
Comments	Wetlands (including marshes, fens and peat bogs) may be underlain by, or lead to formation of, thick deposits of organic material (e.g. peat). Wetlands may also be drained to provide agricultural land and excavated for peat which is then used as a fuel or soil supplement (FEP 1.4.8).
Relevance to Performance and Safety	Contaminants that might have migrated from the repository may be contained in the water, and the peat, found in wetlands. Contaminated peat may be used as fertiliser or drained to provide agricultural land, leading to indirect exposure to humans via uptake into crops or livestock. Peat may also be used as fuel, leading to exposure via inhalation.

	Further, both humans and non-human biota can be subject to external exposure as a result of time spent in wetlands, and internal exposure via indirect ingestion of wetland soil, and foods growing or grazing in the wetland environment.
2000 List	2.3.04

- ***FEP 5.1.5.2: Lakes and rivers***

Description	The surface water bodies, which are large enough to persist for many years, and the processes affecting their potential evolution.
Category	Feature, Process
Comments	Surface water bodies will evolve through a number of processes such as gradual infill, meandering and braiding. Lakes may also be drained to use their sediments for farming, or sediments might be dredged to enrich poor soils. Lakes can also undergo eutrophication and other geochemical changes (e.g. acidification), significantly affecting their ecology. Rivers can change their beds exposing sediments for farming or changing land-use options.
Relevance to Performance and Safety	Contaminants that might have migrated from the repository may be contained in the water in such features. The water in these contaminated features might be extracted directly and used for purposes such as crop irrigation, drinking water for humans and/or livestock, and bathing.
2000 List	2.3.04

- ***FEP 5.1.5.3: Spring and discharge zones***

Description	The locations where the water table intersects the surface, allowing groundwater to flow out onto the surface, and the processes affecting their potential evolution.
Category	Feature, Process
Comments	Springs may be found at various elevations depending on factors such as the lithology and stratigraphy of the geosphere and the location of outcropping geological units. Discharge zones are often low-lying areas such as at the margin or bottoms of lakes and wetlands (bogs and marshes). Spring and discharge zones can be affected by changes in the water table caused by local climate changes, human activities, or changes in topography.
Relevance to Performance and Safety	Contaminants that might have migrated from the repository may be contained in the water in such features. The water in these contaminated features might be extracted directly and used for purposes such as crop irrigation, drinking water for humans and/or livestock, and bathing.
2000 List	2.3.04

- **FEP 5.1.6: Coastal features**

Description	The characteristics of coasts and the near shore, and the processes affecting their potential evolution.
Category	Feature, Process

Comments	Coastal features include headlands, bays, beaches, spits, cliffs and estuaries. The processes operating on these features, e.g. active erosion, deposition, longshore transport, determine the development of the coastal system.
Relevance to Performance and Safety	Both humans and non-human biota can be subject to exposure from contamination that has migrated to coastal features from the repository. Exposure can be via external irradiation, and the consumption of foods available in contaminated coastal areas. Furthermore, water from contaminated coastal areas may be abstracted, desalinated and used for purposes such as crop irrigation, drinking water for humans and/or livestock, and bathing.
2000 List	2.3.05
References	[Ref. 116]

- **FEP 5.1.7: Marine features**

Description	The characteristics of seas and oceans, including the sea bed, and the processes affecting their potential evolution.
Category	Feature, Process
Comments	Marine features include oceans, ocean trenches, shallow seas, and inland seas. Processes operating on these features such as erosion, deposition, thermal stratification and salinity gradients, determine the behaviour and the development of the marine system.
Relevance to Performance and Safety	Both humans and non-human biota can be subject to exposure from contamination that has reached marine features from the repository. Exposure pathways include external exposure from immersion in the water, and consumption of foods produced in marine water. Furthermore, water from contaminated marine features may be abstracted, desalinated and used for purposes such as crop irrigation, drinking water for humans and/or livestock, and bathing.
2000 List	2.3.06
References	[Ref. 116]

- **FEP 5.1.8: Atmosphere**

Description	The characteristics of the atmosphere, including capacity for transport of contaminants, and the processes affecting their potential evolution.
Category	Feature, Process
Comments	The atmosphere may be divided into a near-surface layer, in which contaminants are subject to uptake by plants, and the wider atmosphere above the surface environment.
Relevance to Performance and Safety	Contaminants migrating from the repository may enter the atmosphere either in gaseous form, or in particulate form as a result of resuspension. Within the atmosphere there are several physical processes – transport of gases, aerosols and dust – as well as chemical and photochemical reactions, which will affect the concentration of contaminants in the atmosphere that humans and non-human biota are exposed to. All potential human activities, both indoors and outdoors, may give rise to exposures due to atmospheric concentrations of contaminants. These activities include inhalation of

	radioactive vapours as well as airborne particulates, external immersion, and the ingestion of deposited material also forms a potential exposure route.
2000 List	2.3.07
References	[Ref. 117]

- **FEP 5.1.9: Vegetation**

Description	The characteristics of terrestrial and aquatic vegetation, including algae and fungi, both as individual plants and in mass, and the processes affecting their potential evolution.
Category	Feature, Process
Relevance to Performance and Safety	Soil containing any repository-derived contaminants, and/or the use of water that contains any repository-derived contaminants, will lead to contaminated vegetation. For some contaminants, exposure from the atmosphere may be possible. Contaminated vegetation may be consumed by humans and non-human biota directly, may be consumed by livestock. It is also possible for humans to be exposed to contaminants contained in the vegetation via non-ingestion exposure pathways. These pathways include external and inhalation exposure following the use of vegetation in building materials, the use of compost (rotted vegetation) as a fertiliser for crops, and the burning of vegetation, either as a fuel or as part of farming practices.
2000 List	2.3.08

- **FEP 5.1.10: Animals**

Description	The characteristics of the terrestrial and aquatic animals both as individual animals and as populations, and the processes affecting their potential evolution.
Category	Feature, Process
Relevance to Performance and Safety	Animals could be subjected to exposure from contaminants in the biosphere in the same manner as humans (ingestion, inhalation, external exposure), where their food, water, soil and/or atmosphere contains repository-derived contaminants that might reach the biosphere. Humans may be exposed to contamination in animals either directly via ingestion of animal products (e.g. milk, lamb, eggs), or indirectly via physical contact, the use of animal excretions to fertilise crops, or as a building material.
2000 List	2.3.09

- **FEP 5.1.11: Climate and weather**

Description	The characteristics of weather and climate, and the processes affecting their potential evolution.
Category	Event, Process
Comments	Climate and weather are characterised by precipitation, temperature, pressure and wind speed and direction. Accounting for variability in these characteristics, extreme events such as drought, flooding, storms and snow melt are identified. In addition to long-term variations (FEPs 1.3.1 and 1.3.2), daily and seasonal variations can have a wide

	influence. For example, these variations affect irrigation requirements for agricultural crops, habitat for animal populations and the source of drinking water.
Relevance to Performance and Safety	Climate and weather will determine the availability and quality of surface water resources, and thus the demands of the local community on potential contaminated near-surface aquifers to extract water for irrigation, bathing and ingestion. Climatic conditions will also influence the nature of the crops that can grow. Climate and weather may influence other behaviours of both humans and non-human biota, such as time spent outdoors, and even diet. All these factors will influence the migration of and exposure to any repository-derived contaminants that might reach the biosphere.
2000 List	2.3.10
References	[Ref. 51], [Ref. 228]

- **FEP 5.1.12: Hydrological regime and water balance (near-surface)**

Description	The near-surface hydrology at a catchment scale and soil water balance, and the processes affecting its potential evolution.
Category	Feature, Process
Comments	The hydrological regime includes movement of water and consideration of extremes such as drought, flooding, storms and snow melt. Key components are run-off (precipitation water that flows laterally over the top of the soil into a water body), and interflow (precipitation water that flows laterally through the soil into a water body). They are important in determining the flushing rate of surface-water bodies and, together with precipitation and evapotranspiration, determine irrigation water needs.
Relevance to Performance and Safety	This FEP includes processes that are important in determining the flushing rate of surface-water bodies and, together with precipitation and evapotranspiration, determine irrigation water needs and therefore the migration of any repository-derived contaminants that might reach the biosphere.
2000 List	2.3.11

- **FEP 5.1.13: Erosion and deposition**

Description	The erosional and depositional events and processes that operate in the surface environment, and their potential evolution.
Category	Event, Process
Comments	Relevant events and processes include rock fall, landslides, fluvial and glacial erosion and deposition, denudation, aeolian erosion and deposition. These processes will be controlled by factors such as the climate, vegetation, topography and geomorphology.
Relevance to Performance and Safety	Repository-derived contaminants that might reach the biosphere and are bound to the soil/sediment will move due to erosion and deposition events and processes.
2000 List	2.3.12
References	[Ref. 229]

- **FEP 5.1.14: Ecological/biological/microbial systems**

Description	The relationships between populations of animals, plants and microbes.
Category	Event, Process
Comments	Characteristics of these systems include the vegetation regime, and natural cycles such as forest fires or flash floods that influence the development of the ecology. The animal and plant populations occupying the surface environment are an intrinsic component of its ecology. Their behaviour and population dynamics are regulated by the wide range of processes that define the ecological system. Human activities have significantly altered the natural ecology of most environments. Elements and minerals cycle through the biosphere between biotic and abiotic components, and from one organism to another. At a given location, the biotic components combine to form the ecological/biological/microbial system.
Relevance to Performance and Safety	Any repository-derived contaminants that might reach the biosphere, will enter these systems. They will influence the contaminant transfer pathways and the rate of transfer of contaminants from one system component to another.
2000 List	2.3.13

FEP 5.2: Human characteristics and behaviour

Description	The characteristics and habits of the human individuals or populations, who are potential receptors for any contaminants that are able to leave the repository and be transported through the geosphere to the near-surface environment, either by natural processes or due to human activities.
Category	FEP Subgroup
2000 List	2.4
References	[Ref. 10], [Ref. 31], [Ref. 173], [Ref. 174], [Ref. 181]

- **FEP 5.2.1: Physical characteristics**

Description	The ethnicity of humans, including metabolism, physiology, age, health state, gender and ethnicity.
Category	Feature
Comments	Humans vary in their metabolism (chemical and biochemical reactions that occur in connection with the production and use of energy) and physiology (body and organ form and function).
Relevance to Performance and Safety	This FEP relates to physical characteristics of humans that might affect their susceptibility to any repository-derived contaminants that might reach the biosphere. Susceptibility to contaminants varies with age, sex and reproductive status. Children and infants, although similar to adults, often have characteristic differences (e.g. respiratory rates, food types, ingestion of soil) that may lead to different exposure characteristics. In addition to the variation in individual humans, different groups might have a genetic tendency towards certain features that may affect their susceptibility to contaminants.
2000 List	2.4.01, 2.4.02

References	[Ref. 118], [Ref. 119]

- **FEP 5.2.2: Community characteristics**

Description	The characteristics, behaviour and lifestyle of groups of humans that might be considered as potential exposure groups (PEGs) in an assessment.
Category	Feature
Relevance to Performance and Safety	This FEP covers the characteristics of a whole community, which will impact upon individual behaviours and thus exposure mechanisms to any repository-derived contaminants that might reach the biosphere. The type and location of a community will affect both the dietary and fluid intake of individuals, and also the manner in which they prepare the food and fluids prior to consumption. Consideration of the community as a whole will also inform other behaviours, such as time spent outside and other non-consumption based habits.
2000 List	2.4.05

- ***FEP 5.2.2.1: Community type***

Description	The general nature and size of the community, and in particular their degree of self-sufficiency and their use of land and water.
Category	Feature, Process
Comments	A range of community types and associated behaviours can be considered including rural/agricultural, coastal, urban/industrial, and hunter-gatherer. Hunter/gathering describes a subsistence lifestyle employed by nomadic or semi-nomadic groups who roam relatively large areas of land hunting wild game and/or fish, and gathering native fruits, berries, roots and nuts, to obtain their dietary requirements.
Relevance to Performance and Safety	Each community type will have a particular set of behaviours, e.g. occupancy time of the exposed area, time spent indoors, diet, intake rates of food and fluids, and so could be exposed to any repository-derived contaminants via different pathways and at different rates.
2000 List	2.4.05, 2.4.08, 2.4.09, 2.4.10, 2.4.11

- ***FEP 5.2.2.2: Community location***

Description	The location of the community relative to areas which might be contaminated by any repository-derived contaminants that might reach the biosphere.
Category	Feature
Relevance to Performance and Safety	This FEP relates to the potential locations at which repository-derived contaminants might be released into the surface environment and the potential for humans to make use of the land for a range of activities such as food production and leisure activities and so impacts the contaminant exposure pathways considered.
2000 List	2.4.05, 2.4.08, 2.4.09, 2.4.10, 2.4.11

- ***FEP 5.2.2.3: Water source***

Description	The origin of water sources used by humans.
Category	Feature
Comments	Humans require water for domestic purposes (drinking, cooking, washing and bathing), irrigating gardens and large agricultural fields used for crops and forage, to provide drinking water for livestock, and to serve other purposes such as supply and maintenance of water for fish hatcheries or process water for industry. Different sources might be used for different purposes; for instance, water used for domestic purposes might derive from a dedicated water-supply well whereas water for irrigation may be taken from a nearby lake or from a different water-supply well. In addition, the volume of water required, and hence the type of water source will be affected by the size, lifestyle and occupations of the community, and additional sources might be required for a large community.
Relevance to Performance and Safety	The origin of the water source used by humans will directly affect their potential for exposure, noting that they may use multiple water sources, some of which may be contaminated with repository-derived contaminants, to meet their differing requirements.
2000 List	2.4.05, 2.4.08, 2.4.09, 2.4.10

- ***FEP 5.2.2.4: Dwellings***

Description	The houses or other structures of shelter in which humans spend time.
Category	Feature
Relevance to Performance and Safety	Materials used in the construction of human dwellings, the nature of their construction and their location are important factors in affecting potential human exposure to contaminants. Some of the materials used may be contaminated with repository-derived contaminants.
2000 List	2.4.07
References	[Ref. 120]

- **FEP 5.2.3: Diet and fluid intake**

Description	The intake of food and water by humans and the compositions and origin of intake.
Category	Feature, Process
Comments	The diet of humans can vary greatly, both qualitatively and quantitatively. Potential food types include vegetables and fruit (e.g. grains, legumes, cultivated and wild fruits and berries), terrestrial animal products (e.g. meat and milk), and aquatic animal products (e.g. fish, crustaceans and molluscs). Humans may inadvertently ingest soil with food or from their hands. The total amount of food consumed can also vary with factors such as age and degree of physical activity.
Relevance to Performance and Safety	This FEP influences the pathways and rates of exposure of humans to any repository-derived contaminants that might reach the biosphere.
2000 List	2.4.03

- ***FEP 5.2.3.1: Farming diet***

Description	The food and water intake characteristics of persons living a farming lifestyle. See Figure 4 for an example of self-sufficient farming. **Figure 4: Self-sufficient farming.**  **Credit: L. Limer.**
Category	Process
Comments	The community’s food intake may have a high proportion of plant food grown on local (and potentially contaminated) soil, as well as domesticated animals and fish. Water would come from wells or surface water bodies. The type of farming household can vary from self-sufficient to an “industrial” or monoculture operation.
Relevance to Performance and Safety	This FEP influences the pathways and rates of exposure of humans to repository-derived contaminants that might reach the biosphere.
2000 List	2.4.03

- ***FEP 5.2.3.2: Hunter/gatherer diet***

Description	The food and water ingested by persons living a hunter/gatherer lifestyle.
Category	Process
Comments	This FEP relates to the diet of a community of hunter-gatherers. Hunter/gathering describes a subsistence lifestyle employed by nomadic or semi-nomadic groups who roam relatively large areas of land hunting wild game and/or fish, and gathering native fruits, berries, roots and nuts, to obtain their dietary requirements. Typically, the community’s food intake would have a high proportion of fish and wild game, with little agriculture, water would come from springs or other surface water bodies, and a high percentage of their time may be spent outdoors.

Relevance to Performance and Safety	This FEP influences the pathways and rates of exposure of humans to repository-derived contaminants that might reach the biosphere.
2000 List	2.4.03

- ***FEP 5.2.3.3: Other diets***

Description	Other diets that cannot be adequately represented by a farming household diet or a hunter/gatherer diet (e.g. fast food).
Category	Process
Comments	The present-day diet of many communities around the world comprises to a large extent food which has not been wholly grown by, foraged for or hunted by the community under consideration. Many foodstuffs can be bought into an area, having been produced in locations away from the potential source of contamination. If a present-day community such as this was considered in a safety assessment, then the proportion of food coming from outside of the potentially contaminated area would need to be accounted for.
Relevance to Performance and Safety	This FEP influences the pathways and rates of exposure of humans to repository-derived contaminants that might reach the biosphere.
2000 List	2.4.03

- **FEP 5.2.4: Habits (excluding diet)**

Description	The non-diet related behaviour of humans, including time spent in various environments, pursuit of working and leisure activities and uses of materials.
Category	Process
Comments	Habits will be influenced by agricultural practices and human factors such as culture.
Relevance to Performance and Safety	This FEP relates to activities that might lead to the exposure of humans other than the consumption of food and fluids. Smoking, ploughing, fishing, and swimming are examples of behaviour that might give rise to particular modes of exposure to repository-derived contaminants that might reach the biosphere.
2000 List	2.4.04

- **FEP 5.2.5: Food preparation and water processing**

Description	The treatment of food stuffs and water between raw origin and consumption.
Category	Process
Comments	Once a crop is harvested or an animal slaughtered it may be subject to a variety of storage, processing and preparation activities prior to human or livestock consumption. Water sources may be treated prior to human or livestock consumption, e.g. chemical treatment and/or filtration.

Relevance to Performance and Safety	The treatment of food stuffs and water between raw origin and consumption may lead to the enhancement or reduction in the concentration of any repository-derived contaminants that might reach the biosphere.
2000 List	2.4.06
References	[Ref. 121]

○ FEP 5.3: Contaminant migration [biosphere]

Description	The processes that directly affect the migration of any repository-derived contaminants in the biosphere.
Category	FEP Subgroup
2000 List	3.2
References	[Ref. 11], [Ref. 29], [Ref. 30], [Ref. 32], [Ref. 171], [Ref. 188], [Ref. 189]

▪ FEP 5.3.1: Water-mediated migration [biosphere]

Description	The processes related to migration of any repository-derived contaminants in surface and near-surface water in the aqueous phase (including dissolved gases) and as particulate matter in surface water bodies.
Category	Process
Comments	Particulate matter includes colloids and suspended sediment in surface and near-surface water bodies. The movement of sediment by erosion is covered by FEP 5.3.3.
Relevance to Performance and Safety	This FEP relates to the migration of dissolved and particulate forms of any repository-derived contaminants that might reach the biosphere and result in exposure of human and non-human biota.
2000 List	3.2.07
References	[Ref. 122], [Ref. 123]

▪ *FEP 5.3.1.1: Groundwater discharge to biosphere*

Description	The groundwater, potentially containing repository-derived contaminants, and the processes leading to its discharge into surface and near-surface water bodies and soils/sediments.
Category	Feature, Process
Comments	This FEP relates to groundwater, potentially containing repository-derived contaminants, discharging from the geosphere into the biosphere via the geosphere-biosphere interface zone (GBIZ). The nature of the GBIZ will vary depending upon site-specific geological, hydrological and climatic factors.
Relevance to Performance and Safety	Consideration will need to be given to the degree of any dilution of the contamination in the surface/near-surface water upon entering the biosphere.

2000 List	3.2.07
References	[Ref. 124], [Ref. 125], [Ref. 126]

- ***FEP 5.3.1.2: Migration associated with surface soil and overburden***

Description	The migration of any repository-derived contaminants in water through the surface soil and overburden.
Category	Process
Relevance to Performance and Safety	Migration of any repository-derived contaminants by advection, diffusion and dispersion in soil pore water will be affected by characteristics such as soil texture, mineralogy, porewater pH and composition. Contaminants may also move through the soil profile via processes such as infiltration and interflow, and across the soil via surface runoff.
2000 List	3.2.07
References	[Ref. 127]

- ***FEP 5.3.1.3: Migration associated with surface water bodies***

Description	The migration of any repository-derived contaminants in dissolved or particulate form in surface water bodies such as rivers, lakes and seas.
Category	Process
Relevance to Performance and Safety	Migration of any repository-derived contaminants by advection, diffusion and dispersion in surface water bodies will be affected by characteristics such as water flow rates, water temperature and chemical gradients.
2000 List	3.2.07
References	[Ref. 30], [Ref. 128]

- ***FEP 5.3.1.4: Dissolution and precipitation [biosphere]***

Description	The dissolution and precipitation of any repository-derived contaminants in the biosphere under prevailing environmental conditions.
Category	Process
Comments	Dissolution is the process by which constituents of a solid or gas dissolve into solution. Dissolution is controlled by changes in pressure, temperature and gas concentrations in the biosphere. Precipitation occurs when chemical species in solution react to produce a solid that does not remain in solution.
Relevance to Performance and Safety	Any repository-derived contaminants moving through the biosphere could be subjected to precipitation or dissolution as a result of different local conditions, or by active microbial and plant processes. These processes can change in response to processes such as daily and seasonal changes in meteoric precipitation, temperature, and land use change. Dissolution into the liquid phase will increase the mobility of the contaminants, whilst precipitation would lead to their retention in that part of the biosphere.
2000 List	3.2.01, 3.2.06

References	[Ref. 129]

- ***FEP 5.3.1.5: Speciation and solubility [biosphere]***

Description	The chemical speciation and solubility of any repository-derived contaminants in the biosphere under prevailing environmental conditions.
Category	Process
Comments	The concentration of an element in aqueous solution (at equilibrium) reflects the solubility of the solid compounds which contain the element. Factors such as temperature, gas partial pressure, ionic strength, the presence of complexing agents and pH and Eh conditions affect solubility. These factors also affect the chemical form and speciation of the element. Thus different solids of the same element may have different solubilities in a particular solution.
Relevance to Performance and Safety	Speciation of any repository-derived contaminants in the biosphere can be particularly important because of the relatively large concentrations of oxygen and carbon dioxide dissolved in rain water and the soil pore water and the presence of organic complexes and compounds. Bacteria, microbes and plants may chemically transform contaminants and thereby change their sorption and solubility properties.
2000 List	3.2.02, 3.2.05, 3.2.06
References	[Ref. 127], [Ref. 130], [Ref. 131]

- ***FEP 5.3.1.6: Sorption and desorption [biosphere]***

Description	The sorption/desorption processes affecting the migration of any repository-derived contaminants through the biosphere under prevailing environmental conditions.
Category	Process
Comments	Sorption describes the physico-chemical interaction where dissolved species adhere to a solid phase. Desorption is the opposite. Two sorption-desorption processes are commonly considered: ion-exchange processes involving an electrostatic or ionic attraction between charged dissolved species and oppositely charged surfaces; and chemisorption involving the formation of a chemical bond. Neutral species and (usually) anions are generally not strongly sorbed. Factors affecting sorption in the biosphere include soil/sediment texture and composition, pH and Eh conditions, and temperature.
Relevance to Performance and Safety	Sorption and desorption of a contaminant will influence its partitioning between solid and fluid phases within the biosphere, and thereby affect the concentration of the contaminant in the fluid phases and hence its potential mobility. Generally, compared to solid-phase dissolution and precipitation, the rates of sorption and desorption tend to be rapid. Hence, these processes influence the rate at which contaminants migrate.
2000 List	3.2.03
References	[Ref. 30], [Ref. 132], [Ref. 133]

- ***FEP 5.3.1.7: Colloid transport [biosphere]***

Description	The transport of colloids and interaction of any repository-derived contaminants with colloids migrating through the biosphere under prevailing environmental conditions.

Category	Process
Relevance to Performance and Safety	Colloids (particles with diameters typically less than 10 µm) may influence contaminant migration in a variety of ways: retarding migration by sorption of aqueous radionuclide species and subsequent filtration; or, enhancing migration by sorption and migration with flowing water.
2000 List	3.2.04

- **FEP 5.3.2: Gas-mediated migration [biosphere]**

Description	The migration of any repository-derived contaminants in gas or vapour phase or as fine particulate or aerosol in gas or vapour through the biosphere.
Category	Process
Relevance to Performance and Safety	Repository-derived contaminants may enter the atmosphere as a result of a variety of processes including transpiration, suspension of soil/sediment, volatilisation from water bodies (including near-surface aquifers) or soil/sediment, degassing, production of radon gas from the decay of natural and/or repository-derived uranium, thorium and radium, and direct discharge of gases from the geosphere. Contaminants may also enter the indoor atmosphere from: use of contaminated water in showers; suspension of dust brought in on clothing or footwear; or from infiltration of contaminated water and gases into basements. The atmospheric system may represent a significant source of dilution for these contaminants. For example, advection and dispersion by wind can move contaminants from local to more dispersed regional areas. However, in the near-surface layer, contaminants such as ^{14}C-labelled methane may be subject to uptake by plants.
2000 List	3.2.09, 3.1.04, 3.1.06, 3.2.10
References	[Ref. 134], [Ref. 135]

- **FEP 5.3.3: Solid-mediated migration [biosphere]**

Description	The transport of any repository-derived contaminants in solid phase in the biosphere.
Category	Process
Comments	This might result from processes such as the glacial/fluvial erosion, landslide, solifluction, bioturbation and sedimentation.
Relevance to Performance and Safety	This FEP relates to the migration of any repository-derived contaminants bound to solid particles, such as soil and sediment. The processes of most interest are large-scale erosion/sedimentation processes that are associated with external factors, such as regional erosion and sedimentation (FEP 1.2.8) and glacial and ice-sheet effects (FEP 1.3.5). However, smaller-scale processes can also occur that affect the local distribution of contaminants on shorter timescales. These include the bioturbation of soils and the silting of water bodies.
2000 List	3.2.06, 3.2.08

- **FEP 5.3.4: Human-action-mediated migration [biosphere]**

Description	The transport of any repository-derived contaminants in the biosphere as a direct result of human actions.
Category	Process
Comments	Includes processes such as the dredging of contaminated sediments from lakes, rivers and estuaries and placing them on land, the ploughing of soils, which result in the mixing of the top layers of agricultural soil, and irrigation of soils.
Relevance to Performance and Safety	This FEP relates to human actions that would disturb and potentially redistribute solid materials or water, and thus subject any repository-derived contaminants associated with the solid material or water to be moved also. These processes can act to dilute and disperse contaminants in the environment through mixing processes. However, they can also act to enhance contaminant concentrations in the environment. For instance, contaminants can be accumulated in compost piles or animal and human waste and then used as soil conditioners.
2000 List	3.2.12

- **FEP 5.3.5: Uptake of contaminants by animals and plants**

Description	The incorporation of any repository-derived contaminants into animal and plant species.
Category	Process
Relevance to Performance and Safety	This FEP relates to the incorporation of any repository-derived contaminants into animals and plants. Some of these may be consumed by humans or animals. Plants may become contaminated either as a result of direct deposition onto their surfaces or indirectly as a result of uptake from contaminated soils or water via the roots, or via uptake of gases via the leaves. Animals may become contaminated as a result of ingesting contaminated plants, or directly as a result of ingesting or inhabiting contaminated soils, sediments and water sources, or via inhalation of contaminated particulates, aerosols or gases.
2000 List	3.2.11, 3.2.13
References	[Ref. 30], [Ref. 127], [Ref. 132], [Ref. 136]

- **FEP 5.3.6: Radioactive decay and ingrowth [biosphere]**

Description	The spontaneous disintegration or de-excitation of an atomic nucleus, resulting in the emission of sub-atomic particles and energy and the formation of a new progeny (or "daughter") nucleus in the biosphere.
Category	Process
Relevance to Performance and Safety	There will be radioactive decay and ingrowth of radionuclides in the biosphere. In post-closure assessment, radioactive decay chains are often simplified, e.g. by assuming equilibrium for the shorter-lived radionuclides in biosphere migration calculations. However, their contribution to dose needs to be taken into account in dose calculations.
2000 List	3.1.01
References	[Ref. 118], [Ref. 137]

○ FEP 5.4: Exposure factors

Description	The processes and conditions that directly affect the health or give rise to other impacts on human beings and the environment from given concentrations of any repository-derived contaminants in environmental media.
Category	FEP Subgroup
2000 List	3.3
References	[Ref. 32], [Ref. 33], [Ref. 34], [Ref. 171], [Ref. 178], [Ref. 179], [Ref. 180], [Ref. 189]

▪ FEP 5.4.1: Contaminated drinking water and food

Description	The presence of any repository-derived contaminants in drinking water, foodstuffs or drugs that may be consumed by humans, and associated processes.
Category	Feature, Process
Comments	Contaminants may be incorporated into the food chain through contaminated soil, water and air (see for example FEP 5.3.5).
Relevance to Performance and Safety	Repository-derived contaminants may be incorporated into the food chain through contaminated soil, water and air. Water used for drinking is particularly important because it can provide a direct pathway of contaminant ingestion, with few delays. However, processes such as bioconcentration, bioaccumulation and biomagnification can increase concentrations of some contaminants in foodstuffs and may result in more significant exposures to particular contaminants.
2000 List	3.3.01
References	[Ref. 30], [Ref. 132], [Ref. 136]

▪ FEP 5.4.2: Contaminated non-food products

Description	The presence of any repository-derived contaminants in human manufactured materials or environmental materials that have special non-food uses, and the associated processes.
Category	Feature, Process
Relevance to Performance and Safety	Examples of materials that could be contaminated include: wood and rock used as building material and household furnishings; natural fibres and animal skins used in clothing; and peat, charcoal and biogas (from plant materials, faeces and refuse, or from trapping methane from garbage disposal sites, bogs and sediments) for use in house heating.
2000 List	3.3.03

▪ FEP 5.4.3: Other contaminated environmental media

Description	The presence of any repository-derived contaminants in environmental media other than drinking water, foodstuffs, drugs or non-food products, i.e. soil, water, sediment and air, and associated processes.
Category	Feature, Process

Relevance to Performance and Safety	Concentrations in environmental media are used to assess the impact of any repository-derived contaminants in the biosphere on non-human biota, and to assess the external exposure and inhalation routes for humans (for example from the inhalation of radon and radon progeny from the decay of natural and/or repository-derived uranium, thorium and radium). Concentrations in environmental media are also usually required to determine the contaminant concentrations in food. Some media might attain higher concentrations than their surroundings because of natural processes such as bioaccumulation or evaporation of water. Moreover, human practices such as watering of gardens might lead to higher concentrations or accumulation of contaminants.
2000 List	3.3.02
References	[Ref. 30], [Ref. 132], [Ref. 136], [Ref. 230]

- **FEP 5.4.4: Exposure modes**

Description	The exposure of humans and other organisms to any repository-derived contaminants that might reach the biosphere.
Category	Process
Comments	Exposure modes can be broadly categorised as internal and external with respect to the human body or affected non-human biota. Internal exposure means the contaminant enters and may temporarily or permanently reside in the affected organism. External exposure means the contaminant is outside the organism at all times, although radiation and energy might be transferred into the organism.
Relevance to Performance and Safety	Radiotoxic and chemotoxic species differ in their ability to affect organisms. Radiotoxic materials can lead to impacts through internal or external exposure. Chemotoxic species are generally only of concern from internal exposure. Chemicals may be sorbed through skin or surfaces of non-human biota, but subsequent impacts are usually from internal exposure. However, there may be exceptions, for example allergic skin reactions that occur with nickel.
2000 List	3.3.04
References	[Ref. 11]

- ***FEP 5.4.4.1: Exposure of humans***

Description	Exposure modes to any repository-derived contaminants affecting humans.
Category	Process
Relevance to Performance and Safety	The most important modes of exposure to contaminants are generally: ingestion (internal exposure) from drinking or eating contaminated water or foodstuffs; inhalation (internal exposure) from inhaling gaseous or particulate contaminants; external exposure as a result of direct irradiation from radionuclides deposited on, or present on, the ground, buildings or other objects. Exposure can also come from immersion in contaminated water bodies, direct radiation from airborne plumes of radioactive materials, injection through wounds, and absorption through the skin for some species.
2000 List	3.3.04
References	[Ref. 11], [Ref. 118]

- ***FEP 5.4.4.2: Exposure of non-human biota***

Description	Exposure modes to any repository-derived contaminants affecting animals and plants.
Category	Process
Comments	Non-human biota can be divided into two broad groups: domesticated and cultivated species, and wild and indigenous species.
Relevance to Performance and Safety	The exposure modes would be similar to those for humans: ingestion, inhalation, external irradiation and skin absorption. However, the relative importance of these pathways is likely to be quite different from humans and also between species. The extent of territory utilised by animals (defined as their 'home range') needs to be considered. Some animals have a limited home range and may reside in a small area, whereas others may have a home range that encompasses an area much larger than that potentially affected by the repository.
2000 List	3.3.04
References	[Ref. 136], [Ref. 138], [Ref. 139], [Ref. 140], [Ref. 230]

- **FEP 5.4.5: Dosimetry and biokinetics**

Description	The dependence between radiation or chemotoxic effect and amount and distribution of radiation or chemical agent in the organs, tissues and whole body.
Category	Process
Relevance to Performance and Safety	This FEP relates to the committed dose that humans or non-human biota might get following exposure to any repository-derived contaminants that might reach the biosphere, and the distribution, retention and excretion of the contaminants from within the living organism.
2000 List	3.3.05
References	[Ref. 118], [Ref. 119], [Ref. 138]

- ***FEP 5.4.5.1: Dosimetry and biokinetics for humans***

Description	The dependence between radiation and chemical toxicity effect and the amount of radiation or chemical agent in human organs, tissues, and whole body.
Category	Process
Relevance to Performance and Safety	This FEP relates specifically to dosimetry and biokinetics in humans for any repository-derived contaminants that might reach the biosphere. Doses from radioactive contaminants depend on factors that include the exposure mode (e.g. internal or external exposure), the metabolism with regard to the radiotoxic substance, the residence time in the tissue or organ, the energy and type of radioactive emissions of the radionuclide and any progeny, the age of the human at exposure and the lifetime commitment to the exposure. Similar comments apply to chemotoxic effects, except that chemical and biochemical disruption of cell functions, not radioactive emissions, affect the tissues of the body. The chemical form of a compound plays an important role in determining whether and how the toxic component interacts with cells and tissues.

2000 List	3.3.05
References	[Ref. 118], [Ref. 119], [Ref. 141], [Ref. 147], [Ref. 148], [Ref. 149], [Ref. 150], [Ref. 151]

- ***FEP 5.4.5.2: Dosimetry and biokinetics for non-human biota***

Description	The dependence between radiation or chemical toxicity effect and the amount of radiation or chemical agent in animal organs, tissues and the whole body and/or plant tissues and the whole plant.
Category	Process
Relevance to Performance and Safety	This FEP relates specifically to dosimetry and biokinetics in non-human biota for any repository-derived contaminants that might reach the biosphere. While the same principles as assumed for humans will apply, the specific details of the biokinetic behaviour of the radioactive contaminants, and the associated dosimetry, in non-human biota will differ from humans, and between species. The same principles apply to chemotoxic substances.
2000 List	3.3.05
References	[Ref. 138], [Ref. 139], [Ref. 140], [Ref. 230]

- **FEP 5.4.6: Radiological toxicity/effects**

Description	The effect of radiation on humans and other organisms from any repository-derived radionuclides (and/or their progeny) that might reach the biosphere.
Category	Process
Relevance to Performance and Safety	This FEP relates specifically to the radiological effects of exposure to any repository-derived radionuclides, which can be classified in several different ways. For example: somatic or genetic, occurring in the exposed individual or in the offspring of the exposed individual, respectively; and stochastic or non-stochastic (deterministic) where the probability of the effect is a function of dose received or the severity of the effect is a function of dose received and no effect may be observed below some threshold, respectively. Another issue of potential concern is synergistic (combined) effects of two or more radiotoxic species.
2000 List	3.3.06
References	[Ref. 141]

- ***FEP 5.4.6.1: Radiological toxicity/effects for humans***

Description	The effects of radiation on humans from any repository-derived radionuclides (and/or their progeny) that might reach the biosphere.
Category	Process
Relevance to Performance and Safety	Radiation exposure can have a wide variety of effects on humans depending upon the exposure levels. At low exposure levels, cancer induction (carcinogenesis) and genetic effects are of main concern, possibly because of mutations that may lead to cancer or, if

	the reproductive cells are affected, hereditary effects that may be detrimental and transmitted to future generations.
2000 List	3.3.06
References	[Ref. 118], [Ref. 119], [Ref. 141]

- ***FEP 5.4.6.2: Radiological toxicity/effects for non-human biota***

Description	The effects of radiation on animals and plants from any repository-derived radionuclides (or their progeny) that might reach the biosphere.
Category	Process
Relevance to Performance and Safety	For non-human biota, the goal in safety assessment is usually to evaluate potential effects at a population or community level. This involves assessing the potential risks of unacceptable mortality, decreased growth, or reproductive impairment for populations exposed to any repository-derived radionuclides (and/or their progeny) that might reach the biosphere. If the effects are widespread throughout a population of some non-human biota, there could also be consequential effects, such as disruption of food webs or ecosystems.
2000 List	3.3.06
References	[Ref. 138], [Ref. 139], [Ref. 142], [Ref. 143], [Ref. 230]

- **FEP 5.4.7: Chemical toxicity/effects**

Description	The effects on humans and other organisms of any repository-derived chemotoxic species (and/or their degradation products) that might reach the biosphere.
Category	Process
Relevance to Performance and Safety	Some components of the waste packages or the repository can be chemically toxic to humans and other organisms. The repository can include a wide range of radiologically stable, but potentially toxic species, such as heavy metals and persistent organic species. Chemical toxicity can also be relevant for some radioactive elements, for example uranium is a heavy metal and as such is chemically toxic. Another issue of potential concern is synergistic (combined) effects of two or more chemotoxic species.
2000 List	3.3.07
References	[Ref. 144], [Ref. 145]

- ***FEP 5.4.7.1: Chemical toxicity/effects for humans***

Description	The effects on humans of any repository-derived chemotoxic species (and/or their degradation products) that might reach the biosphere.
Category	Process
Relevance to Performance and Safety	Human exposure to chemically toxic substances can involve a wide range of effects, including teratogenic (developmental disturbances), mutagenic effects (mutations that may lead to cancer or hereditary changes transmitted to future generations) and

	carcinogenic (cancer inducing) effects and thus interfere with reproduction, growth and survival.
2000 List	3.3.07
References	[Ref. 146]

- ***FEP 5.4.7.2: Chemical toxicity/effects for non-human biota***

Description	The effects on animals and plants of any repository-derived chemotoxic species (and/or their degradation products) that might reach the biosphere.
Category	Process
Relevance to Performance and Safety	Chemical toxicity has the same range of effects on non-human biota as it does on humans, although toxicity may vary between species.
2000 List	3.3.07
References	[Ref. 138], [Ref. 145]

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Appendix: Conversion table from IFEP List 1.0 (2000 List) to IFEP List 3.0 (2019 List)

IFEP List 1.0	IFEP List 3.0	IFEP List 1.0	IFEP List 3.0
1	1	2.2.02	4.1.1
1.1	1.1	2.2.03	4.1.1
1.1.01	1.1.2	2.2.04	4.1.2
1.1.02	1.1.5	2.2.05	Multiple items
1.1.03	1.1.6	2.2.06	4.1.7, 4.2.3
1.1.04	1.1.7	2.2.07	4.1.6, 4.2.2
1.1.05	1.1.11	2.2.08	4.1.8, 4.2.4
1.1.06	1.1.6	2.2.09	4.1.9, 4.2.5
1.1.07	1.1.3, 3.1.1	2.2.10	4.1.5, 4.2.1
1.1.08	1.1.1	2.2.12	4.1.4
1.1.09	1.1.4	2.2.13	4.1.3
1.1.10	1.1.9	2.3	5.1, 5
1.1.11	1.1.10	2.3.01	5.1.1
1.1.12	1.1.8	2.3.02	5.1.3, 5.1.3.1, 5.1.3.2, 5.1.3.3
1.1.13	Multiple items	2.3.03	5.1.4
1.2	1.2	2.3.04	5.1.5, 5.1.5.1, 5.1.5.2, 5.1.5.3
1.2.01	1.2.1, 1.2.2	2.3.05	5.1.6
1.2.02	1.2.3	2.3.06	5.1.7
1.2.03	1.2.4	2.3.07	5.1.8
1.2.04	1.2.5	2.3.08	5.1.9
1.2.05	1.2.6	2.3.09	5.1.10
1.2.06	1.2.7	2.3.10	5.1.11

IFEP List 1.0	IFEP List 3.0	IFEP List 1.0	IFEP List 3.0
1.2.07	1.2.8	2.3.11	5.1.12
1.2.08	1.2.9	2.3.12	5.1.13
1.2.09	1.2.11	2.3.13	5.1.14
1.2.10	1.2.12	2.4	5.2, 5
1.3	1.3	2.4.01	5.2.1
1.3.01	1.3.1	2.4.02	5.2.1
1.3.02	1.3.2	2.4.03	5.2.3, 5.2.3.1, 5.2.3.2, 5.2.3.3
1.3.03	1.3.3	2.4.04	5.2.4
1.3.04	1.3.4	2.4.05	5.2.2, 5.2.2.3, 5.2.2.1, 5.2.2.2
1.3.05	1.3.5	2.4.06	5.2.5
1.3.06	1.3.6	2.4.07	5.2.2.4
1.3.07	1.3.7	2.4.08	5.2.2.1, 5.2.2.2, 5.2.2.3
1.3.08	1.3.8	2.4.09	5.2.2.1, 5.2.2.2, 5.2.2.3
1.3.09	1.3.9	2.4.10	5.2.2.1, 5.2.2.2, 5.2.2.3
1.4	1.4	2.4.11	5.2.2.1, 5.2.2.2
1.4.01	1.4.1	3	Multiple items
1.4.02	1.4.4, 1.4.12	3.1	2, 3, 4, 5
1.4.03	1.4.7	3.1.01	2.3.6.1, 3.2.6.1, 5.3.6
1.4.04	1.4.5	3.1.02	Multiple items
1.4.05	1.4.6	3.1.03	2.1.2.1, 2.1.2.3
1.4.06	1.4.8	3.1.04	2.4.2, 2.5.2, 3.3.2, 2.3.5.2, 5.3.2
1.4.07	1.4.9	3.1.05	2.1.2.2
1.4.08	1.4.2	3.1.06	2.4.2, 2.5.2, 3.3.2, 2.3.6.3, 2.3.6.4, 3.2.6.3, 5.3.2

IFEP List 1.0	IFEP List 3.0	IFEP List 1.0	IFEP List 3.0
1.4.09	1.4.3	3.2	2.4, 2.5, 3.3, 4.3, 5.3, 2, 3, 4, 5
1.4.10	1.4.11	3.2.01	2.4.1.1, 2.5.1.4, 3.3.1.4, 4.3.1.5, 5.3.1.4
1.4.11	1.4.10	3.2.02	3.3.1.5, 2.4.1.3, 2.5.1.5, 4.3.1.6
1.5	1.5	3.2.03	2.4.1.4, 2.5.1.6, 3.3.1.6, 4.3.1.7, 5.3.1.6
1.5.01	1.5.1	3.2.04	2.3.4.8, 2.5.1.7, 3.2.4.8, 3.3.1.7, 4.3.1.8, 5.3.1.7, 2.4.3
1.5.02	1.5.2	3.2.05	2.4.1.3, 2.5.1.5, 4.3.1.6, 5.3.1.5, 2.3.4.7, 3.2.4.7
1.5.03	Multiple items	3.2.06	2.3.5.2, 5.3.1.4, 5.3.1.5, 3.2.5.2, 5.3.3
2.1	2.3, 3.1, 3.2, 2, 3	3.2.07	2.4.1, 2.4.1.2, 2.5.1, 2.5.1.1, 2.5.1.2, 2.5.1.3, 3.3.1, 3.3.1.1, 3.3.1.2, 3.3.1.3, 4.3.1, 4.3.1.1, 4.3.1.2, 4.3.1.3, 4.3.1.4, 5.3.1, 5.3.1.1, 5.3.1.2, 5.3.1.3
2.1.01	2.1.1, 2.1.1.1, 2.1.1.2	3.2.08	2.4.3, 5.3.3, 3.3.3, 4.3.3
2.1.02	2.1, 2.1.2, 2.1.2.4	3.2.09	2.4.2, 2.5.2, 3.3.2, 4.3.2, 5.3.2
2.1.03	2.2, 2.2.1	3.2.10	5.3.2
2.1.04	Multiple items	3.2.11	5.3.5
2.1.05	3.1.2, 3.1.3, 3.1.4	3.2.12	2.4.4, 3.3.4, 4.3.4, 5.3.4
2.1.06	3.1.5	3.2.13	5.3.5
2.1.07	2.3.2.3, 2.3.3.2, 2.3.3.3, 2.3.3.4, 3.2.3.1, 3.2.3.2, 3.2.3.3, 2.3.3, 2.3.3.1, 3.2.3	3.3	5.4, 5
2.1.08	2.3.2, 2.3.2.1, 3.2.2, 3.2.2.1, 3.2.2.2	3.3.01	5.4.1

IFEP List 1.0	IFEP List 3.0	IFEP List 1.0	IFEP List 3.0
2.1.09	2.3.2.4, 2.3.4.1, 2.3.4.2, 2.3.4.3, 2.3.4.4, 2.3.4.5, 2.3.4.6, 3.2.4.1, 3.2.4.2, 3.2.4.3, 3.2.4.4, 3.2.4.5, 3.2.4.6, 2.3.4, 3.2.4	3.3.02	5.4.3
2.1.10	3.2.5.1, 2.3.5, 2.3.5.1, 3.2.5	3.3.03	5.4.2
2.1.11	2.3.1, 2.3.1.1, 2.3.1.2, 2.3.1.3, 2.3.2.2, 3.2.1	3.3.04	5.4.4, 5.4.4.1, 5.4.4.2
2.1.12	2.3.3, 2.3.3.1, 3.2.3, 2.3.4, 3.2.4, 2.3.5, 2.3.5.1, 3.2.5, 2.3.2.5, 2.3.3.5, 3.2.3.4, 3.2.3.5	3.3.05	5.4.5, 5.4.5.1, 5.4.5.2
2.1.13	2.3.6, 2.3.6.2, 2.3.6.5, 3.2.6, 3.2.6.2, 3.2.6.4, 4.2.6	3.3.06	5.4.6, 5.4.6.1, 5.4.6.2
2.1.14	2.3.6.6, 3.2.6.5	3.3.07	5.4.7, 5.4.7.1, 5.4.7.2
2.2	4.1, 4.2, 4	3.3.08	Multiple items
2.2.01	3.1.6		