LLW Repository Ltd

Low Level Waste Repository

LLWR Environmental Safety Case

A Features, Events & Processes and Uncertainty Tracking System to Support the 2011 ESC

A report prepared by National Nuclear Laboratory for and on behalf the Low Level Waste Repository Site Licence Company.

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National Nuclear Laboratory

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Candida Lean and Mark Willans, March 2010

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EXECUTIVE SUMMARY

The Low Level Waste Repository (LLWR) near the village of Drigg is the UK's principal facility for the disposal of solid low level radioactive waste. The LLWR Site License Company is currently undertaking a programme of work leading to the production of an Environmental Safety Case by May 2011 (2011 ESC). The 2011 ESC will be submitted to the Environment Agency in order to satisfy Requirement 6 of Schedule 9 of the LLWR's current Authorisation.

In support of the programme of work leading up to the submission of the 2011 ESC, NNL have developed, in conjunction with staff from the LLWR, a tracking system for the management of Features, Events and Processes (FEPs) and documentation of associated uncertainties. As part of this work, a FEP list has been defined for the 2011 ESC.

An identification of the factors relevant to the performance of a disposal system, and assurance that the important processes and uncertainties have been appropriately and adequately represented is central to confidence in the completeness of safety assessments. In the case of the LLWR, a high level of understanding of the relevant factors has been developed through iterative safety assessments and supporting studies carried out over the past decade. Thus, it was considered most appropriate to develop the 2011 ESC FEP list and consideration of uncertainties based on the models that are proposed for use in the 2011 ESC, which are in turn based on that detailed experience and results of previous assessments. This leads to a FEP and uncertainty tracking system that is directly linked to the assessment models that will be used and cases that will be evaluated.

The identification of FEPs and uncertainties has, therefore, been based on a consideration what the most important factors are for each of the assessment model pathways (groundwater pathway, gas pathway, coastal erosion and human intrusion) and taking account of the conceptual understanding of each pathway. This approach ensures that those FEPs that are relevant to scenarios, models and cases supporting the 2011 ESC are identified, while also giving scope to identify and record FEPs that are not directly represented in those scenarios, models and cases. This avoids the complexity of the previous (2002) LLWR FEP list, which contained over 1400 FEPs at a level of detail that could not always be realistically modelled. It also ensures that the 2011 ESC FEP list is closely linked to the assessment calculations. The current list of 308 FEPs is structured by pathway and model domain and is appended to this report. It has been audited against the 2002 FEP list to check that all relevant FEPs from the 2002 FEP list have been considered.

The FEP and uncertainty tracking system is implemented as a Microsoft Excel™ spreadsheet including screens and macros to assist in the management of the identified FEPs and associated uncertainties. The system includes: details of each FEP; a topic area expert's judgement of the relevance and realisation of the FEP within the LLWR system; an assessment of the scientific and data uncertainties around each FEP; and details of how the FEP and, where appropriate, associated uncertainty is treated in the safety assessment and overall ESC. Data entry to the tracking system is controlled through a defined process and password protections. Data and judgements are entered via user-friendly forms. The same forms or screens can be examined by other users or reviewers to interrogate the database in a logical manner.

The system allows the identification of how a specific FEP has been considered within the 2011 ESC and the tracking of the key FEPs associated with each pathway and model. The system also provides a means by which significant uncertainties can be identified, rated according to expert judgement on the importance to sub-system performance, and record how the uncertainty is treated in the 2011 ESC. This is intended to support the

LLWR in developing a register of significant uncertainties as required by the Environment Agency.

The FEP and uncertainty tracking system has been populated by NNL based on their expert knowledge of previous conceptualisation and assessment work that has been undertaken at the LLWR and their understanding of what is likely to be included in the 2011 ESC assessment models as advised by LLWR staff. The system also contains a full listing of all reference material that has been used in its population and details of the audit of the 2011 FEP list against the 2002 ESC FEP list.

As assessment models and cases are developed in support of the 2011 ESC, there will be a need to review and update many of the entries in the FEP and uncertainty tracking system, principally associated with the FEP and uncertainty treatment data fields. As the tracking system is intended to be a 'live' system (i.e. subject to regular update as necessary), it is recommended that, in parallel with the completion of the 2011 assessment models, a 'frozen' version of the database is made to complete the audit trail for the 2011 ESC.

LLW Repository Ltd. understands that demonstration of the appropriate treatment and management of FEPs and uncertainties will be vital to the robustness of the 2011 safety assessment and the overall acceptability of the 2011 ESC. The development and use of the 2011 ESC FEP list and the FEP and uncertainty tracking system, as described in this report, provides a good foundation to achieving this requirement. The tracking system provides a transparent means for documenting and justifying the treatment of FEPs and associated uncertainties in the 2011 ESC. As such, the system will be of use in developing safety assessments in support of the 2011 ESC, and should also be of value to technical reviewers of the assessments.

VERIFICATION STATEMENT

This document has been verified and is fit for purpose. An auditable record has been made of the verification process. The scope of the verification was to confirm that : -

- The document meets the requirements as defined in the task specification/scope statement
- The constraints are valid
- The assumptions are reasonable
- The document demonstrates that the project is using the latest company approved data
- The document is internally self consistent
- The document is consistent with the Microsoft Excel™ spreadsheet implementation of the FEP and uncertainty tracking system

HISTORY SHEET

Issue Number	Date	Comments
Issue 0.1	27/11/2009	NNL approved version
Issue 1.0	19/1/2010	Update in line with comments from Trevor Sumerling of the LLWR
Issue 1.1	15/3/2010	Update to address minor comments on Issue 1.0

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1. Introduction

The Low Level Waste Repository (LLWR) near the village of Drigg is the UK's principal facility for the disposal of solid low level radioactive waste (LLW). The LLWR Site License Company (SLC), LLW Repository Ltd., is currently undertaking a programme of work leading to the production of an Environmental Safety Case by May 2011 (2011 ESC). The 2011 ESC will be submitted to the Environment Agency in order to satisfy Requirement 6 of Schedule 9 of the LLWR's current Authorisation.

LLW Repository Ltd. understands that demonstration of appropriate treatment and management of Features, Events and Processes (FEPs) and uncertainties within the 2011 ESC will be vital to the robustness of the 2011 LLWR safety assessment and the overall acceptability of the ESC. A transparent system for documenting and justifying the treatment of identified FEPs and associated uncertainties is essential for demonstrating that assessment models are appropriate and fit for purpose by ensuring that all relevant factors have been considered in their development. Furthermore, there is a regulatory requirement to demonstrate that all uncertainties that have a significant effect on the ESC have been documented and adequately managed.

NNL have developed, in conjunction with staff from the LLWR, a Microsoft Excel™ spreadsheet based tracking system for the management of FEPs and associated uncertainties. The benefits of such a system lie in the ability to rapidly and transparently identify both the means by which a specific FEP has been considered within the 2011 ESC and to track the key FEPs associated with each model (at a detailed and at an assessment level). The system also provides a means by which uncertainties can be documented and tracked, which will allow the LLWR to develop a register of significant uncertainties and a strategy for managing significant uncertainties, as required in the Guidance on Requirements for Authorisation (GRA) (Environment Agency *et al*., 2009).

This report describes the development of the 2011 ESC FEP list and the FEP and uncertainty tracking system. The FEP and uncertainty tracking system is issued in conjunction with this report (Lennon, 2010).

This report is divided as follows:

- Section 2 provides background to the project, describing general goals for FEP management, how they have previously been derived as part of a systematic approach for undertaking assessments of the LLWR and the basis for FEP management in the 2011 ESC.
- Section 3 details how a FEP list has been derived for the 2011 ESC and audited against the previous, 2002, LLWR FEP list. The 2011 ESC FEP list is provided in Appendix 1.
- Section 4 describes the development of the FEP and uncertainty tracking system tool, including the key functional design aspects of the tool. Appendix 2 contains example entries taken from the audit of the 2011 FEP list against the 2002 FEP list and Appendix 3 provides example entries from the tracking system.
- A summary and conclusions are provided in Section 5.
- Section 6 provides references.

2. Background

2.1. General goals for FEP management

A common element in many scenario generation methodologies for radioactive waste disposal facilities is the initial construction of a comprehensive list of FEPs that could directly or indirectly influence the disposal system and the migration and fate of radionuclides within it. BNFL (2002a) defines FEPs as "any factors that may influence the disposal system and/or the development of the safety case". Their use helps ensure that all relevant factors have been taken into consideration. These FEPs are usually identified from the disposal system description.

As recognised by the Nuclear Energy Agency (NEA, 2000), "formal documentation of the identification of relevant FEPs, and recording of information related to each FEP, can have several benefits.

Within a project:

- development of a FEP list provides an opportunity for broad discussion amongst the project team and independent experts to identify the relevant FEPs;
- descriptive information and references added against each FEP provides a source of information that can be used during scenario or model development activities;
- a FEP list and database provides a framework to record information about a FEP, whether or not the FEP is included in assessment models and even through its importance may be uncertain; and
- the models used in an assessment can be audited against the list of FEPs with a view to ensuring that all important processes are included, or to assist in specifying further model developments or data acquisition.

Both within a project and for external audiences (e.g. the public or regulators):

- the extent of the project FEP database indicates the range of FEPs that have been given at least qualitative consideration; and
- clear descriptions of each FEP, their relevance and importance, and how each FEP is treated (e.g. in quantitative analysis), generates confidence in the logic and thoroughness of the assessment."

2.2. FEP management for the 2002 Post-Closure Safety Case

The previous (2002) LLWR FEP list was derived using a systematic process, an approach that identified relevant interactions on the basis of a detailed understanding of the main components of the disposal system and the processes responsible for its evolution (BNFL, 2002a,b and references therein). This is consistent with International Atomic Energy Agency (IAEA) recommendations on the use of a systematic framework for the development of a safety assessment: "the adoption of a systematic assessment framework is intended to provide a formal basis for external review of the logic of the underlying assumptions adopted in a safety case. This approach helps to provide assurance that the assessment has effectively addressed all potentially relevant FEPs and taken account of the ways in which combinations of these FEPs might produce qualitatively different outcomes. In addition, a systematic approach should provide the

setting for demonstrating how uncertainties associated with the future evolution of the disposal system have been addressed and assimilated into the safety case" (IAEA, 2004). The 2002 FEP list was audited against the NEA generic FEP list (NEA, 2000) to check for completeness and to identify possible omissions.

The 2002 LLWR FEP list contained a total of 1405 FEPs relating to the LLWR and that part of the local environment directly relevant to the determination of assessment end points. A further 37 external FEPs (EFEPs), relating to the environment external to the LLWR and its immediate surroundings (e.g. relating to human activities and natural processes of a regional or global nature such as climate change and sea level rise), were also defined.

The 2002 LLWR FEP list is therefore considered comprehensive, certainly in terms of site understanding in 2002. However, the large number of defined FEPs made their management a non-trivial issue, and the manner in which FEPs were considered within the 2002 Post-Closure Safety Case (PCSC), and associated uncertainties, was not always transparent. In particular, no FEP database was constructed, thereby making it difficult to determine which FEPs had been considered, either qualitatively or quantitatively, and, if so, their importance and means of treatment. Furthermore, understanding of the LLWR and the environment local to it has moved on from 2002. There has been no wish to repeat the detailed process used to define the 2002 FEP list. Instead, as described subsequently, it was decided to develop the 2011 ESC FEP list using a 'top-down' approach, based on expert knowledge.

2.3. Basis for FEP management for the 2011 ESC

A number of iterations of safety assessment have already been carried out for the LLWR, including initial calculations undertaken for the 2000 Status Report on the development of the 2002 PCSC (BNFL, 2000), the 2002 Post-Closure Radiological Safety Assessment (BNFL, 2002a,b,c) and calculations supporting the LLWR Authorisation Schedule 9 Requirement 2 submission in 2008 (e.g. Paksy and Henderson, 2008; Galais and Fowler, 2008; Ball *et al*., 2008). Additional calculations are also available to support site understanding, including recent cases to determine the impact of delayed coastal erosion (Paksy *et al*., 2009), the development of an estuary or lagoon feature (Willans and Galais, 2009) and the migration of gas into a building on the site (Sumerling, 2009).

Thus, understanding of the LLWR, its environment and their future evolution has moved on from 2002. Work is currently ongoing to develop the assessment models that will support the 2011 ESC, building on that improved understanding.

Work is underway on detailed supporting models to investigate specific parts of the system, including the near field (e.g. Kwong *et al*., 2008; Small *et al*., 2008a,b, 2009) and groundwater flow (e.g. Henderson, 2008a,b; Henderson *et al*., 2008; Jackson, 2009). This information will feed into the GoldSim assessment models supporting the 2011 ESC (see, for example, Kelly and Jackson, 2009).

Through the work undertaken to date, it is considered that there is already a good level of understanding of the key factors that are likely to influence site impacts. This includes the present day situation (i.e. neglecting potential effects associated with future climate change and assuming that waste and site management practices remain consistent with those today) and in terms of a reasonable range of potential futures and waste management options.

The process used in the development of the 2011 FEP list and the tracking system is described in Section 3.

3. Development of the 2011 FEP List

3.1. Terminology and approach

The LLWR has made specific definitions for the terms 'scenarios', 'models' and 'cases' which, to ensure clarity, were adhered to during development of the FEP and uncertainty tracking system:

- Waste and management scenarios – broad assumptions for UK waste arisings, waste treatments, acceptance at the LLWR and facility design and management.
- Assessment scenarios – broad description of (assumptions for) the future evolution of the disposal system and its environment. For example, the 'Reference Scenario' includes:
    - broadly expected climate development, including coastal regression;
    - a range of likely degradations of the engineered barrier system;
    - the site not being intruded into (but potentially exposed groups are oblivious to exposure);
    - a stylised biosphere being broadly consistent with the present day situation, and accounting for landform and climate change, land use and human habits; and
    - contaminant release initially by the groundwater and gas pathways, and at later times by coastal erosion.
- Assessment model – the assembly of FEPs and interactions that are treated in a given case or set of assessment models, including conceptual models (descriptive) and implemented models (as implemented by given equations or software).
- Assessment case – a specified set of conditions and assumptions within a scenario.
- Pathway – general modes by which radionuclides migrate or humans come in to contact with radioactivity. Four pathways have been identified: groundwater, gas, natural disruption (coastal erosion) and human intrusion.

The building blocks for the assessment models and cases are the FEPs. Retaining the 2002 definition, these are the many factors that may influence the disposal system and/or the development of the safety case (BNFL, 2002a). However, for the 2011 assessment, the focus is on identifying and characterising those FEPS within the context of the assessment models and cases and at a level of detail commensurate with our ability to represent and models the FEPs.

The objective is to develop and apply a simple methodology and framework to track the FEPs and uncertainties that are:

(1) included in the models and cases to be considered in the 2011 ESC;

(2) addressed by scoping or side calculations; or

(3) not currently addressed.

The tracking method should carry enough information to indicate clearly how a given FEP or uncertainty is being treated and references to supporting work as needed. The methodology must be simple, clear and directed towards the safety assessment scenarios, models and cases that will be analysed in the 2011 ESC; and the FEP and

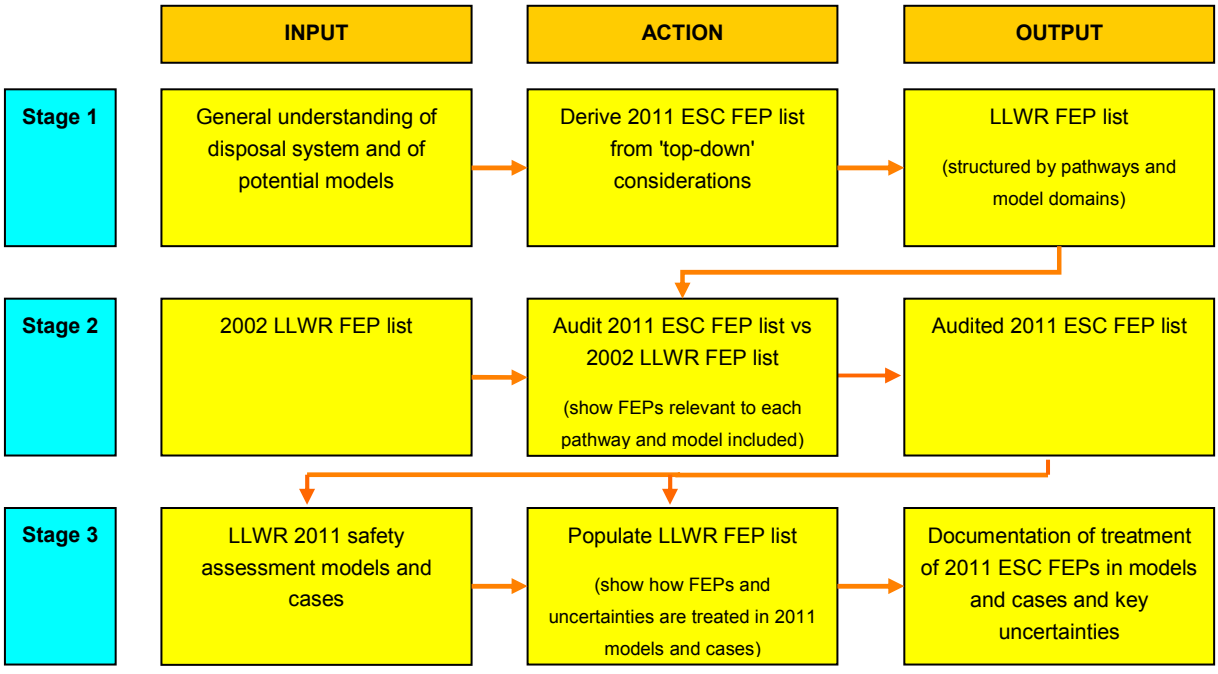
uncertainty tracking system must carry the minimum information needed to satisfy traceability and clarity.

3.2. Process for development of the 2011 FEP list

Using information from all the iterations of assessment that have been undertaken to date at the LLWR, it was considered appropriate to develop the 2011 ESC FEP list based on identification of what the most important factors are for each pathway (groundwater, gas, natural disruption (coastal erosion) and human intrusion) and sphere (near field, geosphere and biosphere). This approach has ensured that those FEPs that are applicable to scenarios, models and cases supporting the 2011 ESC are assessed in the FEP and uncertainty tracking system, describing FEPs at a level of detail that is consistent with their implementation in the assessment. This approach avoids the complexity of the 2002 FEP list. The 2002 FEP list was, however, used to undertake an audit to ensure that all relevant FEPs were captured.

A three stage process was defined to develop the 2011 FEP list and the FEP and uncertainty tracking system, as shown in Figure 1.

Figure 1: Process for the development of the FEP and Uncertainty tracking system



3.3. Information and resources

In the development of the 2001 FEP list, the audit of the 2011 FEP list against the 2002 LLWR FEP list and the population of the FEP and uncertainty tracking system, the following key sources of information were taken into account:

- the 2002 PCRSA and PCSC, including the PCRSA scenarios, models and calculation cases, the PCRSA results and the subsequent review by the Environment Agency;
- the LLWR Authorisation Schedule 9 Requirement 2 submission; and
- subsequent and ongoing work.

Personnel involved in this work were considered to be suitably qualified and experienced in the specific subject area in which they were working (e.g. near field biogeochemistry or biosphere studies) and to possess an appropriate level of knowledge on the scenarios, models and cases supporting the 2011 ESC. From NNL, this comprised the following people:

- Candida Lean (geosphere, gas pathway, coastal erosion, human intrusion and miscellaneous FEPs);
- Alan Wareing (inventory);
- Matthew Randall (near field, geochemistry and gas pathway);
- Joe Small (near field, geochemistry and gas pathway);
- Andras Paksy (engineering and human intrusion);
- Ed Henderson (engineering and geosphere);
- Mark Willans (biosphere, dose factors and miscellaneous FEPs); and
- Nathalie Galais (biosphere and dose factors).

Support was provided by staff from the LLWR in the derivation of the 2011 FEP list and the format of entries in the tracking system. This included Trevor Sumerling (gas pathway, coastal erosion, human intrusion and biosphere), Andy Baker (near field) and John Shevelan (geosphere). The FEP descriptions and uncertainty descriptions, however, are as developed by NNL staff.

3.4. Stage 1: initial development and structure of 2011 FEP list

The first stage involved the derivation of the 2011 ESC FEP list from 'top-down' principles, based on general understanding of disposal system and of potential models. 'Top-down' in this context refers to a general understanding of the disposal system and the functionality and parameterisation of potential computer based models that are likely to be used for the 2011 ESC. This enabled the 2011 ESC FEP list to be derived taking into account the bounds imposed by the models and avoiding levels of detail (inherent in the previous 2002 FEP list) that could not be realistically modelled. Effectively, the 2011 ESC FEP list covers all those factors that are considered in the definition of conceptual models and development of the safety assessment supporting the 2011 ESC.

Structure of the 2011 FEP list

The 2011 ESC FEP list has been developed assuming that future waste disposal at the LLWR is consistent with current plans for site development (i.e. "expected" or reference arisings, waste treatments, acceptance criteria, and facility design and management). The FEPs are divided at the highest level into three groups:

- FEPs that are common to all pathways;
- pathway-specific FEPs (i.e. groundwater, gas, coastal erosion and human intrusion); and
- FEPs that are not modelled (but which may be considered qualitatively and discounted).

Pathway-specific FEPs are divided according to the pathway(s) they relate to. Within each pathway, the FEPs are then divided according to major conceptual model domains (e.g. near field, geosphere and biosphere for the groundwater pathway) and further divided in line with the models being considered (e.g. near field FEPs are sub-divided for the trenches, vaults and site engineering). Areas of commonality between the assessments of FEPs for each pathway, in particular for the near field, were taken into consideration.

Using this approach, the 2011 ESC FEP list was derived by the topic area experts listed in Section 3.3. Following iteration between staff from the LLWR and NNL, an agreed list of 308 FEPs was derived. It is reproduced in Appendix 1.

3.5. Stage 2: Audit of 2011 FEP list against the 2002 list

The second stage comprised an audit of the 2011 ESC FEP list against the 2002 LLWR FEP list, which was undertaken by NNL. This audit provided a mechanism for identifying which of the FEPs in the 2002 FEP list are taken through to the 2011 FEP list (either as a FEP in its own right or as a part of a higher level FEP). The audit also gave the opportunity to identify whether any key FEPs were missing from the 2011 FEP list.

A total of 1405 FEPs and 37 EFEPs from the 2002 FEP list were reviewed against the FEPs in the 2011 FEP list. The FEPs in the 2002 list were categorised as follows:

- included in the 2011 FEP list as a standalone FEP;
- subsumed within a higher level FEP in the 2011 FEP list; or
- not included within the 2011 FEP list.

A brief statement on the reason for 2002 FEPs not being included in the 2011 FEP list was given. In the majority of cases this was because many of the 2002 FEPs were defined at too high a level of detail to be considered in the 2002 PCRSA and could not practicably be included in the modelling supporting a near-surface disposal facility safety case (e.g. 'groundwater flow in the near field resulting in dissipation of heat', 'gas produced in vaults resulting in desiccation of cut-off wall' and 'influence of unsaturated zone water on microbiota - provides substrate for microbes'). Other FEPs were not considered as they were not of relevance to the timescales of interest to the 2011 ESC (e.g. relating to glacial or cold climate processes) or to geological processes (e.g. orogeny or volcanic activity). Reference identifiers (ids) of related FEPs in the 2011 FEP list were given for those 2002 FEPs that are carried through to the 2011 FEP list either as standalone FEPs or as part of a higher level FEP.

No additional FEPs were identified by the audit at a level appropriate to be added to the 2011 FEP list.

The full results of the audit are documented within the FEP and uncertainty tracking system (Lennon, 2010).

3.6. Stage 3: Populating the 2011 FEP and uncertainty tracking system

The third stage of the process comprised the population of the FEPs and uncertainty tracking system, showing how FEPs are treated in the 2011 safety assessment models and cases. Population of the system and checking of entries was carried out by NNL and is discussed further in Section 4. The tracking system has been developed taking into account the benefits recognised by the NEA in terms of providing a source of information that can be used during model development, providing a framework to record

information about a FEP and allowing an audit of assessment models against the FEP list to ensure that all relevant factors have been taken into consideration (Section 2.1 and NEA, 2000).

4. The FEP and Uncertainty Tracking System

The FEP and uncertainty tracking system has been developed as a Microsoft Excel™ spreadsheet based system. This section describes the functionality of the FEP and uncertainty tracking system and the information contained within it.

4.1. Information held in the FEP and uncertainty tracking system

Guidance on the data fields included within the FEP and uncertainty tracking system for each FEP is given in Table 1. A user guide for the use and management of the database is provided by Lean and Lennon (2010).

Table 1: Data fields in the FEP and uncertainty tracking system

Field	Explanation / comment	Field content
FEP id	Unique letter code associated with the pathway in which the FEP resides and a sequential number.	Letter and number code
FEP category	Also incorporated in id code, but useful for clarity within each worksheet.	Text field
FEP name	Self-explanatory.	Text field
FEP description	Topic area expert description of the relevance and realisation of the FEP within the LLWR system; based on scientific understanding.	Text field
Uncertainty description	Consideration of the scientific and data uncertainties around this FEP.	Text field
FEP and uncertainty judgement	Topic area expert's judgment on the "local" importance of the uncertainty, coded as High, Medium or Low. (This indicates how important it will be to represent the uncertainty.)	*Drop-down box – 3 options:* High = significant uncertainty or variability and impact on sub-system performance Medium = some uncertainty or variability and some impact Low = either little/no uncertainty or little/no impact on sub-system performance
FEP and uncertainty treatment description	How the FEP, and if necessary the uncertainty, is/are treated, and why this is reasonable/supported.	Text field
FEP and uncertainty treatment	How the FEP and uncertainty is treated in the 2011 performance assessment calculations.	*Drop-down box – 6 options:* None (e.g. because assigned "Low" above, or because standard stylised assumptions are applicable) Alternative model Alternative (variant) case (i.e. substantially different input

Field	Explanation / comment		Field content
		parameter set or boundary conditions) Parameter variation – deterministic Parameter variation – probabilistic Not modelled	
Key references	List of key references; with number for identification within each record.		Text field
Working comments	Place to add reminders about refinement or more work needed on this record. Generally, will be blank at the time of version freeze.		Text field
QA & acceptance	Contractor QA (author & checker) and LLWR acceptance boxes – names and dates – as in prototype.		Names and dates boxes
Record history	Update history (use the same day rule).		Date list and iteration number
Uncertainty management	LLWR view on the importance of the uncertainty and whether this uncertainty has been satisfactorily "bottomed out" in the assessment, or needs additional assessment or management going forwards from the 2011 ESC.		Text field
Uncertainty management – code 1 – importance	LLWR judged importance of FEP and uncertainty.	*Drop-down box – 3 options:* Negligible impact Significant for safety assessment Significant for ESC	
Uncertainty management - code 2 – satisfaction level	LLWR judged satisfaction level with current treatment of FEP and uncertainty.	*Drop-down box – 3 options:* Content Minor concerns (some work needed) Serious concerns	
Peer review or Environment Agency comments	Blank field for peer reviewers or the Environment Agency to use when reviewing the FEP tracking system.		Text field

Data entry to the FEP and uncertainty tracking system is controlled through the use of forms, thereby allowing the user to enter data and interrogate the database in a logical manner. The forms also provide a user-friendly means of viewing the information in the system.

In the case that existing information in the database requires updating, for example to take account of new data, all original entries are saved to a separate worksheet within the database to maintain a full audit trail of changes. A same day rule is used for tracking of changes to avoid partially complete updates being recorded on every save. The record history of each entry details the date of the most recent entry and the number of iterations made to each FEP.

The system also includes an uncertainty tracking worksheet which allows the user to list all FEPs that are associated with uncertainties that may have significance on either the

overall ESC or on calculated site impacts. Uncertainties may be listed according to expert judgement on the importance of the uncertainty in the FEP and its impact on sub-system performance (the 'FEP and uncertainty judgement' data field) and also on the means by which the FEP and uncertainty is treated in the 2011 ESC (the 'FEP and uncertainty treatment' data field). This worksheet is designed to support the development of a register of significant uncertainties.

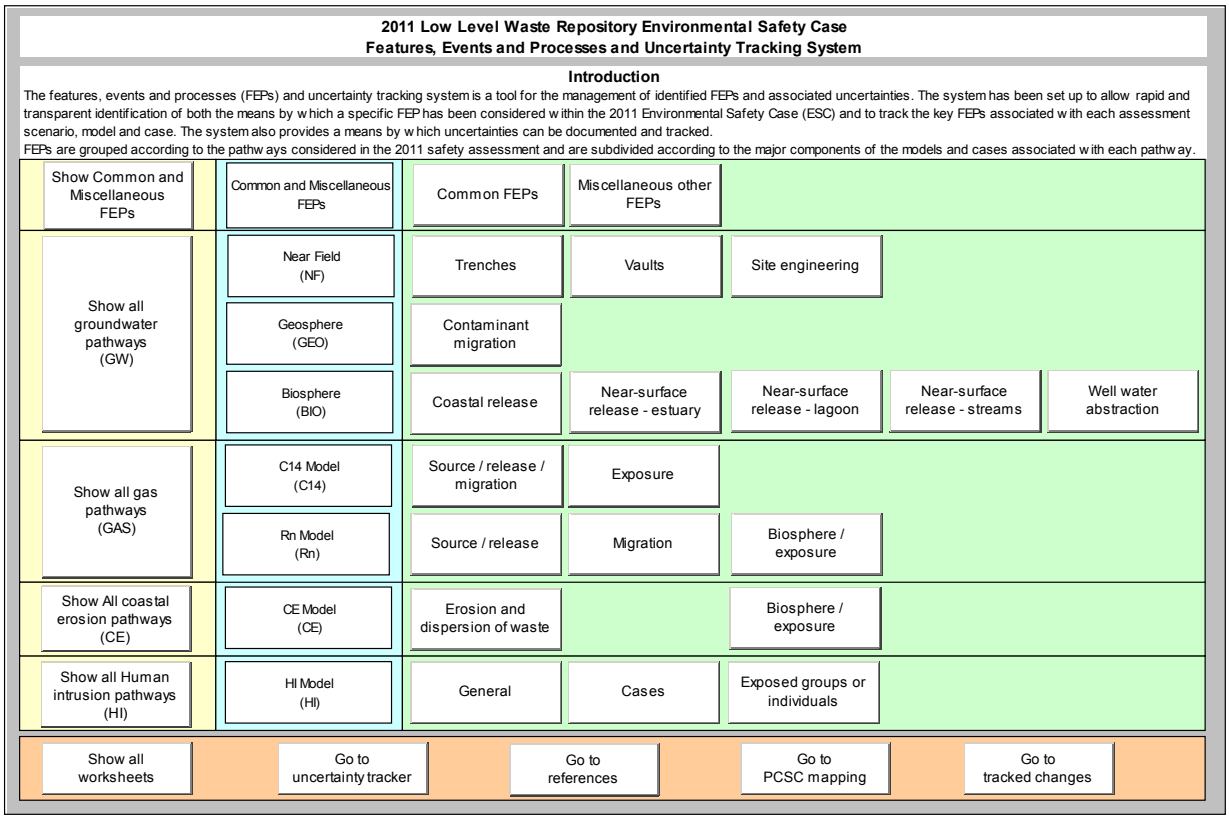
4.2. User interface

The opening worksheet of the FEP and uncertainty tracking system tool contains the title of the tool with authorship, verification and approval together with a history sheet record of design stages. The tool has been extensively verified and checked prior to approval in accordance with NNL quality assurance procedures.

The second worksheet contains 'read me' information and provides details of the content of each of the worksheets in the FEP and uncertainty tracking system and guidance on its use and population (in accordance with the user guide: Lean and Lennon, 2010).

After the opening worksheets, the tool contains a worksheet entitled 'MAIN' that contains the high level user interface for the FEP and uncertainty tracking system, which is illustrated in Figure 2. This user-friendly front page enables the user to quickly search for information relating to specific parts of the 2011 safety assessment.

Figure 2: Interface for the FEP and uncertainty tracking system



A separate worksheet within the FEP and uncertainty tracking system is used to store information relating to each of the pathways and major conceptual model domains (sub-division of the FEP list is shown in the tables in Appendix 1). Tabs on the high level user interface worksheet allow the user to quickly navigate to information on FEPs relating to

specific pathways or conceptual model domains. The interface has been colour-coordinated in order to make it more user-friendly:

- yellow panel – pathways;
- blue panel – models; and
- green panel – conceptual model domains associated with the pathways and models.

Specific information can also be reached via tabs at the bottom of the spreadsheet; due to the large number of separate worksheets, the user can choose to make these tabs hidden to improve readability via the yellow 'show' and 'hide' tabs.

The user interface also has a bottom panel of boxes (orange panel) which allows the user to access more specific information. This includes:

- the uncertainty tracker, which allows listing of FEPs according to expert judgement on the importance of the uncertainty in the FEP and its impact on sub-system performance and also on the means by which the FEP and uncertainty is treated in the 2011 ESC;
- a list of all reference material used in the population of the FEP and uncertainty tracking system;
- the audit of the 2002 LLWR FEP list with the 2011 ESC FEP list; and
- a record of original data entries that have been subsequently updated, in order to maintain an audit trail.

4.3. Audit of the 2011 FEP list against the 2002 FEP list

As noted above, the results of the audit of the 2011 FEP list against the 2002 FEP list are provided in a worksheet, 'PCSC Mapping', within the FEP and uncertainty tracking system. This worksheet is accessible via a command button on the high level user interface, 'MAIN', worksheet.

The following information is included within the audit worksheet:

- 2002 FEP:
  - 2002 reference number;
  - description; and
  - key words, which were used to map the FEPs in the 2002 FEP list and relate to major components or features of the disposal facility and its environs and, thus, provide a simple means of relating FEPs to 'types' of process, such as physical processes, chemical processes *etc*;
- whether the 2002 FEP is included within the 2011 FEP list ('yes - as standalone FEP', 'yes - included within another FEP' or 'no') ;
- FEP id's of the related 2011 FEPs;
- comments, providing brief statement on the reason for 2002 FEPs not being included in the 2011 FEP list; and
- QA boxes for the author and checker (names and dates).

Example entries in the audit worksheet are provided in Appendix 2.

4.4. Population of the FEP and uncertainty tracking system

The FEP and uncertainty tracking system has been populated by NNL topic area experts based on their expert knowledge of previous conceptualisation and assessment work that has been undertaken and their understanding of what is likely to be included in the 2011 ESC assessment models, as described in Sections 2.3 and 3.3.

When completing the form, the authors were required to:

- consider the treatment of each FEP in terms of the scenarios, models and cases that are proposed for inclusion in the 2011 ESC, whilst noting that these are yet to be finalised;
- note that some FEPs will be relevant to more than one pathway, however, the method of treatment may vary between pathways;
- detail how the FEP is treated at a scenario and conceptual model level and how it will be implemented in the safety assessment;
- consider uncertainty associated with the FEP, covering, e.g. the conceptual understanding of the implications of the FEP, the ability to adequately represent the FEP in models/cases, the availability/quality of supporting data and the likely influence of the FEP on site impacts; and
- clearly document reference material.

All entries made to the system to date by NNL have been thoroughly checked by NNL topic area experts. In particular, the checkers were required to confirm that:

- there is sufficient information for justification of the treatment of each FEP at a scenario, conceptual and model level;
- there is an adequate discussion of uncertainty and that the significance of any uncertainties is appropriately assessed;
- references are correctly identified;
- the information is fit-for-purpose; and
- a proof read has been carried out.

The current status of entries in the system is as follows:

- Data fields relating to the FEP description, the uncertainty description and the FEP and uncertainty description and judgement may be considered complete.
- Data fields relating to the FEP and uncertainty treatment and treatment description may be considered preliminary, given that work is still ongoing on development of the models supporting the 2011 ESC. The 'working comments' data field has been used to record where entries are likely to need update.
- Data fields relating to the LLWR view on the importance of the uncertainty, and whether this uncertainty has been satisfactorily considered in the assessment, and peer review or Environment Agency comments have been left blank.

The FEP and uncertainty tracking system is intended to be a live database (i.e. subject to update as necessary). It is therefore recommended that, in parallel with the completion of the 2011 assessment models, a ‘frozen’ version of the database is made to complete the audit trail for the 2011 ESC. At the point of creation of the frozen version, a ‘clean’

version of the tracking system could be created, removing the original data entries that have been saved in the 'Tracked Changes' worksheet. This would enable the tracking system to be distributed to stakeholders, for example, the Environment Agency.

The entries are included within the FEP and uncertainty tracking system (Lennon, 2010). It is outside the scope of this report to include all information contained within the tracking system, however, some example entries are included in Appendix 3 for reference. These examples demonstrate how the 'working comments' data field has been used to identify where information may need to be updated.

5. Summary and conclusions

NNL have developed, in conjunction with staff from the LLWR, a tracking system for the management of FEPs and documentation of associated uncertainties for the 2011 ESC. As part of this work, a 2011 ESC FEP list has been defined.

An identification of the factors relevant to the performance of a disposal system, and assurance that the important processes and uncertainties have been appropriately and adequately represented is central to confidence in the completeness of safety assessments. In the case of the LLWR, a high level of understanding of the relevant factors has been developed through iterative safety assessments and supporting studies carried out over the past decade. Thus, it was considered most appropriate to develop the 2011 ESC FEP list and consideration of uncertainties based on the models that are proposed for use in the 2011 ESC, which are in turn based on that detailed experience and results of previous assessments. This leads to a FEP and uncertainty tracking system that is directly linked to the assessment models that will be used and cases that will be evaluated.

The identification of FEPs and uncertainties has, therefore, been based on a consideration of what the most important factors are for each of the assessment model pathways (groundwater pathway, gas pathway, coastal erosion and human intrusion) and taking account of the conceptual understanding of each pathway. This approach ensures that those FEPs that are relevant to scenarios, models and cases supporting the 2011 ESC are identified, while also giving scope to identify and record FEPs that are not directly represented in those scenarios, models and cases. This avoids the complexity of the previous (2002) LLWR FEP list, which contained over 1400 FEPs at a level of detail that could not always be realistically modelled (BNFL, 2002a). It also ensures that the 2011 ESC FEP list is closely linked to the assessment calculations. The current list of 308 FEPs is structured by pathway and model domain and is appended to this report. It has been audited against the 2002 FEP list to check that all relevant FEPs from the 2002 FEP list have been considered.

The FEP and uncertainty tracking system is implemented as a Microsoft Excel™ spreadsheet including screens and macros to assist in the management of the identified FEPs and associated uncertainties. The system includes: details of each FEP; a topic area expert's judgement of the relevance and realisation of the FEP within the LLWR system; an assessment of the scientific and data uncertainties around each FEP; and details of how the FEP and, where appropriate, associated uncertainty is treated in the safety assessment and overall ESC. Data entry to the tracking system is controlled through a defined process and password protections. Data and judgements are entered via user-friendly forms. The same forms or screens can be examined by other users or reviewers to interrogate the database in a logical manner.

The system allows the identification of how a specific FEP has been considered within the 2011 ESC and the tracking of the key FEPs associated with each pathway and model. The system also provides a means by which significant uncertainties can be identified, rated according to expert judgement on the importance to sub-system performance, and record how the uncertainty is treated in the 2011 ESC. This is intended to support the LLWR in developing a register of significant uncertainties as required by the Environment Agency.

The FEP and uncertainty tracking system has been populated by NNL based on their expert knowledge of previous conceptualisation and assessment work that has been undertaken at the LLWR and their understanding of what is likely to be included in the 2011 ESC assessment models as advised by LLWR staff (Lennon, 2010). The system also contains a full listing of all reference material that has been used in its population and details of the audit of the 2011 FEP list against the 2002 ESC FEP list.

As assessment models and cases are developed in support of the 2011 ESC, there will be a need to review and update many of the entries in the FEP and uncertainty tracking system, principally associated with the FEP and uncertainty treatment data fields. Where applicable, the need to update entries is noted in the 'working comments' data field. When data is updated, all original entries are saved to a separate worksheet within the database to maintain a full audit trail of changes; the record history of each entry records the date of the most recent entry and the number of iterations made to each entry. As the tracking system is intended to be a 'live' system (i.e. subject to regular update as necessary), it is recommended that, in parallel with the completion of the 2011 assessment models, a 'frozen' version of the database is made to complete the audit trail for the 2011 ESC. At the point of creation of the frozen version, a 'clean' version of the tracking system could be created, removing the original data entries that have been saved in the 'Tracked Changes' worksheet and enabling the tracking system to be distributed to stakeholders, for example, the Environment Agency.

LLW Repository Ltd. understands that demonstration of the appropriate treatment and management of FEPs and uncertainties will be vital to the robustness of the 2011 LLWR safety assessment and the overall acceptability of the 2011 ESC. The development and use of the 2011 ESC FEP list and the FEP and uncertainty tracking system, as described in this report, provides a good foundation to achieving this requirement. The tracking system provides a transparent means for documenting and justifying the treatment of FEPs and associated uncertainties in the 2011 ESC. As such, the system will be of use in developing safety assessments in support of the 2011 ESC, and should also be of value to technical reviewers of the assessments.

6. References

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Appendix 1: 2011 FEP List

The 2011 FEP list is detailed in the tables below. It is divided according to the four exposure pathways to be considered in the 2011 ESC:

- groundwater pathway;
- gas pathway;
- coastal erosion pathway; and
- human intrusion pathway.

The FEP list is further sub-divided according to the major components of the models/cases being considered in the 2011 safety assessment (e.g., for the groundwater pathway, near field, geosphere and biosphere). In addition, FEPs have been defined that are common to all pathways (e.g. waste forms for key radionuclides and dose factors) and miscellaneous FEPs that have been considered but are not taken forward in the assessment models.

The 2011 FEP list is detailed in the following tables:

- Table A1.1 FEPs that are common to all pathways
- Table A1.2 Groundwater pathway: Near field trenches
- Table A1.3 Groundwater pathway: Near field vaults
- Table A1.4 Groundwater pathway: Near field site engineering
- Table A1.5 Groundwater pathway: Geosphere
- Table A1.6 Groundwater pathway: Biosphere coastal release
- Table A1.7 Groundwater pathway: Biosphere release to estuary
- Table A1.8 Groundwater pathway: Biosphere release to lagoon
- Table A1.9 Groundwater pathway: Biosphere release to streams
- Table A1.10 Groundwater pathway: Biosphere well water abstraction
- Table A1.11 Gas pathway: Carbon-14, source/release/migration
- Table A1.12 Gas pathway: Carbon-14, exposure
- Table A1.13 Gas pathway: Radon, source/release
- Table A1.14 Gas pathway: Radon, migration
- Table A1.15 Gas pathway: Radon model, biosphere/exposure
- Table A1.16 Coastal erosion pathway: Erosion and dispersion of waste
- Table A1.17 Coastal erosion pathway: Biosphere/exposure
- Table A1.18 Human Intrusion: General
- Table A1.19 Human Intrusion: Cases
- Table A1.20 Human Intrusion: Exposed groups or individuals
- Table A1.21 Miscellaneous other FEPs

Information given in each table covers the relevant pathway, category (relating to specific part of the system being described, for example, system features and migration pathway characteristics) and the FEP name. A description of each FEP, together with details on how it is considered within the 2011 ESC, is given in the FEP and uncertainty tracking system (Lennon, 2010).

Table A1.1: FEPs that are common to all pathways

Pathway	Category	FEP name
FEPs that are common to all pathways	LLWR-specific (RN = radionuclide)	Trenches inventory
		Vault 8 inventory
		Future vaults inventory
		Key RN waste forms and distribution - H-3
		Key RN waste forms and distribution - C-14
		Key RN waste forms and distribution - Cl-36
		Key RN waste forms and distribution - Tc-99
		Key RN waste forms and distribution - I-129
		Key RN waste forms and distribution - Ra-226
		Key RN waste forms and distribution - U isotopes
		Key RN waste forms and distribution - Th-232
		Key RN waste forms and distribution - Pu isotopes
	General	Radionuclide decay and ingrowth
		Dose factors - ingestion & inhalation, adults
		Dose factors - ingestion & inhalation, infants & children
		Dose factors - external irradiation
		Dose factors - minor modes
		Dose factors - radon and radon daughters
		Radiological dose-to-risk factor

Table A1.2: Groundwater pathway: Near field trenches

Pathway	Category	FEP name
Groundwater pathway: Near field, trenches	Sub-system features	Trenches - general characteristics
		Trenches - waste form characteristics (as disposed)
		Management - now and future
	Environment conditions	Water inflow and infiltration
		Hydraulic/hydrologic conditions and evolution
		Waste form conditions and evolution
		Overall trench physical conditions and evolution
		Eh conditions and evolution
		pH conditions and evolution
		Microbiological processes and evolution
		Gas generation and reactions (effect on groundwater path)
	Radionuclide release and migration	Release from waste form - metals
		Release from waste form - organics/cellulosics
		Release from waste form - U release from MgF
		Release from waste form - other particular waste forms
		Radionuclide solubility
		Radionuclide sorption
		Colloids
		Complexation

Table A1.3: **Groundwater pathway: Near field vaults**

Pathway	Category	FEP name
Groundwater pathway: Near field, vaults	Sub-system features	Vaults - general characteristics
		Vault 8/9 - waste forms and containers
		Post innovations - waste form & containers
		Management - now and future
	Environment conditions	Water inflow and infiltration
		Hydraulic/hydrologic conditions and evolution - V8/9
		Hydraulic/hydrologic conditions & evolution - post-innovations
		Container/grout conditions and evolution - V8/9
		Container/grout conditions and evolution - post-innovations
		Waste form conditions and evolution - V8/9
		Waste form conditions and evolution - post-innovations
		Overall vault physical conditions and evolution - V8/9
		Overall vault physical conditions and evolution - post-innovations
		Eh conditions and evolution
		pH conditions and evolution
		Microbiological processes and evolution - V8/9
		Microbiological processes and evolution - post-innovations
	Radionuclide release and migration	Release from waste form - metals
		Release from waste form - organics/cellulosics
		Release from waste form - U release from MgF
		Release from waste form - other particular waste forms
		Release from waste form - effect of innovations
		Radionuclide solubility
		Radionuclide sorption
		Colloids
		Complexation

Table A1.4: **Groundwater pathway: Near field site engineering**

Pathway	Category	FEP name
Groundwater pathway: Near field, Site engineering	Sub-system features	Trench design (overall)
		Vault design (overall) - V8/9
		Vault design (overall) - assumed future vault design
		Profiling
		Engineered cap
		Cut-off walls
		Vertical drains
		Site drainage
		Site vegetation (planned)
		Management - now and future
	External changes (Note HI and CE are detailed	Site development after release
		Temperature and rainfall variation
		Natural vegetation changes
		Erosion

Pathway	Category	FEP name
	elsewhere)	Groundwater and infiltration changes
	Engineering performance	Trench performance
		Vault performance
		Cap performance
		Cut-off walls performance
		Underground site drainage performance
		Above site drainage performance
		Water balance
	Radionuclide release/ migration from the site	Groundwater pathways
		Eh conditions and evolution
		pH conditions and evolution
		Radionuclide migration

Table A1.5: **Groundwater pathway: Geosphere**

Pathway	Category	FEP name
Groundwater pathway: Geosphere	System features	Regional and local geology - Quaternary geology
		Regional and local geology - Sandstone geology
		Regional and local hydrogeology - unsaturated zone
		Regional and local hydrogeology - upper groundwater
		Regional and local hydrogeology - Regional groundwater
		Effects of site engineering
		Effects of climatic change
		Effects of coastal change
		Migration pathways & discharge zones
		Groundwater abstraction (wells)
	Migration pathway characteristics	Upper groundwater migration paths
		Regional groundwater migration paths
		Upper groundwater geochemistry
		Regional groundwater geochemistry
		Effects of repository leachate
	Migration pathway / radionuclide release modelling	Pathway - via regional and local groundwater to the coast
		Pathway - via regional and local groundwater to the estuary
		Pathway - discharge to local streams
		Pathway - abstraction from well between the site & coast
		Contaminant speciation and solubility
		Hydraulic retardation / dispersivity
		Chemical retardation / sorption
		Colloids, sources, stability and effects
		Complexants, sources, stability and effects
		Microbial/biological processes
		Potential for gas/volatile release en route

Table A1.6: **Groundwater pathway: Biosphere coastal release**

Pathway	Category	FEP name
Groundwater pathway: Biosphere, coastal release	System features	Geosphere Biosphere Interface (GBI)
		Coastal Features
		Marine Features
	Dispersion / accumulation processes	Entry to shore and seabed water and sediments
		Shore and sea water and sediment movement/balance
		Sorption / desorption to/from sediments
		Sedimentation and resuspension
		Uptake in flora
		Uptake in fauna
	Radionuclide exposure modelling	Specific exposure sources - non foodstuff
		Specific exposure sources - foodstuffs
		PEG - occupational beach user (fisherman)
		PEG - recreational beach user (dog walker, swimmer)
		PEG - semi-resident (beach hut, caravan)

Table A1.7: **Groundwater pathway: Biosphere release to estuary**

Pathway	Category	FEP name
Groundwater pathway: Biosphere, release to estuary	System features	Geosphere Biosphere Interface (GBI)
		Estuarine features
		Marginal features
	Dispersion / accumulation processes	Estuarine water & sediment movement/balance
		Sorption / desorption to/from sediments
		Sedimentation and resuspension
		Transfer to / exchange with marginal land
		Uptake in flora
		Uptake in fauna
	Radionuclide exposure modelling	Specific exposure sources - non foodstuff
		Specific exposure sources - foodstuffs
		PEG - occupational estuary user (fisherman)
		PEG - recreational estuary user (boats, swimmer)
		PEG - semi-resident (house boat)

Table A1.8: Groundwater pathway: Biosphere release to lagoon

Pathway	Category	FEP name
Groundwater pathway: Biosphere, release to future lagoon	System Features	Geosphere Biosphere Interface (GBI)
		Lagoon features
		Marginal features
	Dispersion / accumulation processes	Lagoon water & sediment movement/balance
		Sorption / desorption to/from sediments
		Sedimentation and resuspension
		Transfer to / exchange with marginal land
		Uptake in flora
		Uptake in fauna
	Radionuclide	Specific exposure sources - non foodstuff

Pathway	Category	FEP name
	exposure modelling	Specific exposure sources - foodstuffs
		PEG - occupational lagoon user (fisherman)
		PEG - recreational lagoon user (boats, swimming)
		PEG - semi-resident (house boat)

Table A1.9: **Groundwater pathway: Biosphere release to streams**

Pathway	Category	FEP name
Groundwater pathway: Biosphere, release to local streams	System Features	Geosphere Biosphere Interface (GBI)
		Water courses
		Adjacent land
	Dispersion / accumulation processes	Stream water & sediment movement/balance
		Sorption / desorption to/from sediments
		Sedimentation and resuspension
		Transfer to / exchange with marginal land
		Uptake in flora
		Uptake in fauna
		Entry to lagoon or estuary water and sediments
	Radionuclide exposure modelling	Specific exposure sources - non foodstuff
		Specific exposure sources - foodstuffs
		PEG - occupational stream user (adult smallholder)
		PEG - other stream users

Table A1.10: Groundwater pathway: Biosphere well water abstraction

Pathway	Category	FEP name
Groundwater pathway: Biosphere, well water abstraction	System features including water uses	Geosphere Biosphere Interface (GBI)
		Domestic/immediate use
		Agricultural use
	Dispersion / accumulation processes	Accumulation in soil
		Soil turnover
		Uptake in flora
		Uptake in fauna
	Radionuclide exposure modelling	Specific exposure sources - domestic water supply
		Specific exposure sources - non foodstuff
		Specific exposure sources - foodstuffs
		PEG - occupational well user (farmer)
		PEG - residential well user (house or caravan)

Table A1.11: **Gas pathway: Carbon-14, source/release/migration**

Pathway	Category	FEP name
Gas pathway: Carbon-14, source/ release/ migration Note: for C-14 (and radon), human actions	Site features, conditions and processes	Operational period
		Post-operational period
		Final cap design
		Long-term cap performance (with respect to gas) natural processes
		Long-term cap performance (with respect to gas) human actions
	Trench	C-14 trench inventory and waste association

Pathway	Category	FEP name
that affect cap integrity are treated here. Excavation into the waste and immediate and consequent impacts are treated under human intrusion.	features, conditions and processes	Modes for release of C-14 labelled gases from waste
		Trench conditions relevant to gas generation/release
		Trench conditions relevant to gas migration
		Trench soil and hardcore layer
		Trench gas monitoring data
	Vault features, conditions and processes	C-14 Vault 8 inventory and waste association
		C-14 Future Vaults inventory and waste association
		Modes for release of C-14 labelled gases from waste
		Vault conditions relevant to gas generation/release
		Vault conditions relevant to gas migration
	Profiling and cap features, conditions and processes	Gas migration in profiling
		Gas migration in cap - intact
		Chemical retardation/containment
		Migration in cap - damaged or degraded
		Exchanges between gas and groundwater
		C-14 migration in groundwater

Table A1.12: **Gas pathway: Carbon-14, exposure**

Pathway	Category	FEP name
Gas pathway: Carbon-14, exposure	Radionuclide biosphere/ exposure modelling	Release to open air
		Entry into agricultural system (soil and vegetation)
		Exposure via foodstuff/diet
		Entry to building
		Entry into non-agricultural conditions
		PEG - farmer on the cap
		PEG - residential

Table A1.13: **Gas pathway: Radon, source/release**

Pathway	Category	FEP name
Gas pathway: Radon, source/ release	Radon specific issues	Specifics of U/radon decay chain and implications
		Specifics of radon decay and daughters
		Specifics of Th/thoron decay chain and implications
	Site features, conditions and processes	Operational period
		Post-operational period
		Final cap design
		Long-term cap performance (with respect to gas) natural processes
		Long-term cap performance (with respect to gas) human actions
	Trench features, conditions and processes	Ra-226 trench inventory and waste association
		U-234 trench inventory and waste association
		Radon emanation
		Trench conditions relevant to gas release and migration
		Trench soil and hardcore layer
		Radon monitoring data
	Vault features, conditions and processes	Ra-226 Vault inventory and waste association
		U-234 trench inventory and waste association
		Radon emanation

Pathway	Category	FEP name
		Vault conditions relevant to gas release and migration

Table A1.14: **Gas pathway: Radon, migration**

Pathway	Category	FEP name
Gas pathway: Radon, migration	Profiling and cap features, conditions and processes	Profiling and cap characteristics
		Migration in groundwater
		Migration in gas phase - molecular diffusion
		Migration in gas phase - advection with carrier gas
		Migration in gas phase - barometric pumping
		Migration in gas phase - differential pressure effects
		Effect of building on the cap

Table A1.15: **Gas pathway: Radon model, biosphere/exposure**

Pathway	Category	FEP name
Gas pathway: Radon model, biosphere/ exposure	Radionuclide biosphere/ exposure modelling	Release to open air
		Entry and accumulation in buildings
		Empirical relationships
		Occupancy and human habits
		Dose factors for radon and radon daughter exposure
		Other sources of radon

Table A1.16: **Coastal erosion pathway: Erosion and dispersion of waste**

Pathway	Category	FEP name
Coastal erosion pathway: Erosion and dispersion of waste	Nature and timing of erosion	Climate change and sea-level rise
		Coastal morphology and development, general
		Rate and direction of erosion with respect to the disposal area
		Timing and nature of erosion
		Human actions - sea defences
	Erosion of wastes	Physical characteristics of vault structures and waste
		Physical characteristics of trench structures and waste
		Physico-chemical characteristics of vault waste (V8/9)
		Physico-chemical character of vault waste, post innovations
		Physico-chemical characteristics of trench waste
		Key RN distribution & waste form associations in vaults
		Key RN distribution & waste form associations in trenches

Table A1.17: **Coastal erosion pathway: Biosphere/exposure**

Pathway	Category	FEP name
Coastal erosion pathway: Exposure/ biosphere	Exposure sources and dispersion	Cliff
		Storm beach
		Foreshore/intertidal area
		Offshore region
		Estuary
		Bulk dispersion processes
		Size and density-dependent sorting
		Leachate migration
	Radionuclide dispersion / accumulation processes	Shore and sea water and sediment movement/balance
		Sorption / desorption to/from sediments
		Sedimentation and resuspension
		Uptake in flora
		Uptake in fauna
	Radionuclide exposure modelling	Specific exposure sources - external irradiation
		Specific exposure sources - inhalation
		Specific exposure sources – inadvertent ingestion
		Specific exposure sources - foodstuffs
		Specific exposure sources - small items
		PEG - occupational beach user (fisherman)
		PEG - recreational beach user (dog walker, swimmer)
		PEG - semi-resident (beach hut, caravan)

Table A1.18: **Human Intrusion: General**

Pathway	Category	FEP name
Human intrusion: General	General arguments	Site controls and direct supervision
		Passive controls
		Effect of engineered cap and profiling
		Coastal erosion

Table A1.19: **Human Intrusion: Cases**

Pathway	Category	FEP name
Human intrusion: Cases	Events possible at any time	Intentional or planned intrusion
		Aircraft crash
	Events possible after site planning controls lapse or cease	Site geotechnical investigation
		Onsite water abstraction well
		Housing development
		Leisure or light industrial development
		Farm / small holding
		Building with cellar
		Cap material removals
	Events possible after coastal erosion reveals on repository	Informal scavenging
		Local organised excavation
		Larger-scale commercial excavation
		Technical or archaeological investigation

Table A1.20: Human Intrusion: Exposed groups or individuals

Pathway	Category	FEP name
Human intrusion: Exposed groups or individuals	Those engaged in intrusion	Driller (site investigation)
		Geotechnical laboratory
		Manual excavation worker
		Excavation machine driver/worker
	Those dwelling on site or exposed to excavated material	House on the cap dweller
		Farmer / smallholder
		Building on excavated waste/vault materials
		Waste mixed with agricultural soil
		Metal recovery

Table A1.21: Miscellaneous other FEPs

Pathway	Category	FEP name
Miscellaneous other FEPs	FEPs that are not mentioned above, have been considered but are not included in assessment models	Plant intrusion into cap or waste
		Animal intrusion
		Earthquake
		Tsunami
		Terrorism or other malicious acts

Appendix 2: Example entries in the audit of the 2011 FEP list against the 2002 FEP list

FEP Number	Description	Key words	Included in 2011 FEP list?	Related FEPs	Comments
I/A2/1.1	Influence of the Geosphere on the Near-field - Groundwater flow into the Near-field resulting in: generation of leachate flux	Flow – direction	yes - included within another FEP	GW_NF_SE_EC_05	-
I/A3/2.6	Influence of the Biosphere on the Near-Field - Infiltration influenced through: dissipation of heat	Heat	no		FEP not included in 2002 PCRSA
II/G6/1	Influence of the solid geology on microbiota - provides a substrate for microbes (including niches)	Biological – substrate	yes - included within another FEP	GW_GEO_CM_MPRRM_010	-
III/C4/3.1	Influence of water bodies on human community - Potential source of exposure - Ingestion	Potential Exposure Group – exposure	yes - included within another FEP	Common_Gen_02. Common_Gen_03; GW_BIO_CR_REM_03; GW_BIO_CR_REM_04; GW_BIO_CR_REM_05; GW_BIO_NSRFE_REM_03; GW_BIO_NSRFE_REM_04; GW_BIO_NSRFE_REM_05; GW_BIO_NSRFL_REM_03; GW_BIO_NSRFL_REM_04; GW_BIO_NSRFL_REM_05; GW_BIO_NSRS_REM_03; GW_BIO_NSRS_REM_04; GW_BIO_WW_REM_04; GW_BIO_WW_REM_05	-
1.3.05	Climatic processes and effects -Glacial and ice sheet effects, local	EFEP	no		Not of relevance over timescales of interest
1.5.02	Future human actions (Active) - Animal/plant intrusion into the wastes	EFEP	yes - as standalone FEP	Misc_Other_01; Misc_Other_02	-

Appendix 3: Example entries in the FEP and uncertainty tracking system

Field name	**FEPs that are common to all pathways**	**Coastal erosion: erosion and dispersion of waste**	**Miscellaneous other FEPs**
FEP ID	Common_Gen_1	CE_E_NTE_001	Misc_Other_3
FEP category	General	Nature and timing of erosion	FEPs that are considered but not included in assessment models
FEP name	Radionuclide decay and growth	Climate change and sea-level rise	Earthquake
FEP description	The natural phenomenon of radioactive decay of radionuclides including daughters as associated with the various LLWR inventories and taking into account the assessment period.	Both climate change and associated sea level change need to be considered over the timescales of relevance to the 2011 LLWR ESC. Current predictions indicate that the global climate is likely to warm over the next 100s to 1,000s of years, leading to significant sea level rise due to thermal expansion and the melting of on-land ice. Even without significant seal level rise, extrapolation of present day erosion rates indicate that the LLWR will be affected by coastal erosion. The effect of sea level rise is expected to accelerate the process. Glacial conditions (significant sea-level fall) are not expected to occur within the next 100,000 years.	A large seismic event would have the potential to disrupt the LLWR (e.g. through rupture or liquefaction) and to modify the hydrological and hydrogeological characteristics local to it.
Uncertainty description	There are uncertainties associated with determining which daughter products should be included in the decay chains given their half-lives in relation to the duration and output time resolution of the assessment. Bifurcation of decay chains can also occur.	Rates of future climate change and sea level rise are subject to substantial uncertainty. The international BIOCLIM project [1]) has set out alternative scenarios for future climate change over the timescales of relevance to radioactive waste disposal assessment. The impact of the BIOCLIM scenario are assessed in Ref [2] which adopts three broad scenarios from BIOCLIM: one involving an extended interglacial without significant warming or sea level rise (not considered likely) and two with different magnitudes of global warming and sea level rise. In the latter scenarios, mean sea level rises of 2 to 10 m are expected within 1,000 years, rising to 7.3 to 24.6 m by 3 ky AP, stabilising to 6.5 to 23.8 m above present day levels after this time. This uncertainty is related to the stability of the Greenland and Antarctic ice sheets.	The LLWR is currently, and will continue to be, exposed to a limited risk of seismic hazard from nearby shallow earthquakes of moderate magnitude, short duration and modest peak intensity [1]. There is no evidence to suggest that that an earthquake of sufficient magnitude to damage the LLWR has occurred in at least the last 10,000 years. As discussed by Ref [2], the region is seismically quiescent and the credible likelihood of an event occurring over the next 100,000 years which could damage the LLWR is minimal.

Field name	FEPs that are common to all pathways	Coastal erosion: erosion and dispersion of waste	Miscellaneous other FEPs
FEP ID	Common_Gen_1	CE_E_NTE_001	Misc_Other_3
FEP and U judgement	Low	High	Low
FEP and U treatment description	The radioactive decay of radionuclides and the specification of daughters within associated decay chains together with decay constants are standard information [1]. For the previous 2002 LLWR Post Closure Radiological-Safety Assessment, [2] has provided robust criteria for simplifying the decay chains which can be taken forwards as is towards the 2011 ESC.	The impacts of climate change and sea level rise on the nature and timing of erosion of the LLWR is developed illustratively and semi-quantitatively, including the results of coastal erosion modelling in the update to Ref [2]. This leads to estimates of the timing and rate of erosion of the facility, and estimates of sea-level stand at the time of erosion. This is used to inform the definition of 3 assessment cases: (1) rapid early destruction (2) protracted exposure of waste (3) partial inundation during erosion.	The effects of an earthquake on the LLWR are not included in the assessment due to the low probability of an event of sufficient magnitude to damage the LLWR occurring.
FEP and U treatment	Not considered	Alternative cases	None
References	[1] ICRP, 1983. [2] Thorne, 2002.	[1] BIOCLIM, 2004. [2] Thorne and Kane, 2007.	[1] Hunter, 2003. [2] BNFL, 2002.
Working comments	Ensure there is consistency relating to radionuclides within decay chains used and those assumed in secular equilibrium which may be embodied within the dose coefficients	An update of Ref [2] is planned for spring 2010.	

DISTRIBUTION

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