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National Cooperative for the
Disposal of Radioactive Waste

TECHNICAL REPORT 02-23

Project Opalinus Clay

FEP Management for Safety Assessment

Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis)

December 2002

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Summary

The aims of and the approach used in the FEP management process are:

- The FEP management process has to consider and reflect the approach used by science to describe a disposal system and the approach used when modelling the system as described by science.
  - Science describes its findings with respect to the system and its behaviour and evolution "as a whole", which results in the identification of a set of ***key safety-relevant phenomena***, their expected evolution and associated uncertainties, and possible deviations with respect to the expected evolution.
  - Modellers abstract and fragment the description by science into building blocks that form a suitable basis to develop and apply corresponding quantitative models. This results in a description of the system and its evolution in terms of ***Super-FEPs*** (as groupings of more detailed FEPs) with a reference realisation and alternative realisations to reflect the uncertainties identified by science.
  - To ensure that the modellers have considered all the information (and uncertainties) identified by science, a check is made that, for each of the ***key safety-relevant phenomena***, at least one corresponding ***Super-FEP*** exists; this also includes the corresponding uncertainties. At the same time, a check is made that for each ***Super-FEP***, a corresponding ***key safety-relevant phenomenon*** exists that justifies the inclusion of the Super-FEP in the modelling approach.
  - The FEP management process also keeps track of the ***reserve FEPs*** (FEPs that are considered likely to occur and to be beneficial to safety, but which are deliberately excluded from the assessment cases), and of ***outstanding issues with the potential to compromise safety*** (if there are any).
- The FEP management process has to ensure that a sufficiently broad set of assessment cases is analysed by suitable tools (assessment codes).
  - The ***Super-FEPs*** and their realisations are assessed with respect to their relevance to safety and – if considered relevant – are identified for inclusion into one or more assessment cases. The grouping of the different ***Super-FEPs*** and their realisations into ***assessment cases*** is carried out by looking at their effects on the broad behaviour / evolution of the system, including a check of the effects of the interaction between individual Super-FEPs. Assessment cases addressing similar effects are grouped together into specific scenarios. Cases within a scenario are distinguished by the different conceptualisations of one or more key phenomena or – if the conceptualisation of phenomena is the same – by variations of one or more model parameters.
  - The adequacy of the tools used for the quantitative analysis of the different assessment cases is carried out through a ***qualification of codes*** (in general terms and in terms of ***Super-FEPs***) and a check that the codes applied to analyse a specific case are actually able to reflect all the ***safety-relevant aspects of the Super-FEPs*** that are contained within this case.
- The FEP management process has to take all reasonable measures to ensure completeness.
  - At the start of the analysis, an Opalinus Clay FEP Database ***(OPA FEP Database)*** that contains all safety-relevant issues is developed. Completeness is ensured through auditing the ***OPA FEP Database*** against ***International FEP Databases*** that were developed for this purpose; i.e. for each FEP contained in the ***International FEP Data-***

bases, it is checked whether it is included in the ***OPA FEP Database,*** and if not, that an explanation is available why not.

– Throughout the process of screening of irrelevant information and abstraction of the remaining information, audits and checks of the intermediate information databases (***safety-relevant phenomena, Super-FEPs, assessment cases***) against the ***OPA FEP Database*** are performed; i.e. for each of the FEPs contained in the ***OPA FEP Database*** it is checked if it is included in the database audited or if an explanation / justification exists why not.

This process resulted in a set of information (documented in different tables) that is compiled and described in the present report. There is some degree of overlap with other reports; i.e. some of the tables appear in other reports as well as in the present report. The development of this information and the corresponding tables was highly iterative, thus the final results as described in this report only reflect the interrelation between the different pieces of information, without providing a chronological description of how they were derived.

Zusammenfassung

Die Ziele und das Vorgehen im FEP[1]-Management-Prozess sind:

- Der FEP-Management-Prozess hat das Vorgehen bei der wissenschaftlichen Beschreibung des Lagersystems und die modelltechnische Umsetzung dieser wissenschaftlichen Beschreibung zu widerspiegeln.
  - Die wissenschaftliche Beschreibung bezieht sich auf das Verhalten und die Entwicklung des Systems als Ganzes. Dies führt zur Identifizierung eines Satzes von ***sicherheitsrelevanten Schlüssel-Phänomenen***, charakterisiert durch deren erwartete Entwicklung sowie deren Ungewissheiten und mögliche Abweichungen von der erwarteten Entwicklung.
  - Bei der modelltechnischen Umsetzung wird die wissenschaftliche Beschreibung abstrahiert und in Bestandteile zerlegt, die sich als Basis für die Entwicklung und Anwendung von entsprechenden quantitativen Modellen eignen. Daraus resultiert eine Beschreibung des Systems und seiner Entwicklung in der Form von ***Super-FEPs*** (als Gruppierungen detaillierterer FEPs) mit einer Referenz-Realisierung sowie alternativen Realisierungen, welche die im Rahmen der wissenschaftlichen Beschreibung identifizierten Ungewissheiten widerspiegeln.
  - Um sicherzustellen, dass die Modellierer alle Informationen (und Ungewissheiten) der wissenschaftlichen Beschreibung berücksichtigt haben, wird geprüft, ob für jedes ***sicherheitsrelevante Schlüssel-Phänomen*** (einschliesslich seiner Ungewissheiten) mindestens ein entsprechendes ***Super-FEP*** existiert. Parallel dazu wird geprüft, ob für jedes ***Super-FEP*** ein entsprechendes ***sicherheitsrelevantes Schlüssel-Phänomen*** existiert, das die Berücksichtigung des Super-FEPs in der Modellierung rechtfertigt.
  - Der FEP-Management-Prozess führt auch Buch über die ***Reserve-FEPs*** (FEPs, deren Eintreten als wahrscheinlich eingestuft wird und die sich vorteilhaft auf die Sicherheit auswirken, die aber von der Behandlung in der Sicherheitsanalyse bewusst ausgeschlossen werden) und über ***nicht behandelte Fragestellungen mit Gefährdungspotential für die Sicherheit***, falls vorhanden.

- Der FEP-Management-Prozess hat sicherzustellen, dass die Auswahl der analysierten Rechenfälle hinreichend umfassend ist und dass die Werkzeuge (Rechencodes) für ihren Einsatz geeignet sind.
  - Die ***Super-FEPs*** und ihre Realisierungen werden in Bezug auf ihre Relevanz für die Sicherheit beurteilt und – im zutreffenden Fall – für die Berücksichtigung in einem oder mehreren Rechenfällen identifiziert. Die Einbindung der verschiedenen ***Super-FEPs*** und deren Realisierungen in ***Rechenfällen*** wird anhand deren Auswirkungen auf das übergeordnete Verhalten und die Entwicklung des Systems vorgenommen. Dies schliesst eine Prüfung der Auswirkungen von Wechselwirkungen zwischen individuellen Super-FEPs ein. Rechenfälle mit ähnlichen Auswirkungen werden in Szenarien gruppiert. Die Rechenfälle innerhalb eines Szenariums unterscheiden sich durch die Konzeptualisierung eines oder mehrerer Schlüssel-Phänomene oder – bei identischer Konzeptualisierung – durch die Variation eines oder mehrerer Modellparameter.
  - Die Eignung der für die quantitative Analyse der verschiedenen Rechenfälle verwendeten Rechencodes wird – in allgemeiner Form und in Bezug auf ***Super-FEPs*** – anhand

[1] Die *englische* Abkürzung FEP steht für "**F**eatures, **E**vents and **P**rocesses" (dt. Ereignisse und Vorgänge).

eines spezifischen Verfahrens überprüft (***Qualifizierung der Rechencodes***). Ferner wird geprüft, ob der für einen Rechenfall verwendete Rechencode tatsächlich in der Lage ist, alle ***sicherheitsrelevanten Aspekte der Super-FEPs*** abzubilden, die in diesem Rechenfall enthalten sind.

- Der FEP-Management-Prozess hat alle angemessenen Mittel zur Sicherstellung der Vollständigkeit auszuschöpfen.
  - Am Anfang der Analyse stand die Entwicklung einer FEP-Datenbank für den Opalinuston (***OPA FEP-Datenbank***). Deren Vollständigkeit wurde durch Vergleich mit den verfügbaren, zu diesem Zweck entwickelten ***Internationalen FEP-Datenbanken*** überprüft. D.h. für jedes der in den ***Internationalen FEP-Datenbanken*** enthaltene FEP wurde festgestellt, ob es in der ***OPA FEP-Datenbank*** enthalten ist, oder ob eine Erklärung vorliegt, wenn dies nicht der Fall ist.
  - Im Verlaufe des Ausschlussverfahrens irrelevanter Informationen und der Abstrahierung der übrigbleibenden Informationen wurden Prüfungen der intermediären Informations-Datenbanken (***sicherheitsrelevante Schlüssel-Phänomene***, ***Super-FEPs***, ***Rechenfälle***) anhand der ***OPA FEP-Datenbank*** vorgenommen. D.h. für jedes FEP in der ***OPA FEP-Datenbank*** wurde festgestellt, ob es in der überprüften Datenbank enthalten ist, oder ob eine Erklärung bzw. Begründung vorliegt, wenn dies nicht der Fall ist.

Resultat dieses Prozesses ist ein Satz von Informationen (dokumentiert in verschiedenen Tabellen), der im vorliegenden Bericht zusammengestellt und beschrieben wird, wobei einige der Tabellen gleichzeitig auch noch in anderen Berichten aufgeführt sind. Die Ausarbeitung dieser Informationen und der entsprechenden Tabellen erfolgte in hohem Masse iterativ. Die im vorliegenden Bericht dokumentierten Schlussresultate stellen nur die Beziehung der verschiedenen Informationseinheiten untereinander dar, nicht aber die zeitliche Abfolge bei deren Ableitung.

Résumé

Les objectifs et la démarche qui président à la gestion des FEPs (Features, Events and Processes, c'est-à-dire "Caractéristiques, événements et processus") sont les suivants:

- Le processus de gestion des FEPs doit prendre en considération et refléter la démarche utilisée par l'équipe scientifique pour décrire un système de dépôt, ainsi que la démarche suivie pour modéliser ce système à partir de sa description scientifique.
  - La description scientifique présente le système et son fonctionnement dans leur globalité et permet ainsi de définir un ensemble de ***phénomènes déterminants pour la sûreté du dépôt*** ("key safety-relevant phenomena"), puis de prévoir leur évolution et d'identifier les incertitudes qui leur sont associées, ainsi que les divergences possibles par rapport à l'évolution prévue.
  - Lors du processus de modélisation, la description scientifique est simplifiée et découpée en modules, sur la base desquels les modèles quantitatifs pourront être élaborés et appliqués. Cette démarche aboutit à la description du système et de son évolution en termes de ***super-FEPs*** (où sont regroupés des FEPs concernant des aspects plus spécifiques), avec dans chaque cas une "matérialisation de référence" ("reference realisation") et des "matérialisations alternatives" ("alternative realisation") qui reflètent les incertitudes identifiées par la description scientifique.
  - Afin d'assurer que la démarche de modélisation a bien pris en compte l'ensemble de l'information (et des incertitudes) identifiées par la description scientifique, on vérifie que pour chacun des ***phénomènes déterminants pour la sûreté du dépôt***, il existe au moins un ***super-FEP***; ceci concerne également les incertitudes associées à ces phénomènes. Parallèlement, on vérifie que pour chacun des ***super-FEPs***, il existe un ***phénomène déterminant pour la sûreté du dépôt*** qui justifie la prise en considération de ce super-FEP dans la démarche de modélisation.
  - La gestion des FEPs englobe également les ***FEPs de réserve*** (des FEPs, bénéfiques en termes de sûreté, dont la probabilité d'apparition est grande, mais que l'on exclut volontairement des situations envisagées dans le cadre de l'analyse de sûreté), et les ***aspects non traités pouvant entraîner la défaillance du dépôt*** (le cas échéant).
- Le processus de gestion des FEPs doit assurer qu'une gamme suffisamment étendue de situations ("assessment cases") est analysée à l'aide des outils appropriés (les codes d'évaluation).
  - On examine les ***super-FEPs*** et leurs matérialisations en fonction de leur importance pour la sûreté du dépôt et – s'ils sont pertinents – on les incorpore à une ou plusieurs situations qui seront évaluées dans le cadre de l'analyse de sûreté. On regroupe différents ***super-FEPs*** et leurs matérialisations au sein de ***situations*** en observant leurs conséquences sur le comportement général du système et son évolution à long terme, et en vérifiant les conséquences de l'interaction entre les différents super-FEPs. Les situations qui concernent le même type de conséquences sont regroupées en scénarios. Un même scénario renferme des situations qui se différencient par la conceptualisation différente d'un ou plusieurs phénomènes déterminants pour la sûreté ou – si la conceptualisation des phénomènes est identique – par des variations d'un ou plusieurs paramètres de modélisation.
  - Une procédure de ***qualification des codes*** est utilisée pour évaluer (d'une façon générale et en fonction des ***super-FEPs***) les outils utilisés pour l'analyse quantitative des différentes situations. On vérifie également que les codes utilisés pour analyser une situation

donnée sont à même de refléter l'ensemble des ***aspects déterminants pour la sûreté des super-FEPs*** concernés par cette situation.

- Le processus de gestion des FEPs doit inclure toutes les mesures raisonnablement envisageables permettant d'assurer que le catalogue des FEPs soit complet.
  - Au début de l'analyse, on regroupe les FEPs pour les Argiles à Opalinus dans une base de données ***(base de données OPA FEP)*** comprenant l'ensemble des aspects relatifs à la sûreté du dépôt. Pour s'assurer que la liste est complète, on met en regard la ***base de données OPA FEP*** et les ***listes de FEPs*** élaborées dans cet objectif ***au niveau international***. On vérifie ainsi que chacun des FEP figurant dans les ***bases de données internationales*** est également présent dans la ***base de données OPA FEP*** – et que, si tel n'est pas le cas, une explication ou une justification ont été fournies.
  - Tout au long du processus qui consiste à écarter les informations non pertinentes et à traiter l'information restante, on met en regard les bases de données intermédiaires (***phénomènes déterminants pour la sûreté, super-FEPs, situations***) et la ***base de données OPA FEP*** par le biais d'audits et de vérifications. Ainsi, pour chacun des FEPs figurant dans la ***base de données OPA FEP***, on vérifie qu'il est également présent dans la base de données examinée et que, si tel n'est pas le cas, une explication ou une justification ont été fournies.

Cette démarche a abouti à une base d'informations, dont la description et la présentation sous forme de tableaux font l'objet du présent rapport. On observera une certaine redondance, dans la mesure où plusieurs tableaux apparaissent également dans d'autres rapports. La base d'information et les tableaux correspondants ont été compilés au cours d'un processus largement itératif. De ce fait, ce rapport ne fait état que des relations existant entre les différentes informations, sans fournir une chronologie des étapes ayant conduit au résultat final.

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1 Introduction

1.1 Background to this report

This report is a supporting report to the Safety Report within Nagra's Project *Entsorgungs-nachweis*, which considers the feasibility of disposal of spent fuel (SF), vitrified high-level waste (HLW) and long-lived intermediate-level waste (ILW) in a deep geological repository sited in the Opalinus Clay of the Zürcher Weinland in northern Switzerland. Specifically, this report describes the management of FEPs (features, events and processes) within the post-closure radiological safety assessment of such a repository, which is reported in the Safety Report (Nagra 2002a), see Fig. 1.1-1.

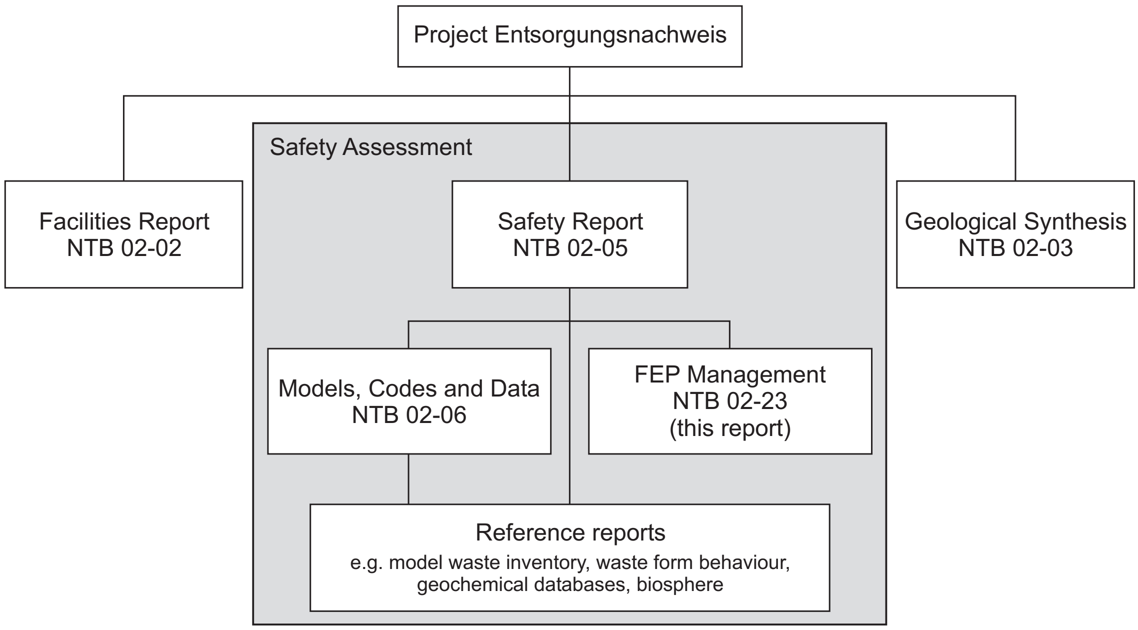

Fig. 1.1-1: Reporting structure for Project *Entsorgungsnachweis* with safety assessment reports indicated by the grey area

The Facilities Report and the Geological Synthesis Report also serve as reference reports to the safety assessment.

1.2 FEP management – its role in safety assessment

A prime concern in the development of all assessments of the long-term safety of the disposal of radioactive waste is the phenomenological "completeness" of the assessment. That is:

- Has a thorough identification been made of all the features, events and processes that could affect the long-term safety?
- Have these features, events and processes been adequately treated in the safety assessment?

In most safety assessments for repositories, this concern is handled by an ordered process of identifying the FEPs that are relevant and, then, screening, reducing and combining FEPs to arrive at a set of cases that should be evaluated in detail. The process, often termed scenario development, is enacted differently within different assessments, with varying degrees of formality, and with differences in the terminology employed, see, for example, NEA (2001). The importance of FEPs as a tool in many safety assessments has been confirmed at an international level by the development of an *International FEP Database* under the auspices of the Nuclear Energy Agency of the OECD (NEA 2000a), and this also provides a useful international benchmark against national safety assessment studies.

The common idea is that the engineered and natural components that make up the disposal system and the processes that determine its performance can be described (or approximated) by a set of discrete and inter-related units of information or phenomenon descriptions termed *FEPs*. The discretisation of a real-world system into FEPs and further processing into safety assessment cases is not unique. Rather it is a product of the judgement of the assessment experts, who are guided by the overall assessment strategy, and work within the limits of the scientific knowledge and the analysis tools that are available.

Through the discretisation:

- *a structure is imposed* on the scientific and technical judgements made, which encourages consideration of the aspects and implications of the various FEPs, and
- *a record is created* of the final judgements made, which can be checked for internal consistency and reviewed by independent experts.

The imposition of this FEP management framework does not lessen the requirement for experienced scientists and assessment experts to examine the available data and to estimate the relative importance of processes and events and to decide how they will be treated in the assessment. Nor does it reduce the need for subjective judgements to overcome practical constraints that may exist such as limitations of the data and calculation tools, or incomplete understanding of the relevant processes. It does, however, provide a platform for communication between the assessment experts and the different scientific experts whose experience must be mobilised, and it encourages the developments of arguments and forces systematic decisions regarding the exclusion / inclusion and treatment of the various FEPs.

1.3 FEP management – its role in Nagra safety assessments

1.3.1 FEP management in past Nagra assessments

The Nagra approach to scenario analysis and FEP management for safety assessment has been developed progressively as reported in Sumerling et al. (1993), Nagra (1994a, Chap. 4), Nagra (1994b, Chap. 3), Sumerling et al. (1999), Sumerling and van Dorp (1999). In the assessments of a HLW repository in the crystalline basement of northern Switzerland (Kristallin-I; Nagra 1994a) and of a formerly proposed L/ILW repository at Wellenberg (Nagra 1994b), the identification and management of FEPs and subsequent scenario development was seen as the central path through the assessment. Experience with these assessments has revealed the complexity of the task. Tab. 1.3-1 lists key experiences related to scenario development from these assessments.

Tab. 1.3-1: Key experiences related to scenario development from past Nagra safety assessments

Taken from Sumerling and van Dorp (1999).

1. It is important to use the scientific and technical experience of the various project staff and find methods (e.g. via meetings, written report by experts and review of draft scenario-related material) to mobilise and incorporate this experience.
2. It is necessary to present and explain the scenario methodology to project staff as the vehicle by which individual experts will be able to contribute to developing the safety assessment.
3. Meetings of experts from various disciplines are a good tool to expand the common understanding of system behaviour and give individuals a better feel for where their contribution fits within an overall framework and what is, and is not, important to safety.
4. Thorough documentation of FEPs, initially by subject experts, provides the scientific and technical information basis. This must then be synthesised into a coherent whole, and decisions on how to treat various FEPs made by experts with an overall understanding of system performance and model capabilities.
5. Given the relatively long time needed to develop new models and the relatively short time sometimes available for an assessment, it is clear that assessment calculations may be constrained by existing capability. The identification of reserve FEPs[2] and open questions[3] is a valuable way to keep track of limitations within current models and calculations and give pointers for future model development and data collection.
6. Audit against international FEP Lists and experience can give broad assurance on completeness, but key processes are often design and / or host rock specific. More detailed assurance of completeness must come from good understanding of the relevant processes in their design, host rock and site-specific context.
7. The discipline of creating a comprehensive FEP catalogue and ensuring traceability to calculations is valuable and gives considerable confidence to reviewers, e.g. in regulatory review, who often focus on issues of completeness.
8. Formal scenario development methods also give a logical framework to safety assessments which is valuable in communicating both to outside audiences and within an assessment project.

1.3.2 FEP management in the safety assessment for Project *Entsorgungsnachweis*

Experience from previous safety assessments led to the decision, for the current safety assessment, to focus more directly on safety and how it is provided by the total disposal system. Thus, the main stream of the assessment focuses more on identifying the *key safety-relevant phenomena*[4] as provided by the host rock and design of the repository, rather than beginning from the comprehensive collation of information about *all possible* FEPs represented by a comprehensive FEP catalogue. This methodology is outlined in Section 2.1 and illustrated in Fig. 2.1-1, and set out in more detail in Chapter 3 of Nagra (2002a).

[2] A *reserve FEP* is a FEP that is considered likely to occur and to be beneficial to safety and which is deliberately excluded from assessment cases, or at least from their analysis, when the level of scientific understanding is insufficient to support quantitative modelling, or when suitable models, codes or databases are unavailable. Reserve FEPs are further discussed in Appendix 5. For a definition of this and other key terms used in the present safety assessment, see also Appendix 5 of Nagra (2002a).

[3] *Open questions* are outstanding issues with the potential to compromise safety (see also Appendix 5). Within the safety assessment for Project *Entsorgungsnachweis*, no such unresolved issues have been identified that might put safety into question.

[4] Short for: key safety-relevant features, phenomena & evolutions (see Tab. A4.1.1).

The current safety assessment is based on an active recognition of, and focus on, the key safety-relevant processes in the development of the *safety concept* and on the development and selection of key safety-relevant phenomena, their mapping onto *Super-FEPs*[5] and the definition of *assessment cases* based on overall system understanding. The comprehensive identification of FEPs and the evaluation of their relevance to the safety assessment is still necessary, of course. This, however, is handled as a parallel activity with audits of the key safety-relevant phenomena, Super-FEPs and assessment cases developed in the safety assessment against a comprehensive listing of individual FEPs in a quasi-independently derived Opalinus Clay FEP Database, or short *OPA FEP Database*. In addition, steps of qualification of the codes, and checking of the representation of Super-FEPs within assessment cases and by the various codes, have been introduced.

The primary role of FEP management in the current safety assessment is thus that of an information management tool and an audit tool. The development of assessment cases, based on the site, the repository design and the relevant scientific understanding, and the development of a system concept[6] and a safety concept, is an active and iterative process carried out in the main stream of the assessment. The FEP management procedure provides a logical framework and map of connections between various assessment elements that can be audited internally and against external benchmarks.

1.4 Organisation of this report

This report is organised as follows:

Chapter 1 provides the background to the role of FEP management generally, in past Nagra safety assessments and in the current safety assessment.

Chapter 2 presents an overview of the safety assessment methodology adopted in Project *Entsorgungsnachweis* and the FEP management processes and products that keep track of the treatment of the FEPs in the assessment. An index is provided to all tables and lists related to FEPs and their treatment in the assessment, and where they can be found.

Chapter 3 describes the stages of FEP management related to the development of a comprehensive OPA FEP Database, its audit against independent international FEP Lists and the screening out of unimportant FEPs.

Chapter 4 describes the stages of FEP management related to the identification of key safety-relevant phenomena, the development of Super-FEPs and the identification of assessment cases, and the audit of these key safety-relevant phenomena, Super-FEPs and assessment cases against the OPA FEP Database.

Chapter 5 describes the stages of FEP management related to the assessment of the capability of assessment codes, the audit of these codes against the Super-FEPs and checks of the capabilities of the codes against the assessment cases for which they are used.

Chapter 6 makes concluding remarks on the FEP management activities and their contribution to the overall confidence in the safety assessment.

Appendices 1-9 list various tables as discussed in the main text.

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5 There is a close correspondence between the key safety-relevant phenomena, which are selected based on scientific understanding, and the Super-FEPs, which are key groupings of FEPs derived for the purpose of quantitative assessment (see Chapter 6 in Nagra 2002a).

6 The system concept is the conceptual model of the disposal system (Nagra 2002a).

2 Assessment methodology, completeness and FEP management

This chapter presents an overview of the safety assessment methodology adopted in Project *Entsorgungsnachweis* and the FEP management processes and products that keep track of the treatment of the FEPs in the assessment. An index is provided to all tables and lists related to FEPs and their treatment in the assessment, and where they can be found.

2.1 Assessment methodology

The safety assessment methodology adopted in Project *Entsorgungsnachweis* is based on the following assessment principles, which are discussed fully in Chapter 3 of Nagra (2002a):

- Focus of the safety case
- Sufficient scientific understanding
- Systematic and defined method
- Multiple arguments for safety
- Documentation

Within the methodology, the OPA FEP Database, the FEP management and the corresponding tables make important contributions with regard to each of the assessment principles.

- **Focus of the safety case** – The FEP management process promotes completeness and provides a comprehensive set of FEPs against which the robustness of the repository system can be examined.

- **Sufficient scientific understanding** – The FEP management process is an important tool through which scientific and technical experts can provide their input to the assessment and prompts the experts to think about their subject expertise within the framework of the safety assessment of the disposal system.

- **Systematic and defined method** – The FEP management process provides a basis for a systematic approach to checking judgements in the assessment, encourages completeness of identification [7] and consideration of relevant phenomena, and provides opportunities for review, audit of FEP information, decisions and judgements.

- **Multiple arguments for safety** – The FEP management process keeps track of the ways in which FEPs are included or conceptualised in assessment cases. It also keeps track of reserve FEPs that are not included in cases, but are expected to contribute positively to safety, and thus give additional confidence in the robustness of the performance of the repository system.

- **Open questions** – The FEP management process also helps to keep track of open questions; i.e. unresolved issues [8].

[7] E.g. identification of areas that scientists contributing to safety assessment might have left out by intuition.

[8] Within the safety assessment for Project *Entsorgungsnachweis*, no unresolved issues have been identified that might put safety into question.

- **Documentation** – This provides a traceable record of information on important phenomena and FEPs at different levels of agglomeration and a record of the representation of FEPs in the assessment.

The overall procedure for constructing the safety case, and the role of FEP management within this procedure, is illustrated in Fig. 2.1-1 (identical to Fig. 3.7-2 from Nagra 2002a). The broad tasks involved in constructing the safety case are described in Section 3.7 of Nagra (2002a) and are summarised below.

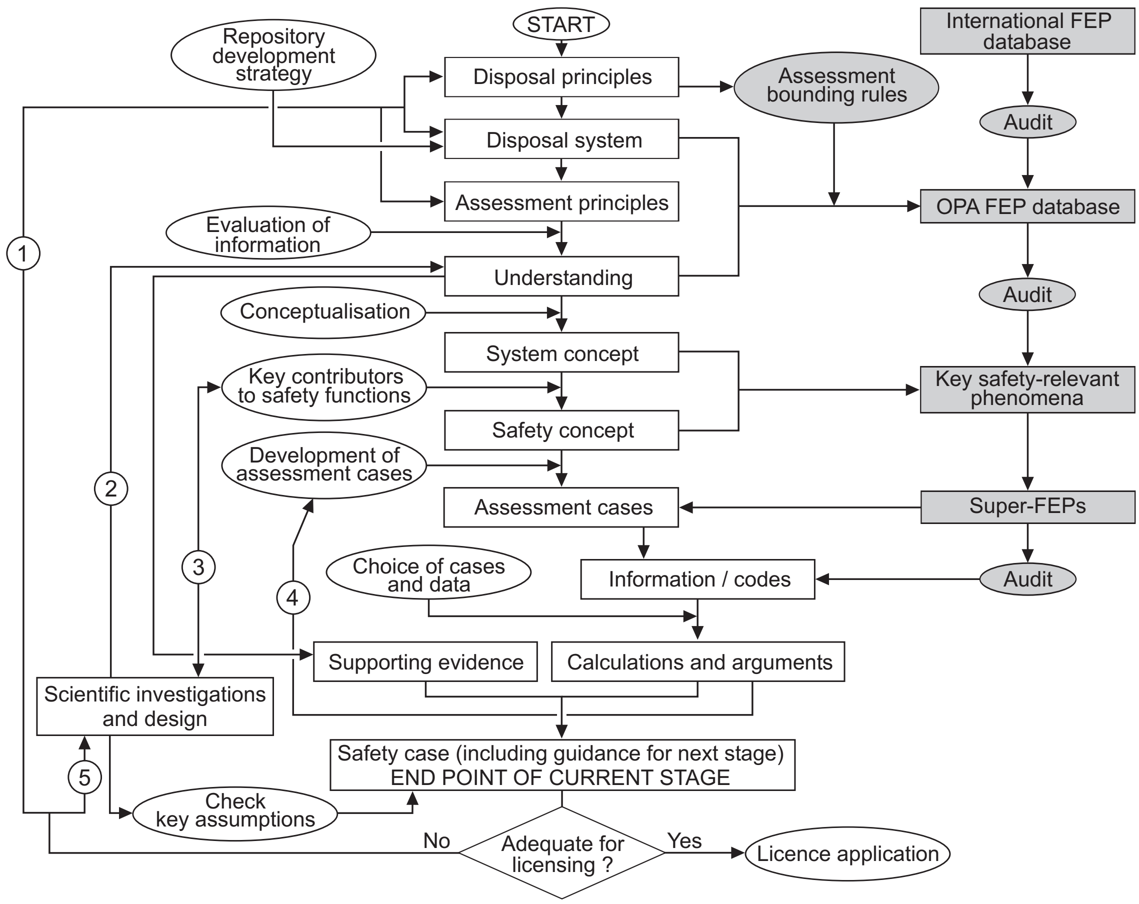

Fig. 2.1-1: The procedure for constructing the safety case (identical to Fig. 3.7-2 from Nagra 2002a)

Key FEP management processes and products are indicated by the shaded boxes.

- **Choosing the disposal system** – The disposal system is chosen according to disposal principles. These include the provision of passive safety, robustness and practicality of demonstration of safety. The disposal system is the result of an iterative repository development strategy.

- **Deriving the system concept** – The starting point for safety assessment is an evaluation of information relevant to the system and results of scientific investigation and design studies. The resulting understanding of phenomena potentially relevant to post-closure safety together with a broad conceptualisation of the evolution of the disposal system and associated uncertainties lead to the system concept.

- **Deriving the safety concept** – Development of the safety concept involves identifying the features of the system that are key contributors to the *safety functions*[9], the so-called *pillars of safety.* Scientific investigations and design studies provide understanding and support for the reliability of these features. Their importance and performance is also investigated by modelling studies and sensitivity analyses.

- **Illustrating radiological consequences** – A range of assessment cases is defined to illustrate radiological consequences and their ranges of uncertainty. Preliminary calculations are used to guide the definition of assessment cases and decisions are taken as to which cases require quantitative evaluation and which should be discussed qualitatively.

- **Compiling arguments and providing guidance for future stages** – The results of the analyses of assessment cases are combined with a range of supporting evidence and qualitative arguments to construct the safety case. Through definition and analysis of a broad range of assessment cases the expected levels of safety of the proposed site and design options are evaluated. Analysis of uncertainties and identification of potentially detrimental FEPs gives guidance to future project stages, including possible design modifications or scientific studies aimed at better characterising relevant processes and avoiding (or mitigating the effects of) detrimental processes.

2.2 Assurance of completeness and FEP management strategy

As already mentioned in Section 1.2, a prime concern in the development of all assessments of the long-term safety of the disposal of radioactive waste is the issue of phenomenological "completeness" of the assessment, see, e.g., NEA (2001). Key questions are:

- Has a thorough identification been made of all the features, events and processes that could affect the long-term safety?
- Have these features, events and processes been adequately treated in the safety assessment?

It can never be proved that an assessment is complete. The disposal system can be sited and designed to favour completeness, however, e.g. by avoiding complex geological features and by selecting engineered barrier materials that are well understood. Beyond this, in the assessment, procedures can be followed to encourage the identification of all potentially relevant phenomena and, equally important, once identified, to ensure that the safety-relevant phenomena have been represented appropriately in the assessment.

In the present safety assessment, an assurance of phenomenological completeness and appropriate treatment is provided by:

- the development of a comprehensive database of FEPs that may be relevant to the safety assessment – the Opalinus Clay FEP Database (*OPA FEP Database*), and
- a careful accounting of the phenomenological scope of assessment cases and the models by which they are represented, in a process termed *FEP management*.

The general strategy is illustrated in Fig. 2.2-1 (based on Fig. 3.7-4 from Nagra 2002a).

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[9] The disposal system provides a number of functions relevant to long-term security and safety, termed *safety functions*. They include i) *isolation of the waste from the human environment, ii) long-term confinement and radioactive decay within the disposal system, and iii) attenuation of releases to the environment.* The *safety functions,* the *pillars of safety* and other key terms are defined in Appendix 5 of Nagra (2002a).

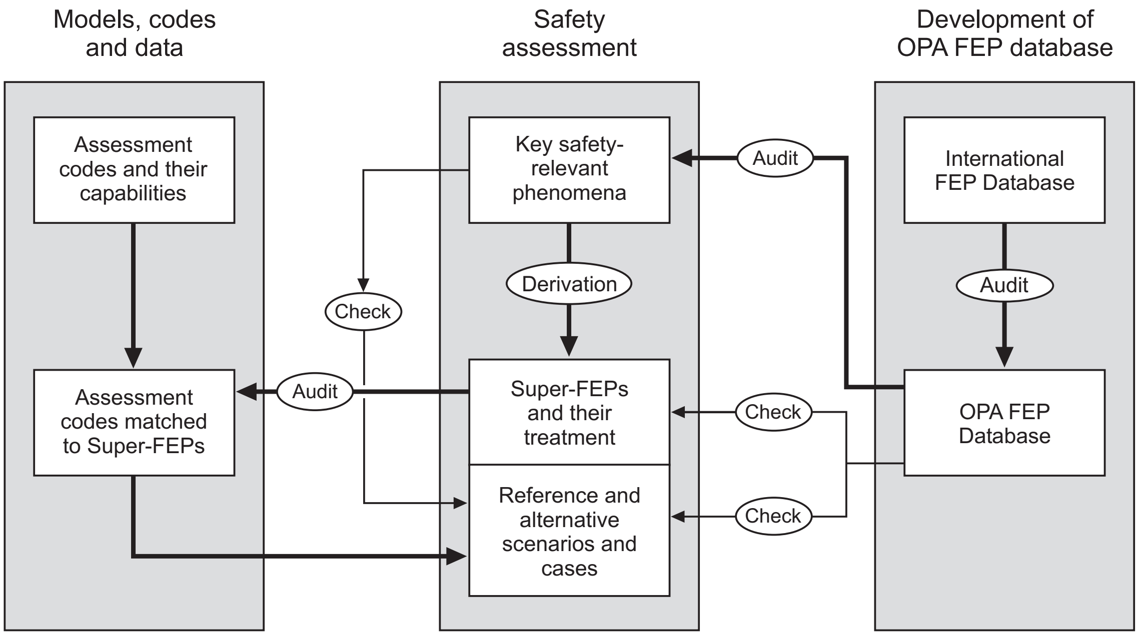

Fig. 2.2-1: Strategy for assurance of phenomenological completeness and appropriate treatment of FEPs in safety assessment by FEP management and audits

The main path of the logic of assurance is indicated by bold connecting arrows.

First, it is recognised that adequate characterisation of the disposal system and thorough scientific understanding of the safety-relevant processes that act therein are the essential foundation. From this basis, three separate lines of work can be identified.

- Assessment codes have been developed, often to represent quite generic systems, but in some cases to represent features and processes that are specific to the disposal system for SF / HLW / ILW in the Opalinus Clay of the Zürcher Weinland. The assessment codes and their capabilities are described in the Models, Codes and Data Report (Nagra 2002b).
- The thorough synthesis of the scientific knowledge concerning the Opalinus Clay disposal system and its performance, including an evaluation of uncertainties, has been assembled in the main stream of the safety assessment as described in Chapters 4 and 5 of the Safety Report (Nagra 2002a). This forms the basis for the selection of scenarios and cases that are treated quantitatively as described in Chapters 6 and 7 of that report.
- In addition, at an early stage of the safety assessment, a comprehensive identification was made of individual FEPs that might be relevant to the safety of the Opalinus Clay disposal system – the OPA FEP Database, as described in this report. The comprehensiveness of this database is encouraged by audits of the database against the NEA International FEP Database (NEA 2000a) and the NEA FEPCAT Database (Mazurek et al. 2002).

Each line of work is advanced incrementally, with periodic comparisons between the state of knowledge and progress in each line, to achieve a consistent and coherent safety assessment.

Within the main stream of the safety assessment, *key safety-relevant phenomena* are identified bearing in mind the total understanding of the disposal system and its functions, and judgements are made regarding their relevance or importance in the *system context*. Similarly, later, the so-called *Super-FEPs* and assessment scenarios and cases are identified with a view to defining a set of calculations that encompass the possible overall system behaviour or to providing relevant illustrations. By contrast the development of the OPA FEP Database is done with the aim of identifying all possibly relevant *individual FEPs*. As a result, the key safety-relevant phenomena and Super-FEPs identified in the safety assessment tend to be agglomerations of the individual FEPs contained in the OPA FEP Database. The aim of FEP management is then:

- to ensure that no individual FEP from the OPA FEP Database has been excluded from consideration without reason in the main stream of the assessment – this is achieved by audits and checks [10] of the key safety-relevant phenomena, Super-FEPs and assessment cases against the OPA FEP Database; and
- to ensure that the computer codes that are used are appropriate to represent the various assessment cases – this is achieved by audits of the codes against the Super-FEPs that they are required to represent (qualification of the codes) and checks of the representation of each Super-FEP by the assessment cases and codes.

There is a close correspondence between the key safety-relevant phenomena, which are selected based on scientific understanding, and the Super-FEPs, which are key groupings of FEPs derived for the purpose of quantitative assessment (see Chapter 6 in the Safety Report). Super-FEPs can thus be regarded as assessment realisations of the key safety-relevant phenomena. It is not always a one-to-one correspondence, however, so that a map is needed between each key safety-relevant phenomenon and its associated uncertainties, and the corresponding Super-FEPs and their alternative realisations. A further aim of FEP management is to carefully check the derivation of Super-FEPs from key safety-relevant phenomena and the mapping of Super-FEPs to the scenarios and cases in which they are represented.

Tables that detail all of the above audits and checks are presented in this report and its appendices, see Section 2.4.

2.3 FEP management processes and products

Fig. 2.3-1 illustrates the relation between FEP management processes and products, expanding on the strategy indicated in Fig. 2.2-1. Fig. 2.3-2, based on Fig. 2.3-1, identifies each of the tables produced in the course of FEP management, their relation to each other, and where they can be found in this and other reports (see Section 2.4).

It is important to understand that the arrows connecting the various bases, processes and products show the logical connection between the various elements in the final safety assessment documentation. They do not show a temporal procedure or order in which various products were achieved. In fact, the safety assessment is a highly iterative and interactive process. Many iterations were carried out of some of the processes, especially the definition of Super-FEPs and of assessment cases. Audits and checks were done preliminarily during the development but only comprehensively after the assessment cases had been frozen. Some codes were developed that were not used to evaluate the final assessment cases. Even the overall connection of all the elements was not established in its final form until most of the technical work and assessment calculations had been completed. This is a reflection of the complex series of inter-related judgements and calculations that must be made in developing the safety assessment.

[10] In this document, *audit* is used to refer to a comparison to an external or independently-derived internal source, and includes the application of subjective judgements. *Check* is used to refer to a comparison where the relationship has already been defined through a preceeding audit or internal derivation. An audit is thus a review of assessment quality, and a check is a comparison ensuring internal consistency.

By its division into three columns, Fig. 2.3-1 indicates which processes and products are mainly related to:

- codes and their use, and hence described in the Models, Codes and Data Report (Nagra 2002b);
- the main stream of safety assessment, and hence described in the Safety Report (Nagra 2002a);
- the development of the OPA FEP Database and its use, described in this report.

This report also describes the overall methodology of FEP management over all three areas, but not the scientific and technical judgements made.

The individual FEP management processes are as follows. As noted above, this does not imply a temporal procedure, but the order here is a logical order in which the processes can be discussed. The letters (a) to (j) are also shown in Fig. 2.3-1 at the appropriate locations.

Development of the OPA FEP Database

(a) A set of assessment bounding rules is devised based on the aims of the assessment and also on regulatory guidance as set down in the disposal and assessment principles, described in Chapter 2 of Nagra (2002a). The assessment bounding rules define the bounds of the safety assessment and exclude classes of conditions and events that are not relevant to the aims of the safety assessment or ruled out by regulatory guidance.

(b) A structured, comprehensive list is developed of FEPs that are potentially relevant to the disposal system under consideration. This is based on previous Nagra assessments, international experience and the scientific understanding of the disposal system. The consideration takes account of the specific characteristics of the disposal system – disposal of SF/HLW/ILW in the Opalinus Clay of the Zürcher Weinland. The scope of the list is constrained by the assessment bounding rules. The output – FEP names and descriptions – is termed the Opalinus Clay FEP Database (OPA FEP Database) and is implemented electronically.

(c) The OPA FEP Database is audited (checked for completeness) against international FEP databases. Specifically the OPA FEP List has been audited against the NEA International FEP List (NEA 2000a) and the NEA FEPCAT Database (Draft version, Mazurek et al. 2002). There are valid reasons why a few of the NEA International FEPs and NEA FEPCAT FEPs are not represented in the OPA FEP List; these reasons are recorded.

(d) The OPA FEP Database is reviewed against the current understanding of the disposal system and its safety, based on the specific design options to be considered and known characteristics of the geological environment and its safety potential. This leads to the screening out of a few OPA FEPs, which can be argued as not being relevant or not able to impact on the safety of the system. Those FEPs not screened out are termed the *safety-relevant OPA FEPs*.

Development of key safety-relevant phenomena, Super-FEPs and assessment cases and their audit

(e) Within the main stream of the safety assessment, *key safety-relevant phenomena* are identified based on the integrated scientific understanding of disposal system evolution, as described in Chapters 4 and 5 of Nagra (2002a). These key safety-relevant phenomena, and their related uncertainties, provide a more convenient basis for discussion and evaluation in the safety assessment than the more numerous individual OPA FEPs.

(f) Also within the main stream of the safety assessment, a set of *assessment cases* and their component *Super-FEPs* is derived. As described in Chapter 6 of Nagra (2002a), the Super-FEPs and their alternative realisations within the assessment cases represent an abstraction of the integrated scientific understanding of the key safety-relevant phenomena. Through systematic checks, it is ensured that all information contained in the key safety-relevant phenomena is considered in the Super-FEPs (and also that for each Super-FEP, a corresponding safety-relevant phenomenon exists that justifies the inclusion of the Super-FEP in the modelling approach, see Appendix 4). The derivation of assessment cases is based on system understanding (which is in turn based on scientific evidence, on so-called "insight models" and on sensitivity analysis) and on expert judgement on the relative importance of uncertainties associated with key safety-relevant phenomena and Super-FEPs and the safety-relevant aspects that are affected by these uncertainties[11]. It is observed that the need for an alternative assessment case normally arises out of uncertainty associated with a key safety relevant phenomenon (see Fig. 5.7-1 in Nagra 2002a) or a Super-FEP (see Tab. 4.2-1), respectively. The assessment cases are grouped within a hierarchy of scenarios, conceptualisations and parameter sets, as discussed in Section 3.7.4 of the Safety Report and as shown in Fig. 2.3-3. It is also checked in how far uncertainties associated with one Super-FEP can affect other Super-FEPs and that this is adequately reflected in the assessment cases (Tab. A5.4.1). The process of developing Super-FEPs leads also to the identification of reserve FEPs and – in principle – open questions. However, no open questions of concern were identified; consequently there are no tables listing open questions.

(g) The key safety-relevant phenomena are audited for completeness against the list of safety-relevant FEPs from the OPA FEP Database. This is done by verifying that each safety-relevant OPA FEP is included within one or more of the key safety-relevant phenomena and their uncertainties. A check is also made that each safety-relevant OPA FEP is included within the corresponding Super-FEPs and assessment cases. Logically this must be so if the Super-FEPs and assessment cases have been properly derived and fully capture the key safety-relevant phenomena and their uncertainties; so this is referred to as a check rather than as an audit.

Qualification and selection of assessment codes

(h) The assessment codes and their capabilities are described in Nagra (2002b). The codes that are available are audited against the Super-FEPs and alternative realisations of the Super-FEPs that are to be represented. This may lead to the recognition of a need to develop a new code or make modifications to existing codes. Once the ability of a code to represent a given set of Super-FEPs is established the code is said to be *qualified*.

(i) The set of assessment cases to be evaluated is compared with the set of qualified codes and an appropriate code, or code combination (model chain), is assigned to each case.

(j) A check is made of the representation of each Super-FEP within each case and its associated codes. Conversely, this also shows the scope of each case, in terms of its component Super-FEPs and realisations, and the codes used to represent them. This is in the nature of a confirmation, since codes have already been selected for each case and their qualification to represent given Super-FEPs has been established.

[11] In order to provide maximal traceability in the derivation of assessment cases, an additional column "Safety-relevant aspects that are affected by uncertainties and design / system options" has been introduced in Tab. A5.2.1 of this report compared to Tab. 6.8-1 of Nagra (2002a).

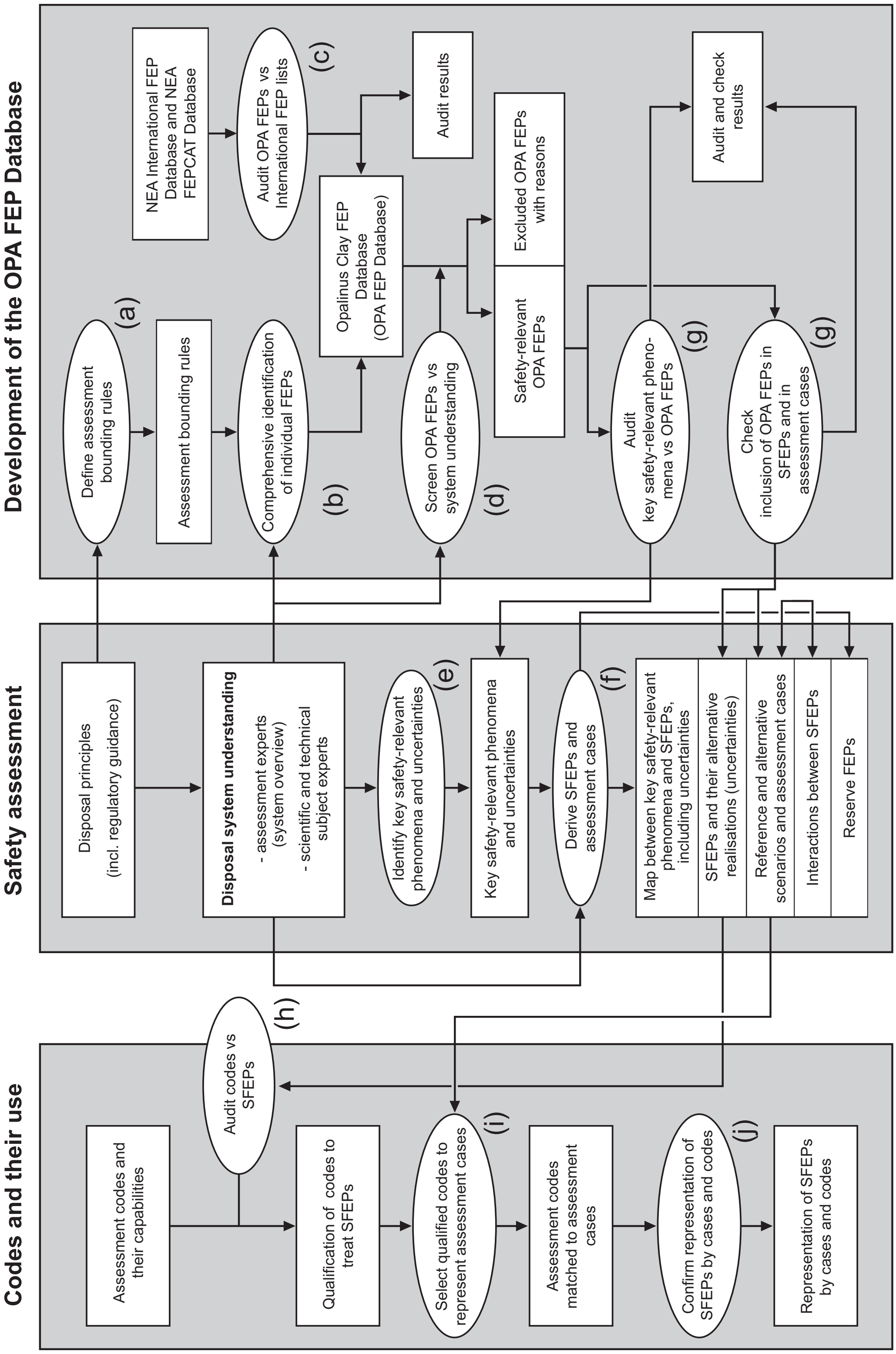

Fig. 2.3-1: The relation between FEP management processes and products, expanding on Fig. 2.2-1

Ellipses represent processes, rectangles represent bases or products of the processes. The letters (a), (b) etc. refer to paragraphs in Section 2.3 which describe the processes. SFEP = Super-FEP.

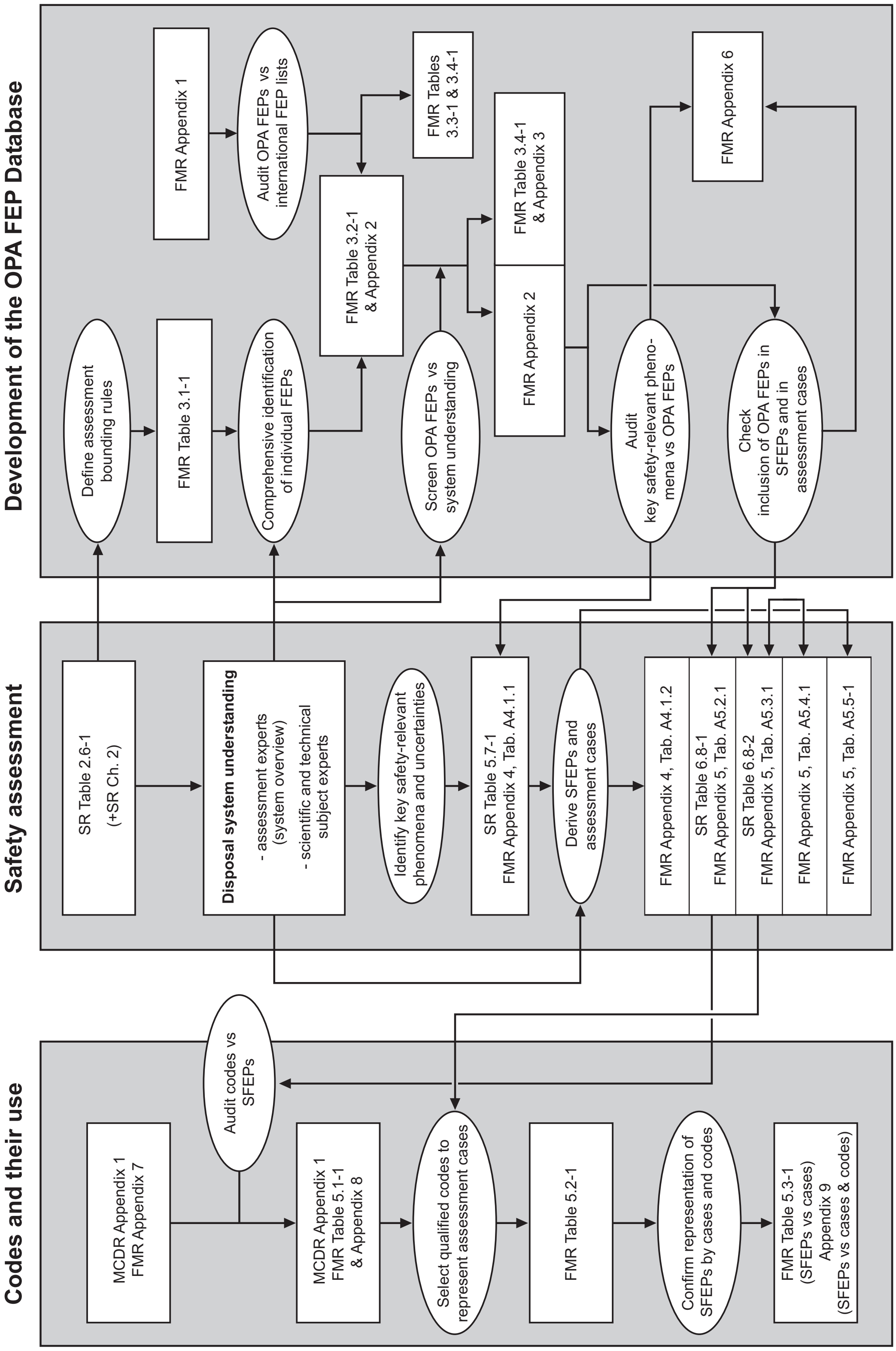

Fig. 2.3-2: The relation between FEP management processes and products as described in Fig. 2.3-1, indicating where the products can be found

See also Tab. 2.4-1. MCDR = Models, Codes and Data Report; SR = Safety Report; FMR = FEP Management Report (this report); SFEP = Super-FEP.

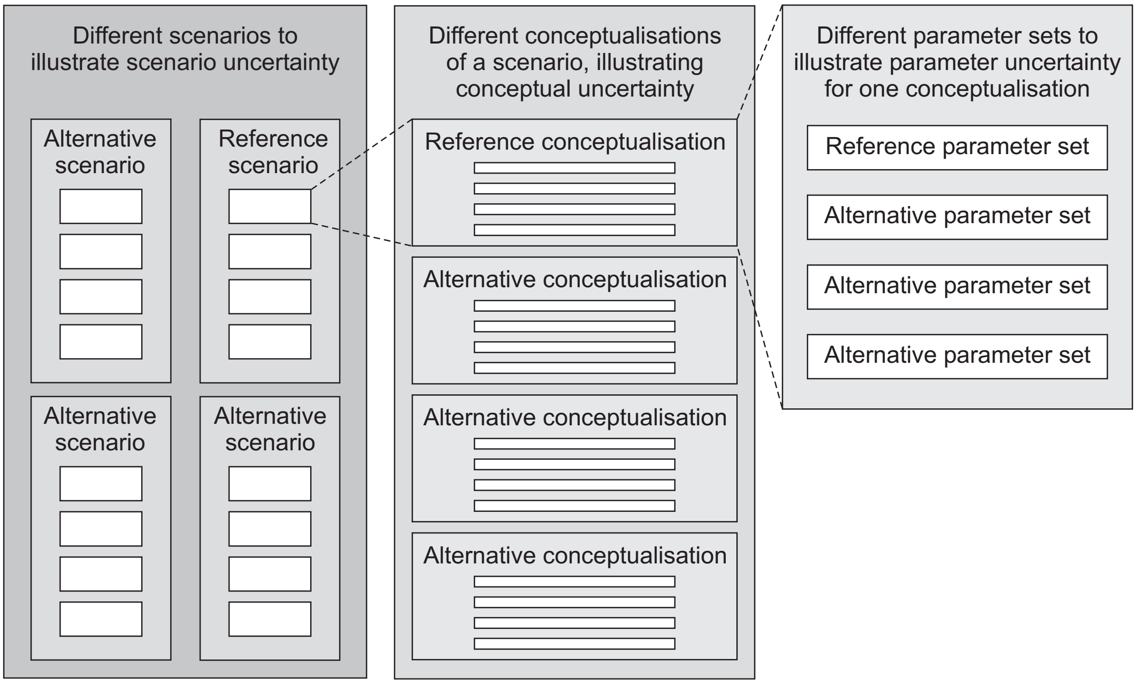

Fig. 2.3-3: The hierarchy of scenarios, conceptualisations and parameter sets

2.4 Complete documentation of the FEP management

The purpose of this report is to describe the FEP management strategy and processes, and to make a complete compilation of the products of FEP management.

The development of the OPA FEP Database is described in Chapter 3 of this report. The processes for the development of the Super-FEPs and assessment cases, and their audit, are described in Chapter 4. The processes for the audit of assessment code capabilities and their matching to assessment cases are described in Chapter 5. The discussion of the scientific evidence and judgements leading to the definition of various key safety-relevant phenomena, Super-FEPs and assessment cases is contained in Nagra (2002a) and underlying reference reports, and the discussion of code capabilities and their matching to cases is contained in Nagra (2002b). In this report, only the mechanics of the processes are outlined for these latter activities. In addition, this report includes the key tables generated during the FEP management, some of which also appear in other reports.

Fig. 2.3-2, based on Fig. 2.3-1, identifies each of the tables produced in the course of FEP management, their relation to each other, and where they can be found in this and other reports. This is expanded on in Tab. 2.4-1, which gives the title of each table and outlines its contents.

Tab. 2.4-1: Complete listing of tables related to FEP management, their content and where they can be found

FMR denotes the FEP management report (i.e. this report), MCDR denotes the Models, Codes and Data Report (Nagra 2002b) and SR denotes the Safety Report (Nagra 2002a).

Table numbers in project reports			**Title of table**
FMR	**MCDR**	**SR**	
1.3-1	-	-	Key experiences related to scenario development from past Nagra safety assessments
2.4-1	-	-	Complete listing of tables related to FEP management, their content and where they can be found (**this table**)
3.1-1	-	-	Assessment bounding rules used in the safety assessment for Project *Entsorgungsnachweis* and related arguments
3.2-1	-	-	The main categories used by the OPA FEP List
3.3-1	-	-	Individual international FEPs to which no corresponding OPA FEP was mapped, listed under the three main reasons
3.4-1	-	-	Generic reasons for screening and OPA FEPs screened out against these reasons
4.2-1	-	-	Range of influence of Super-FEPs and associated uncertainties and design / system options on repository system
5.1-1	A1.2-2	-	The representation of Super-FEPs and their safety-relevant aspects in safety assessment computer codes
5.2-1	2.2-1	6.8-2, but with applied codes added	Summary of the treatment of assessment cases by the codes
5.3-1	-	-	The significance and treatment in assessment cases of uncertainties and design / system options associated with specific Super-FEPs, and qualified codes used to evaluate the cases
A1.1.1	-	-	The NEA International FEP List
A1.2.1	-	-	The NEA FEPCAT List
A2.1.1	-	-	Listing of Opalinus Clay FEPs in category scheme order, incl. screened FEPs (titles only)
A2.1.2	-	-	Listing of Opalinus Clay FEPs in category scheme order (incl. a brief description of each FEP)
A3.2.1	-	-	The mapping of OPA FEPs to the NEA International FEP List
A3.3.1	-	-	The mapping of OPA FEPs to the NEA FEPCAT List
A4.1.1	-	5.7-1, but with key phenomena numbered	Key safety-relevant features and phenomena and uncertainties associated with the disposal system evolution
A4.1.2	-	-	Map between key safety-relevant features and phenomena and their uncertainties and the Super-FEPs and their alternative realisations

Tab. 2.4-1: (Cont.)

Table numbers in project reports			Title of table
FMR	MCDR	SR	
A5.2.1	-	6.8-1, but with additional column and numbering	The significance and treatment in assessment cases of uncertainties and design / system options associated with specific Super-FEPs
A5.3.1	2.2-1, but without codes applied	6.8-2	List of scenarios, "what if?" cases, design and system options and illustration of the effects of biosphere uncertainty with associated conceptualisation and parameter variations
A5.4.1	-	-	Interaction matrix for Super-FEPs and their associated uncertainties
A5.5.1	-	6.8-3	FEPs that are conservatively omitted in defining the assessment cases, including reserve FEPs
A6.1.1	-	-	Audit of the key safety-relevant phenomena and checks of allocation of the OPA FEPs to Super-FEPs and assessment cases
A7.2.1	A1.3-2	-	Phenomena explicitly included in the SPENT model
A7.3.1	A1.4-2	-	Phenomena explicitly included in the STRENG model
A7.4.1	A1.5-2	-	Phenomena explicitly included in the STALLION model
A7.5.1	A1.6-2	-	Phenomena explicitly included in the PICNIC model
A7.6.1	A1.7-2	-	Phenomena explicitly included in the TAME model
A7.7.1	A1.8-2	-	Phenomena explicitly included in the FRAC3DVS model
A7.8.1	A1.9-2	-	Phenomena explicitly included in the Gas Model
A8.2.1	A1.3-1	-	Super-FEPs, their safety-relevant aspects and the ways in which they are represented by the code SPENT
A8.2.2	A1.4-1	-	Super-FEPs, their safety-relevant aspects and the ways in which they are represented by the code STRENG
A8.2.3	A1.5-1	-	Super-FEPs, their safety-relevant aspects and the ways in which they are represented by the code STALLION
A8.2.4	A1.6-1	-	Super-FEPs, their safety-relevant aspects and the ways in which they are represented by the code PICNIC
A8.2.5	A1.7-1	-	Super-FEPs, their safety-relevant aspects and the ways in which they are represented by the code TAME
A8.2.6	A1.8-1	-	Super-FEPs, their safety-relevant aspects and the ways in which they are represented by the code FRAC3DVS
A8.2.7	A1.9-1	-	Super-FEPs, their safety-relevant aspects and the ways in which they are represented by the Gas Model
A9.1.1	-	-	Overview of the representation of Super-FEPs and their safety-relevant aspects in the assessment cases and codes

2.5 Summary

The aims of and the approach used in the FEP management process can be summarised as follows:

- The FEP management process has to consider and reflect the approach used by science to describe a disposal system and the approach used when modelling the system as described by science.
  - Science describes its findings with respect to the system and its behaviour and evolution "as a whole", which results in the identification of a set of ***key safety-relevant phenomena***, their expected evolution and associated uncertainties, and possible deviations with respect to the expected evolution (Appendix 4).
  - Modellers abstract and fragment the description by science into building blocks that form a suitable basis to develop and apply corresponding quantitative models. This results in a description of the system and its evolution in terms of ***Super-FEPs*** (as groupings of more detailed FEPs) with a reference realisation and alternative realisations to reflect the uncertainties identified by science (Appendix 5).
  - To ensure that the modellers have considered all the information (and uncertainties) identified by science, a check is made that, for each of the ***key safety-relevant phenomena***, at least one corresponding ***Super-FEP*** exists; this also includes the corresponding uncertainties. At the same time, a check is made that for each ***Super-FEP***, a corresponding ***key safety-relevant phenomenon*** exists that justifies the inclusion of the Super-FEP in the modelling approach (Appendix 4).
  - The FEP management process also keeps track of the ***reserve FEPs*** (FEPs that are considered likely to occur and to be beneficial to safety, but which are deliberately excluded from the assessment cases), and of ***outstanding issues with the potential to compromise safety***, if there are any (Appendix 5).
- The FEP management process has to ensure that a sufficiently broad set of assessment cases is analysed by suitable tools (assessment codes).
  - The ***Super-FEPs*** and their realisations are assessed with respect to their relevance to safety and – if considered relevant – are identified for inclusion into one or more assessment cases. The grouping of the different ***Super-FEPs*** and their realisations into ***assessment cases*** is carried out by looking at their effects on the broad behaviour / evolution of the system, including a check of the effects of the interaction between individual Super-FEPs. Assessment cases addressing similar effects are grouped together into specific scenarios. Cases within a scenario are distinguished by the different conceptualisations of one or more key phenomena or – if the conceptualisation of phenomena is the same – by variations of one or more model parameters (Section 4.2 and Appendix 5).
  - The adequacy of the tools used for the quantitative analysis of the different assessment cases is carried out through a ***qualification of codes*** (in general terms and in terms of ***Super-FEPs***) and a check that the codes applied to analyse a specific case are actually able to reflect all the ***safety-relevant aspects of the Super-FEPs*** that are contained within this case (Appendices 7 and 8).
- The FEP management process has to take all reasonable measures to ensure completeness.
  - At the start of the analysis, an Opalinus Clay FEP Database ***(OPA FEP Database)*** that contains all safety-relevant issues is developed. Completeness is ensured through auditing the ***OPA FEP Database*** against ***International FEP Databases*** that were developed for this purpose; i.e. for each FEP contained in the ***International FEP***

Databases, it is checked whether it is included in the ***OPA FEP Database,*** and if not, that an explanation is available why not (Appendices 1 to 3).

– Throughout the process of screening of irrelevant information and abstraction of the remaining information, audits / checks of the intermediate information databases (***safety-relevant phenomena, Super-FEPs, assessment cases***) against the ***OPA FEP Database*** are performed; i.e. for each of the FEPs contained in the ***OPA FEP Database*** it is checked if it is included in the database audited or if an explanation / justification exists why not (Appendix 9).

This process results in a set of information (documented in different tables) which is described in this report. The development of this information and the corresponding tables was highly iterative; thus the final results as described in this report only reflect the interrelation between the different pieces of information, without providing a chronological description of how they were derived.

3 Development of the OPA FEP Database

This chapter describes the stages of FEP management related to the development of a comprehensive Opalinus Clay FEP Database, its audit against independent international FEP Lists and the screening out of unimportant FEPs. This corresponds to processes (a) to (d) as set out in Section 2.3.

3.1 Assessment bounding rules

The safety assessment for Project *Entsorgungsnachweis* is guided by the Swiss regulatory principles and guidance, international guidance and specific decisions related to the scope and context of the current phase of safety assessment, see Chapter 2 in Nagra (2002a). These guide and constrain the safety assessment and, in some cases, give specific advice on the consideration or inclusion / exclusion of given types of FEPs from the assessment.

In the Kristallin-I safety assessment (Nagra 1994a) such specific rules on the consideration or inclusion / exclusion of FEPs were termed "screening arguments". In this assessment they are termed "assessment bounding rules". This recognises that as well as being used to screen FEPs that have been placed on the FEP List, their main purpose is to limit consideration beyond certain bounds and to prevent irrelevant FEPs ever being put onto the FEP List. Tab. 3.1-1 lists the assessment bounding rules used in the safety assessment for Project *Entsorgungsnachweis* and related arguments.

Tab. 3.1-1: Assessment bounding rules used in the safety assessment for Project *Entsorgungsnachweis* and related arguments

Assessment bounding rules	**Comments, arguments and examples of FEPs ruled out by the arguments**
Repository construction, operation and closure according to the design	It is assumed that the repository is constructed, operated and closed according to the design and as planned. The event of an abandoned repository is postulated to test the robustness of the system with respect to including a prolonged period of monitoring of the pilot facility (Nagra 2002a, Chapter 2).
No consideration of global and regional disasters	No event that has such severe consequences that the presence of the repository adds only marginally to the consequences needs to be considered. Thus events such as large meteorite impact need not be assessed. Swiss regulations (HSK & KSA 1993) advise that processes and events with considerably more serious non-radiological than radiological consequences do not need to be assessed.
No consideration of malicious acts and war	During repository operations malicious acts will be prevented or mitigated by security arrangements and emergency plans. A closed repository would be an extraordinarily hard target to damage compared to surface installations. Consideration of war and major terrorist attack are beyond the scope of the assessment.

Tab. 3.1-1: (Cont.)

Assessment bounding rules	**Comments, arguments and examples of FEPs ruled out by the arguments**
No consideration of deliberate human intrusion	Future deliberate intrusive actions taken with knowledge of the nature and content of the repository are the responsibility of those that take such actions. Swiss regulations (HSK & KSA 1993) advise that intentional human intrusions do not need to be assessed.
No speculation on future human society and technology	Although changes in human society and technology are likely, they are unpredictable over the time period of interest. It is an internationally accepted convention that the calculated radiological doses and risks to hypothetical human groups dwelling in the future, but with habits and technology similar to that of the present day, are appropriate as *indicators* of repository safety (ICRP 2000). Adoption of these metrics avoids open-ended speculation, especially concerning the biosphere, which in any case should not impact unduly on the decisions taken on repository development.
No speculation on the long-term evolution of the biosphere	Use of the above indicators and the use of stylised "reference biospheres" (IAEA 1999) avoids open-ended speculation concerning the biosphere, which in any case should not impact unduly on the decisions taken on repository development.
Treatment of future human actions	The issues surrounding the assessment of future human actions affecting a deep geological repository are, in some respects, similar to those surrounding the treatment of the biosphere. Any statement about the actions that humans might take in the far future is largely speculative. The relationship between the assessment of such actions and the assessment of the quality of a site and a design is problematic because human actions have the potential to create exposure paths that by-pass the normal safety functions of the repository. These issues have been discussed internationally by a NEA Working Group (NEA 1995), within the NEA IPAG exercise (NEA 2000b) and, most recently, within IAEA Specialists' Meetings (IAEA 2001). The ICRP has also given guidance for the assessment of future human actions (ICRP 1998). In the present safety assessment, future human actions are treated using typical, stylised situations (exploratory activities (sinking of deep boreholes), exploitation of deep groundwater and the abandonment of the repository before final backfilling and sealing) to illustrate system behaviour under these conditions.
No speculation on future evolution of man and other species	Some evolution, especially of food crop species, is likely. As above, however, such changes are unpredictable and open-ended speculation should be avoided as not illuminating to the decisions that need to be taken.
Focus on assessment of radiological impact to humans	The primary aim of the safety assessment is to assess the performance of the repository and the potential for radiological impacts on human health. This is achieved by calculation of radiological doses and risks to hypothetical human groups as above. In this assessment, alternative indicators of performance, e.g. radionuclide flux to and concentrations in the biosphere, are of interest, but not the details of transfer mechanisms related to the exposure of non-human species.

3.2 Development of a comprehensive OPA FEP List

The OPA FEP List was developed based on the Kristallin-I FEP List (Sumerling et al. 1993) and on several ancillary FEP Lists compiled by Nagra and consultant staff considering different aspects of the proposed disposal system, and taking into account the assessment bounding rules listed in Tab. 3.1-1. The ancillary FEP Lists focused on those aspects of the disposal system and its assessment that differed from the system assessed in Kristallin-I, i.e. FEPs related to disposal of spent fuel and of ILW type waste and FEPs related to the performance of the Opalinus Clay as a host rock and migration barrier.

These separate FEP Lists were combined and organised according to a category structure based on the main physical elements of the disposal system and the external factors that may act on that system. Each main category was subdivided, for example FEPs related to each main physical element are divided into:

- features and characteristics of the element,
- environmental processes, i.e. processes acting to change the characteristics of the element over time,
- radionuclide processes, i.e. processes related to the release and migration of radionuclides within and from the element,
- special issues, i.e. additional FEPs requiring special consideration.

The organisation of FEPs within such a structure encourages comprehensiveness by revealing weaker sections in the list and enabling comparison between different categories within the list.

The list was reviewed and modified iteratively. This was done by assigning each category of the list to a Nagra or contractor staff member with expertise in the given area. Their tasks included the drafting of short descriptions of each FEP for internal purposes. These were needed to better define what was meant by the relatively short FEP names; however, they were never intended to reflect the detailed scientific basis of Project *Entsorgungsnachweis* (the scientific basis is documented in numerous reference reports, see Fig. 1.1-1). This process resulted in FEP descriptions that are rather heterogeneous: they have been written by different authors at different project stages and do not always reflect the current understanding. The structuring of the list was also progressively refined so that the final structure is as shown in Tab. 3.2-1. Gaps in the numbering are due to modifications of the structure during its iterative development. The OPA FEP List includes approximately 500 FEPs and is presented in Appendix 2 of this report.

It should be pointed out that in accordance with the assessment bounding rules regarding the biosphere and the treatment of future human actions given in Tab. 3.1-1 and the arguments made in Sections 2.5.4.2 ("The role and treatment of the biosphere") and 2.5.4.4 ("Treatment of future human actions") in Nagra (2002a), typical, stylised situations selected by expert judgement have been analysed for these two topics. Accordingly, in compiling the OPA FEP Database, no rigorous FEP analysis has been carried out for the biosphere and future human actions (including the exposure of individuals involved in an exploratory drilling that intercepts a waste package).

Tab. 3.2-1: The main categories used by the Opalinus Clay FEP List. Gaps in the numbering are due to modifications of the structure during its iterative development.

<table>
<tr><th>Categories for HLW assessment</th><th>Categories for spent fuel (SF) assessment</th><th>Categories for ILW assessment</th></tr>
<tr><td colspan="3">0. Assessment basis</td></tr>
<tr><td colspan="3">0.5 Common FEPs</td></tr>
<tr><td colspan="3">1. Siting and design</td></tr>
<tr><td>2.1 Vitrified HLW</td><td>2.2 Spent fuel</td><td rowspan="2">2.3 ILW waste and packages</td></tr>
<tr><td colspan="2">3.1 Canister (SF and HLW)</td></tr>
<tr><td colspan="2">4.1 Bentonite buffer</td><td>5.3 ILW backfill and liner</td></tr>
<tr><td colspan="2">6.1 Bentonite – host rock (HR) interface</td><td>6.3 Concrete – HR interface</td></tr>
<tr><td colspan="3">7. Opalinus Clay host rock</td></tr>
<tr><td colspan="3">8. Tunnels and shafts</td></tr>
<tr><td colspan="3">9. Geology and hydrogeology (surrounding regime)</td></tr>
<tr><td colspan="3">10. Biosphere (natural characteristics and exposure pathways)</td></tr>
<tr><td colspan="3">11. Geological processes and events (P&E)</td></tr>
<tr><td colspan="3">12. Climatic processes and events (P&E)</td></tr>
<tr><td colspan="3">13. Future human actions</td></tr>
</table>

3.3 Audits against international FEP Lists

The OPA FEP List has been developed, as described above, by a process of accumulation, addition, organisation and rationalisation based mainly on the experience of Nagra staff. In order to promote completeness of the OPA FEP List, an audit is performed where the OPA FEP List is compared to independently-derived FEP Lists. Two such FEP Lists are considered to be most suitable for this purpose:

- The NEA International FEP List (NEA 2000a), which provides a comprehensive list of relatively generically described FEPs intended as either a starting point, or audit tool, for assessment of any solid radioactive waste disposal system.
- The NEA FEPCAT catalogue of FEPs related to natural clays (Mazurek et al. 2002), which is based on a compilation and review of observations and results from experimental studies on natural clay samples in the laboratory and in underground testing facilities.

3.3.1 Audit against the NEA International FEP List

The NEA International FEP List consists of a structured list of 134 FEPs that are generally relevant to the assessment of underground disposal of solid radioactive waste. The list is reproduced in Appendix 1 of this report. Fig. 3.3-1 illustrates the use of this generic FEP List as a key to access and compare project-specific FEP databases. It is expected that:

- within the assessment of a specific disposal system, FEPs will be described that are project-specific examples of international FEPs; and

- the comprehensiveness of a project-specific FEP database (in the sense of its broad scope) can be judged by its coverage of the International FEP List.

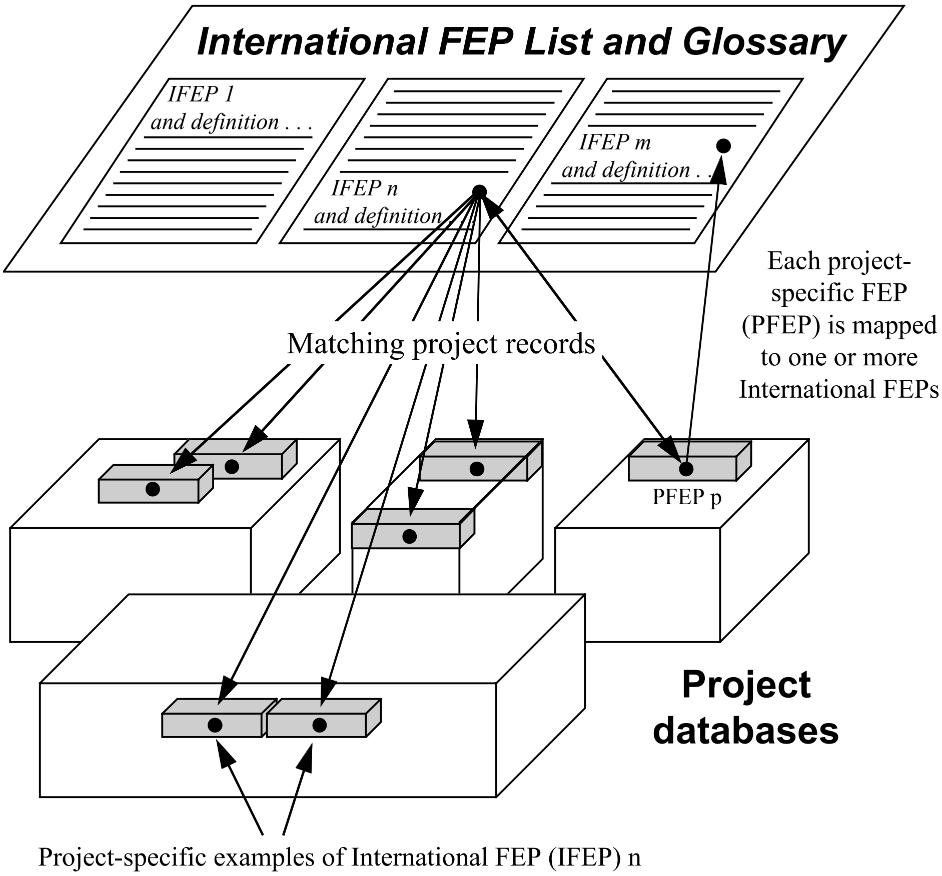

Fig. 3.3-1: The principle of the operation of the NEA International FEP Database

Taken from NEA (2000a).

A preliminary audit of the OPA FEP List against the International FEP (IFEP) List was carried out after a first integrated OPA FEP List had been achieved. This was used to test the audit process and also to make a preliminary check of the comprehensiveness of the OPA FEP List. A recommendation from the first audit was that short descriptions should be added to the OPA FEP names to better define what was meant by each. A second, final, audit of the OPA FEP List against the IFEP List was carried out after the OPA FEP List had been frozen and the above-mentioned short descriptions had been added. The second audit was carried out without reference to the results of the earlier audit.

The audits were carried out, within the OPA FEP electronic database, by a contractor who was not involved in the main stream of the safety assessment for Project *Entsorgungsnachweis*. Each OPA FEP was considered in turn and "mapped" (i.e. connected electronically) to the IFEP or IFEPs that provided a project-specific example or were most closely related. In the first audit, the majority of the 482 OPA FEPs were mapped to single IFEPs, about 10 % were mapped to 2 IFEPs and only a very few to 3 or more IFEPs. In the second audit, with the aid of the short descriptions, a much larger proportion of the OPA FEPs were mapped to more than one IFEP. Approximately 35 % were mapped to only 1 IFEP, 52 % were mapped to 2 IFEPs, 11 % to three IFEPs and 2 % to four IFEPs.

Fig. 3.3-2 shows a summary analysis of the distribution of the OPA FEPs against the NEA International FEP List structure. Appendix 3 records the full analysis of OPA FEPs mapped to each IFEP. The analysis shows a generally reasonable coverage of the categories represented by the NEA IFEP List, but with most weight (i.e. most OPA FEPs) mapped in the NEA categories of "waste and engineered factors", "geological environment" and "contaminant release / migration factors". This is consistent with the focus of the safety assessment for Project *Entsorgungsnachweis.*

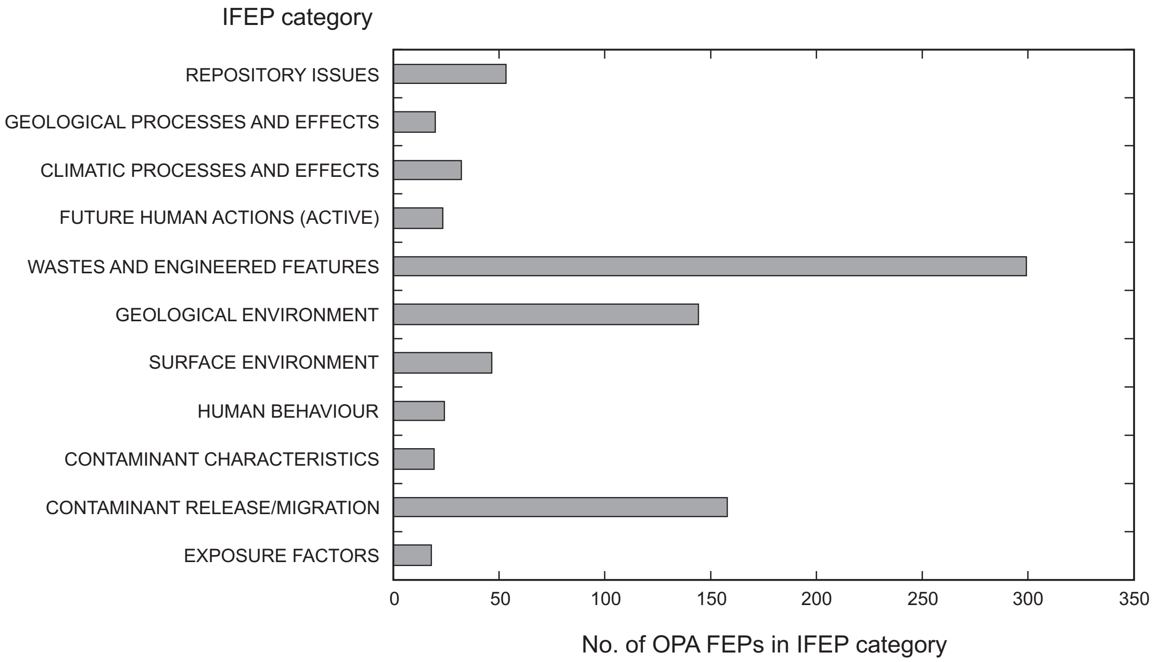

Fig. 3.3-2: The distribution of OPA FEPs against the NEA International IFEP List categories

The IFEPs in the category "ASSESSMENT BASIS" (see Tab. A1.1.1) are not mapped because they are considered outside the FEP management process (see text).

There are a few IFEPs to which no OPA FEP is mapped. The reasons for these omissions can be explained as follows.

- IFEPs related to the definition of assessment scope. These matters are discussed in Chapter 2 of the Safety Report (Nagra 2002a), and in the safety assessment bounding rules, see Tab. 3.1-1 in this report, rather than in the OPA FEP List. Consequently no mapping was performed for such FEPs.
- IFEPs not physically relevant to the proposed disposal system in Opalinus Clay.
- IFEPs unimportant for the proposed disposal system in Opalinus Clay and time scale of concern.

Tab. 3.3-1 identifies individual international FEPs to which no corresponding Opalinus Clay FEP was mapped, and explains why this is so by placing them in different columns corresponding to these reasons. There is one other IFEP to which no OPA FEP is mapped:

- IFEP 3.1.03 "Inorganic solids / solutes" – this was not selected during mapping mainly because this applies to a very large number of FEPs that were already mapped to at least one other IFEP, i.e. the IFEP does not appear to be a very useful heading.

Tab. 3.3-1: Individual international FEPs to which no corresponding OPA FEP was mapped, listed under the three main reasons

The IFEPs in the category "ASSESSMENT BASIS" (see Tab. A1.1.1) are not mapped because they are considered outside the FEP management process.

IFEPs related to the definition of assessment scope	**IFEPs not physically relevant to the proposed disposal system in Opalinus Clay**	**IFEPs unimportant for the proposed disposal system in Opalinus Clay and time scale of concern**	**IFEPs not directly addressed in safety assessment, but covered in Geosynthesis report (Nagra 2002c)**
1.4.08 Social and institutional developments 1.4.09 Technological developments 1.4.10 Remedial actions 1.5.01 Meteorite impact 1.5.02 Species evolution 1.5.03 Miscellaneous and FEPs of uncertain relevance	1.2.09 Salt diapirism and dissolution 1.3.03 Sea level change 1.4.03 Un-intrusive site investigation 1.4.11 Explosions and crashes 2.3.05 Coastal features 2.3.06 Marine features	1.2.05 Metamorphism 2.4.10 Urban and industrial land and water use 2.4.11 Leisure and other uses of environment	1.2.08 Diagenesis

3.3.2 Audit against the NEA FEPCAT List

The NEA FEPCAT project aims at providing, for each included so-called[12] FEP, a critical overview of conclusions and key references related to its current understanding and its potential impact on long-term performance of the geosphere. Experimental information (field, laboratory, numeric) provided by the participating organisations is the primary source of data.

The final NEA FEPCAT report was not available at the time of finalising the safety assessment for Project *Entsorgungsnachweis*, but the NEA FEPCAT List was already in its final form, and the audit was performed using this final NEA FEPCAT List (Mazurek at al. 2002). The FEPCAT Database consists of a structured list of 59 FEPs that are generally relevant to the assessment of underground disposal of solid radioactive waste in argillaceous host rocks. The list is reproduced in Appendix 1 of this report.

[12] See 2nd bullet point in Section 3.3.2.

It is worthwhile noting that the objectives, scope and structure of the FEPCAT Database differ from those of the OPA FEP Database:

- The objective of the FEPCAT Database is to provide information on argillaceous host rocks. This includes repository-induced processes affecting the host rock and long-term geological processes. In contrast, the OPA FEP Database is a comprehensive list of FEPs related to the assessment basis, siting and design issues (incl. all components of the repository system; i.e. near field, geosphere and biosphere) and all possible long-term evolutions (geological processes and events, climatic processes and events, future human actions).
- The FEPCAT Database reflects the scientific view and includes arguments and independent evidence that may be used to support conceptual assumptions and model simplifications and to derive input data in the safety assessment. The FEPCAT Database can thus be viewed to be more closely related to the list of key safety-relevant phenomena, discussed in Section 4.1 and Appendix 4, than to FEPs in the usual sense of the word.
- In the FEPCAT Database, the FEPs are classified according to whether they address issues related to the undisturbed system, to repository-induced perturbations or to long-term evolutions. Within each of these categories, features, events and processes are mixed. In the OPA FEP Database, the FEPs within each of the 18 categories listed in Tab. 3.2-1 are allocated to four sub-categories, namely i) features and characteristics, ii) environmental processes, iii) radionuclide processes, and iv) special issues.

In spite of these differences with regard to objectives, scope and structure, the audit of the OPA FEP Database against the FEPCAT Database is considered to be useful to check the completeness with regard to phenomena related to the host rock, to repository-induced processes affecting the host rock and to long-term geological processes.

The audit shows that 39 FEPCAT FEPs are mapped to one or several OPA FEPs (see Appendix 3). For the remaining FEPCAT FEPs no direct map to the OPA FEP List exists, but they are either considered in the derivation of the geological dataset (16 FEPs) or are used as independent evidence supporting the arguments for the low hydraulic conductivity and long-term stability of the Opalinus Clay (3 FEPs).

3.4 Screening and identification of safety-relevant OPA FEPs

The OPA FEP List was reviewed against the understanding of the disposal system and its safety, based on the specific design options to be considered and specific characteristics of the geological environment and its safety potential. In this process each FEP was considered in turn. The work was carried out by assessment experts that have a broad knowledge of the disposal system and its performance, with reference to experts in specific technical areas where this was required.

This process led to the screening out of a few FEPs that can be argued as not being relevant or not able to impact on the long-term safety of the disposal system. The reasons for screening are recorded in the database. The process also led to a refinement of some of the FEP descriptions. Overall a total of 447 OPA FEPs were carried forward, termed the *safety-relevant OPA FEPs*. Appendix 2 lists all OPA FEPs; screened-out OPA FEPs are indicated by italic text.

Tab. 3.4-1 summarises the screening by indicating the reasons for screening and individual OPA FEPs screened for this reason. Only 35 out of 482 OPA FEPs are considered not safety-relevant, which indicates that the original OPA FEP List is already well focused on safety-relevant issues.

Tab. 3.4-1: Generic reasons for screening and OPA FEPs screened out against these reasons

Reason for screening				
	OPA FEP category no. & name		OPA FEP no. & name within category	
Avoided by design or site selection				
	5.3	ILW backfill and liner	1.05.1	Drainage system
	11.	Geological P&E	2.10	Hydrothermal activity
Conservatively neglected				
	8.	Tunnels & shafts	3.02	Elemental solubility
	10.	Biosphere	2.04	Filtration
Conservative assumption included in all cases				
	2.2	Spent fuel	4.03	Damaged fuel
Effect avoided by design [1]				
	2.3	ILW waste and packages	4.01	Effects of co-disposal with SF/HLW
	4.1	Bentonite buffer	1.01.2	Corrosion of structural elements in HCB blocks
	8.	Tunnels & shafts	4.01	Oil or organic fluid spill
Negligible compared to other included FEPs				
	6.1	Bentonite-HR interface	1.01.1	Rock bolts and mesh
	6.3	Concrete-HR interface	1.01.1	Rock bolts
	7.	OPA host rock	2.05	Microbial activity
Negligible effect [2]				
	4.1	Bentonite buffer	2.07	Microbial activity
	6.1	Bentonite-HR interface	1.07	Microbial activity
	6.3	Concrete-HR interface	1.07	Microbial activity
	8.	Tunnels & shafts	4.04	Chemical plume from ILW
Negligible effect on long term safety [2]				
	2.1	Vitrified HLW	4.02	Handling accidents
	2.2	Spent fuel	4.02	Handling accidents
	2.3	ILW waste and packages	4.00.2	Handling accidents
Not observed in OPA				
	7.	OPA host rock	1.10	Calcite veins
Not physically possible for repository conditions				
	2.3	ILW waste and packages	4.03	Nuclear criticality
	4.1	Bentonite buffer	2.09	Bentonite erosion
Option not assessed [3]				
	1.0	Siting and design	3.03	SF/HLW emplacement panels – alternative design
	1.0	Siting and design	3.05	ILW emplacement tunnels – alternative design
Outside scope of assessment [4]				
	1.0	Siting and design	3.09	Retrievability
	2.2	Spent fuel	1.07	Chemically toxic contaminants
	2.3	ILW waste and packages	1.03	Chemically toxic components
	10.	Biosphere	4.02	Non-radiological effects
	10.	Biosphere	4.03	Radiological effects on non-human biota
	13.	Future human actions	2.02	Surface pollution (soils, rivers)
	13.	Future human actions	2.03	Groundwater pollution
	13.	Future human actions	3.03	Repository records, markers
Ruled out by observations in OPA [5]				
	7.	OPA host rock	4.04	Intrusion of saline groundwater
	8.	Tunnels & shafts	4.03	Intrusion of saline groundwater
Ruled out by HSK/KSA regulation				
	13.	Future human actions	3.01	Intentional intrusion
	13.	Future human actions	3.04	Planning restrictions

Further explanation of reasons for screening in Tab. 3.4-1:

[1] Design will be arranged to avoid any possibility of significant effects.
[2] No significant effects expected.
[3] Refers to alternative design concept not considered in the assessment.
[4] System factor, option or endpoint outside the scope of the assessment.
[5] Not relevant to the system according to site understanding.
[6] Implicitly included in all assessment cases, see also Tab. A2.1-1.

3.5 Summary and conclusions

The aim of this chapter was to describe the stages of FEP management related to the development of a comprehensive Opalinus Clay FEP Database, its audit against independent international FEP Lists and the screening out of FEPs that are considered not to be safety-relevant.

It has been shown that the OPA FEP Database provides a comprehensive information basis, which is broken down into units of information tailored to the purpose of safety assessment (FEP List). This list has been audited against two international FEP Lists, namely the NEA International FEP List and the NEA FEPCAT List. It has been demonstrated that all FEPs contained in these international FEP Lists are covered by one or several FEPs of the OPA FEP List, with the exception of a few FEPs. The omission of these FEPs is justified because they are either outside the defined assessment scope, are not physically relevant to the proposed disposal system in Opalinus Clay or are unimportant for the disposal system and time scale of concern.

In conclusion, it has been shown that no safety-relevant FEP has been overlooked, by comparison with the presently available international FEP Lists (completeness audit), which provides confidence that the available information basis is complete.

4 Identification of key safety-relevant phenomena, development of Super-FEPs and assessment cases and their audit

This chapter summarises the stages of FEP management related to the identification of key safety-relevant phenomena, the development of Super-FEPs and the identification of assessment cases, and the audit of the key safety-relevant phenomena, Super-FEPs and assessment cases against the Opalinus Clay FEP Database. This corresponds to processes (e) to (g) as set out in Section 2.3.

4.1 Identification of key safety-relevant phenomena

Within the main stream of the safety assessment, key safety-relevant phenomena are identified based on the integrated scientific understanding of disposal system evolution, as described in Chapters 4 and 5 of Nagra (2002a). The key safety-relevant phenomena and their related uncertainties represent the integrated scientific understanding of the disposal system and its performance. They provide a more convenient basis for discussion and evaluation in the phenomenological analysis than the more numerous individual OPA FEPs. The key safety-relevant phenomena were identified based on a wide range of considerations, including:

1) Results of previous safety assessments, which provide guidance on processes that are important and their associated uncertainties, although the significantly different engineered barrier systems and host rocks in some cases mean that this guidance must be used with caution.

2) Results of a large number of investigations, many of which were performed specifically for the present safety assessment.

3) Relevant results published in the open literature.

4) Discussions with Nagra experts and consultants regarding the properties of the components of the disposal system and uncertainties in their evolution and interactions.

5) Scoping calculations, which give some insights into the relative importance of various processes and design features.

Due consideration has been given to a manageable level of detail for the various phenomena. Too great a level of detail leads to a very large number of processes, leading to an intractable situation in subsequent abstraction to produce assessment models. The appropriate level of detail is a matter of expert judgement, but is often reasonably clear, because many processes associated with a system component may be subsumed into a single safety-relevant phenomenon (e.g. many processes and characteristics associated with HLW glass are considered in the proposed glass dissolution mechanism and rate). The final list of key safety-relevant phenomena thus represents a condensed form of the scientific understanding available on the detailed characteristics and evolution of the repository system. This information has been developed iteratively and was subject to several reviews by both internal staff members and external experts.

Tab. A4.1.1 in Appendix 4 presents the key safety-relevant phenomena associated with the disposal system evolution. This is identical to Tab. 5.7-1 in the Safety Report (Nagra 2002a) but with the addition of numbers to assist traceability to other tables. The justification for the selection of these phenomena, including the elimination of some of them from further consideration is given in Chapters 4 and 5 of Nagra (2002a). Note that in Tab. A4.1.1, three categories of phenomena / evolutions are defined:

- key safety-relevant phenomena / evolutions related to the reference disposal system,
- key safety-relevant phenomena / evolutions related to system design alternatives,
- speculative phenomena / evolutions involving future human behaviour or the evolution of the surface environment.

The table is intended to capture the safety-relevant phenomena whose significance is judged to be great enough that they should be evaluated further in the context of sensitivity analysis and calculations of radionuclide transport (discussed in Chapter 6 of Nagra 2002a). It also highlights uncertainties associated with the phenomena considered. In a few cases, the table identifies processes that can be eliminated from subsequent calculations of radionuclide transport based on specific arguments, which are again given in Chapter 5 of Nagra (2002a).

4.2 Deriving the Super-FEPs and assessment cases

Also within the main stream of the safety assessment, the key safety-relevant phenomena are evaluated and a set of assessment cases and their component Super-FEPs is derived, as described in Chapter 6 of Nagra (2002a). The Super-FEPs and their alternative realisations represent an abstraction of the key safety-relevant phenomena and their associated uncertainties, which reflect the integrated scientific understanding of the disposal system and its performance. The Super-FEPs thus represent the viewpoint of the safety assessment experts, whereas the key safety-relevant phenomena represent the viewpoint of the scientific experts conducting system analysis and providing input data for the safety assessment. This process also leads to the identification of reserve FEPs. These are listed in Tab. A5.5.1.

Tab. A5.2.1 in Appendix 5 presents the Super-FEPs, their associated uncertainties and design / system options, the significance of uncertainties, the safety-relevant aspects that are affected by uncertainties and design / system options and their treatment in assessment cases. Tab. A5.2.1 fully comprises Tab. 6.8-1 in the Safety Report (Nagra 2002a), but adds numbers to assist traceability to other tables and includes the safety-relevant aspects that are affected by the uncertainties and design / system options. The safety-relevant aspects are key to the description of assessment cases, in so far as their realisations clearly define the conceptual assumptions of the Reference Case and of the alternative cases.

As discussed in Section 2.2, there is a close correspondence between the key safety-relevant phenomena, which are selected based on scientific understanding, and the Super-FEPs, which are key groupings of FEPs derived for the purpose of quantitative assessment (see Chapter 6 in the Safety Report). It is not always a one-to-one correspondence, however, so that a map is needed between each key safety-relevant phenomenon and its associated uncertainties on the one hand and the corresponding Super-FEPs and their alternative realisations on the other hand.

Tab. A4.1.2 in Appendix 4 presents this map between key safety-relevant phenomena (from Tab. A4.1.1) and the Super-FEPs (from Tab. A5.2.1). This table illustrates that there are frequently several Super-FEPs associated with a particular key safety-relevant phenomenon and also that all key safety-relevant phenomena and their uncertainties have been considered and evaluated (in the form of their associated Super-FEPs). Some key safety-relevant phenomena can be shown to have an insignificant effect on safety, based on scientific evidence, on quantitative analysis or on qualitative arguments. In such cases, they are not considered further and no Super-FEP is identified. For completeness' sake, Tab. A4.1.2 also shows the assessment cases that arise from the consideration of the Super-FEPs and their associated uncertainties. At the same time, Tab. A4.1.2 is also used to check that for each Super-FEP, a corresponding key safety-relevant phenomenon exists that justifies the inclusion of the Super-FEP in the modelling approach. This is done by systematically ticking off all the Super-FEPs listed in Tab. A5.2.1 if the Super-FEP is indeed included in Tab. A4.1.2 in connection with a corresponding key safety-relevant phenomenon.

The derivation of assessment cases is based on system understanding (which is in turn based on scientific evidence, on so-called "insight models" and on sensitivity analysis) and on expert judgement on the relative importance of uncertainties associated with the key safety-relevant phenomena (see Fig. 5.7-1 in Nagra 2002a) and the Super-FEPs (see Tab. 4.2-1) and the safety-relevant aspects that are affected by these uncertainties. It is observed that the need for an alternative assessment case normally arises out of uncertainty associated with a key safety-relevant phenomenon or a Super-FEP, respectively. More precisely, those uncertainties leading to an overall system behaviour of a qualitatively different nature compared to that of the Reference Scenario (characterised by diffusion-dominated radionuclide-release through the host rock) are explored within a separate scenario (e.g. related to gas production / release → Alternative Scenario 1 or to future human actions → Alternative Scenario 2) or within a different group. The groups include:

- cases that explore the range of possibilities arising from particular uncertainties affecting the disposal system, where this range can be bounded with reasonable confidence on the basis of available scientific understanding (Reference Scenario and alternative scenarios),
- "what if?" cases to test the robustness of the disposal system,
- cases to address design and system options, and
- cases to scope different (stylised) possibilities for the characteristics and evolution of the surface environment (the biosphere).

Also within each of these groups, different assessment cases exist. If the uncertainty associated with a key safety-relevant phenomenon or a Super-FEP leads to an alternative conceptualisation of a specific phenomenon within a given group, then this is explored with an alternative conceptualisation. If the uncertainty of a Super-FEP leads to an alternative size or rate of a phenomenon, then this is explored by a parameter variation for a given conceptualisation.

The assessment cases are shown grouped according to the different scenarios, "what if?" cases, design and system options and biosphere cases in Tab. A5.3.1 in Appendix 5, with associated conceptualisation and parameter variations. Tab. A5.3.1 is identical to Tab. 6.8-2 in the Safety Report (Nagra 2002a). Each case is defined in terms of the main group (scenarios, "what if?" cases, design and system options, illustrations of biosphere uncertainty), the conceptual assumptions used for modelling specific phenomena, and a set of parameters. The cases are each assigned a number for identification. The first character identifies the scenario, or the fact that it is a "what if? case, a case addressing design and system options, or a case illustrating biosphere uncertainty. The second character (after the point) indicates differences in conceptual assumptions. The third (alphabetical) character indicates differences in the datasets used.

The range of influence of the Super-FEPs and associated uncertainties and design / system options on the repository system is shown in Tab. 4.2-1. This table allows to check the identification and grouping of the assessment cases with respect to the Super-FEPs and their associated uncertainties and the design / system options (Tab. A5.2.1). The analysis of Tab. 4.2-1 indicates that the spectrum of cases considered in Tab. A5.3.1 and their grouping is adequate.

Because interactions between Super-FEPs and their associated uncertainties cannot be excluded, an alternative realisation of one Super-FEP can also lead to a different behaviour of another Super-FEP. These influences, and their treatment in the assessment, are indicated in Tab. A5.4.1. It is found that the influences were properly treated; i.e. either they were explicitly addressed in specific assessment cases, or there is a plausible explanation available why no specific assessment case was derived to evaluate their effects.

Tab. 4.2-1: Range of influence of Super-FEPs and associated uncertainties and design / system options, incl. their treatment in safety assessment, on repository system

Only deviations with respect to the Reference Case are shown. The Super-FEPs and the associated uncertainties and design / system options are from Tab. 6.8-1 of Nagra (2002a). The numbering scheme corresponds to that of Tab. A5.2.1. Those uncertainties leading to an overall system behaviour of a qualitatively different nature compared to that of the Reference Scenario (characterised by diffusion dominated radionuclide release through the host rock) are explored within a separate scenario (e.g. related to gas production / release → AS1 or to future human actions → AS2).

Legend:

(black)	Range of influence of uncertainty / associated radionuclide transport (if it occurs) through host rock only
(grey)	Range of influence of uncertainty / associated radionuclide transport through host rock and tunnels / ramp / shaft and seal system in parallel

RS	Reference Scenario
AS1	Alternative Scenario 1: Release of volatile radionuclides along gas pathways
AS2	Alternative Scenario 2: Release of radionuclides affected by human actions
WIF	"What if?" case to investigate the robustness of the disposal system
DSO	Design / system option
BIO	Illustration of effects of biosphere uncertainty
RC	Reference conceptualisation
AC	Alternative conceptualisation
PV	Parameter variation
NPV	No parameter variation
NAC/SR	No special assessment case defined / reason discussed in Safety Report (NTB 02-05)
NAC/R	No special assessment case defined / reason discussed briefly in Safety Report and in more detail in a dedicated reference report
NAC/C	No special assessment case defined / included in all cases by conservatively assuming the worst possible effect of the uncertainty under consideration
BF	Backfill (SF / HLW: bentonite; ILW: cementitious backfill)

Tab. 4.2-1: (Cont.)

Super-FEP	**Associated uncertainties and design / system options**		**Range of influence of uncertainty**					
			EBS			**Host rock**	**Rocks above & below host rock**	**Bio-sphere**
	Description	**Treatment**	**Matrix**	**Can.**	**BF**	**Tunnels / seals**		
			SF					
B.1.1	**B.1.1.1**		■	■				
Quantities and burnup of fuel and associated radionuclide inventories, including the instant release fraction (IRF)	The possibility for increased nuclear power production	DSO						
	B.1.1.2		■					
	The current trend to higher burnups	RS/RC/PV						
	B.1.1.2a		■	■	■	■	■	
	Chemical state of ^{14}C released from SF	RS/RC/PV						
	B.1.1.3		■					
	The limited information available on the IRF of high burn-up UO_2 fuel and MOX fuel	RS/RC/PV						
B.1.2			■					
Corrosion of cladding (see also "The creation of gas pathways", B.7.1.1)	Whether preferential release of organic ^{14}C from the cladding occurs; corrosion rate of cladding	WIF						
B.1.3			■					
Breaching of cladding	The possibility of early fracturing of the cladding, preventing an extended period of complete containment following canister breaching	NAC/C						
B.1.4	**B.1.4.1**		■					
Dissolution of fuel matrix	Whether the rate of dissolution is controlled by the rate of production of radiolytic oxidants or (if reducing conditions prevail at the fuel surface) by the solubility of U(IV)	RS/AC						
	B.1.4.2		■					
	If the rate of dissolution is controlled by the rate of production of radiolytic oxidants, the proportion of the oxidants that is available for reaction at the fuel surface (not recombined, e.g. with radiolytic reductants)	WIF						

Tab. 4.2-1: (Cont.)

Super-FEP	Associated uncertainties and design / system options		Range of influence of uncertainty					
			EBS			Host rock	Rocks above & below host rock	Bio-sphere
	Description	Treatment	Matrix	Can.	BF	Tunnels / seals		
			SF					
B.1.5								
Criticality	Whether or not it can be completely ruled out	NAC/R						
			HLW glass					
B.2.1								
Quantities of glass and associated radionuclide inventories	Low – compositions specified by the two reprocessors	NAC/SR						
B.2.2								
Dissolution rate of glass	Long-term rates based on extrapolation of much shorter-term experiments; creation of additional surfaces for dissolution by fracturing of glass	RS/RC/PV						
			SF / HLW canisters					
B.3.5	**B.3.5.1**							
Breaching of steel canisters	The conditions under which mechanical failure of corroded canisters will occur; possibility of localised corrosion processes	RS/RC/PV						
	B.3.5.2							
	The remote possibility of (i) breaching prior to 1000 a, and the possibility of (ii) initially defective steel canisters	(i): WIF (ii): NAC/SR						
	B.3.5.3							
	Distribution of canister breaching times	NAC/C						
B.3.6								
Gas generation by steel canister corrosion	See "The creation of gas pathways", B.7.1.1							
B.3.7								
Canister material	Design option of a copper canister with steel insert for SF (or alternative material to mitigate / avoid gas production)	DSO						

Tab. 4.2-1: (Cont.)

Super-FEP	Associated uncertainties and design / system options		Range of influence of uncertainty					
			EBS			Host rock	Rocks above & below host rock	Bio-sphere
	Description	Treatment	Matrix	Can.	BF	Tunnels / seals		
SF / HLW near field								
B.4.1								
The long resaturation time of the repository and its surroundings	The rate of the resaturation process	NAC/SR						
B.4.2	**B.4.2.1**							
Geochemical immobilisation and retardation in the near field	Thermodynamic data and water chemistry	RS/RC/PV						
	B.4.2.1a							
	Colloid filtration by bentonite	NAC/SR						
	B.4.2.2							
	The extent of co-precipitation of radionuclides with secondary minerals derived from SF and glass dissolution and canister corrosion	NAC/C						
	B.4.2.3							
	The extent of sorption of radionuclides on canister corrosion products	NAC/C						
	B.4.2.4							
	The natural concentrations of isotopes in bentonite porewater	NAC/C						
B.4.3								
Migration of radio-lytic oxidants gene-rated at SF surfaces into bentonite buffer	Degree to which these oxidants are scavenged by reductants in the system	WIF						
B.4.4								
Thermal alteration of the bentonite buffer adjacent to the SF / HLW canisters	Existence / extent of any thermally altered region	RS/AC						
B.4.5								
Transport resistances provided by internal spaces (fractures) within the waste forms, by the breached SF / HLW canisters and by corrosion products	The magnitude and time-dependence of these resistances	NAC/C						

Tab. 4.2-1: (Cont.)

Super-FEP	Associated uncertainties and design / system options		Range of influence of uncertainty					
			EBS			Host rock	Rocks above & below host rock	Bio-sphere
	Description	Treatment	Matrix	Can.	BF	Tunnels / seals		
SF / HLW near field								
B.4.6								
Tunnel liner	Design option of concrete or polymer liners for emplacement tunnels in case increased tunnel support required	NAC/SR						
B.4.7								
Hydraulic transport characteristics of bentonite	Compaction of bentonite by tunnel convergence	NAC/SR						
B.4.7.1								
Gas transport characteristics of bentonite	Uncertainties in corrosion rate	NAC/SR						
ILW								
B.3.1								
Quantities of waste and associated radionuclide inventories	Uncertainty in inventories low, but two different waste specifications considered	DSO						
B.3.2								
Breaching of ILW steel drums and emplacement containers	The timing of drum / container breaching	NAC/C						
B.3.3								
Corrosion / dissolution of ILW	Rate of corrosion / dissolution of waste matrix and rate of release of radionuclides	NAC/C						
B.3.3.2								
Immobilisation and retardation in the ILW near field	Thermodynamic data and water chemistry	RS/RC/PV WIF						
B.3.4								
Gas generation	See "The creation of gas pathways", B.7.1.1							
B.4.8								
Hydraulic and gas transport characteristics of the ILW near field	Inflow rate of water; displacement of water by gas into rock and along tunnels	RS/AC						

Tab. 4.2-1: (Cont.)

Super-FEP	Associated uncertainties and design / system options		Range of influence of uncertainty					
			EBS			Host rock	Rocks above & below host rock	Bio-sphere
	Description	Treatment	Matrix	Can.	BF	Tunnels / seals		
ILW								
B.3.3.1								
Compaction of waste / mortar (see B.4.7)	Timing of convergence arising from void reduction of breached, corroded containers	RS/AC						
B.3.3.3								
The long resaturation time of the ILW tunnels	The rate of the resaturation process	NAC/SR						
Tunnels / ramp / shaft and seals								
B.5.1	**B.5.1.1**							
Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)	The hydraulic conductivity of the EDZs with respect to that of the surrounding undisturbed rock	RS/AC						
	B.5.1.2							
	The driving force for flow along the EDZs provided by tunnel convergence	RS/AC						
	B.5.1.3							
	The driving force for flow along the EDZs provided by near field gas, as well as the rate of near field gas production (see also "The migration of repository induced gas", B.7.1)	RS/AC						
B.5.2								
The seals and the surrounding rock (see also "The creation of gas pathways", B.7.1.1)	The possibility of sealed zones being bypassed by relatively permeable EDZs	WIF						

Tab. 4.2-1: (Cont.)

Super-FEP	Associated uncertainties and design / system options		Range of influence of uncertainty					
			EBS			Host rock	Rocks above & below host rock	Bio-sphere
	Description	Treatment	Matrix	Can.	BF	Tunnels / seals		
Opalinus Clay and confining units								
B.6.1	**B.6.1.1**							
Low groundwater flow rate through undisturbed Opalinus Clay (see also "Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones", B.5.1)	The groundwater flow rate through the Opalinus Clay, which is affected by uncertainties of about an order of magnitude	RS/RC/PV WIF						
	B.6.1.2							
	The effects of gas pressure buildup in the near field, tunnel convergence and ice loads on the hydraulic gradient	RS/AC						
	B.6.1.3							
	The eventual increase of hydraulic conductivity caused by erosion of the overburden	WIF						
B.6.1a								
Length of vertical transport path from emplacement tunnels to overlying and underlying formations	Variability in path length	WIF						
B.6.2	**B.6.2.1**							
Geochemical immobilisation and retardation in the Opalinus Clay and confining units	Sorption mechanisms and groundwater composition, diffusivity	RS/RC/PV WIF						
	B.6.2.2							
	The effectiveness of long-term immobilisation processes (precipitation / co-precipitation) in the geosphere	NAC/C						

Tab. 4.2-1: (Cont.)

Super-FEP	Associated uncertainties and design / system options: Description	Associated uncertainties and design / system options: Treatment	Range of influence of uncertainty: EBS: Matrix	EBS: Can.	EBS: BF	Host rock (Tunnels / seals)	Rocks above & below host rock (Tunnels / seals)	Bio-sphere
Opalinus Clay and confining units								
B.6.3	**B.6.3.1**							
Homogeneity	The possibility of low transmissivity (i.e. 10^{-10} $m^2 s^{-1}$ or less) undetected discontinuities in the Opalinus Clay	WIF						
	B.6.3.2							
	The possibility of higher-transmissivity discontinuities, faults and repository-induced fractures	WIF						
B.6.4								
Migration of high pH plume from ILW backfill into Opalinus Clay	The depth of migration, and associated physical and chemical changes in the clay	NAC/R						
B.6.5								
Radionuclide transport through the confining units and regional aquifers	Transport-relevant properties of the confining units and regional aquifers	RS/AC						
The barrier system (general)								
B.7.1	**B.7.1.1**							
The migration of repository induced gas	The possibility that gas pathways are created through host rock and the uncertainty in gas permeability that might allow the transport of ^{14}C in a volatile form with flowing gas	AS1/RS/PV						
	B.7.1.2							
	The possibility that the EDZs would allow the tunnels / ramp / shaft to provide gas pathways and the uncertainties in gas permeability	AS1/AS/PV						
	B.7.1.3							
	The rate of gas generation by corrosion of the SF / HLW canisters	AS1/NPV						

Tab. 4.2-1: (Cont.)

Super-FEP	Associated uncertainties and design / system options		Range of influence of uncertainty					
			EBS			Host rock	Rocks above & below host rock	Bio-sphere
	Description	Treatment	Matrix	Can.	BF	Tunnels / seals		
The barrier system (general)								
	B.7.1.4							
	Rapid transport of radio-nuclides as volatile species through continuous gas path	WIF						
	B.7.1.5							
	The rate of generation of gas by ILW	AS1/NPV						
	B.7.1.6							
	Extent of preferential release of organic ^{14}C from SF cladding	AS1/NPV						
B.7.2	**B.7.2.1**							
Future human actions	Possibility of future drilling of a borehole inadvertently affecting the barrier system	AS2						
	B.7.2.2							
	Possibility of future extraction of drinking water from a deep well drilled into the Malm aquifer and the production rate of such a well should it be created	AS2						
	B.7.2.3							
	Possibility of the repository being abandoned before it is backfilled and sealed	AS2						
The surface environment								
B.8								
Climatic evolution	The nature and timing of climate change	BIO						
B.9								
Geomorphological evolution	Properties of the discharge area for groundwater conveying radionuclides	BIO						

4.3 Audits and checks against the OPA FEP Database

The key safety-relevant phenomena are audited for completeness against the list of safety-relevant FEPs from the OPA FEP Database. This is done by checking that each safety-relevant OPA FEP is included within one or more of the key safety-relevant phenomena and their uncertainties. A check is also made that each safety-relevant OPA FEP is included within one or more of the Super-FEPs and assessment cases. Logically this must be so if the Super-FEPs and assessment cases have been properly derived and fully capture the key safety-relevant phenomena and their uncertainties, with the exception of those phenomena that are excluded from further consideration (see Section 4.2 and Tab. A4.1.2); so this is referred to as a check rather than an audit. In many cases, individual OPA FEPs are associated with multiple Super-FEPs and with a number of assessment cases. It is acknowledged that this often involves expert judgement and thus, the outcome cannot be expected to be unique. Nonetheless, it is felt that the systematic application of this process has greatly enhanced confidence in phenomenological completeness of the safety assessment. Reserve FEPs as well as those that are not considered safety-relevant are also noted.

Appendix 6 presents the results of the audit of key safety-relevant phenomena against the OPA FEP database, and a check of consequent allocation of OPA FEPs to Super-FEPs and assessment cases. For completeness, the listing of OPA FEPs also includes screened-out FEPs. The results indicate that in the vast majority of cases, the OPA FEPs can be directly linked to key safety-relevant phenomena and the Super-FEPs, and that the OPA FEP under consideration is explicitly included in at least one assessment case. For those cases where this is not true, a plausible explanation is available why not.

4.4 Summary and conclusions

In this section, a summary of the various elements of FEP management and audits related to the identification of key safety-relevant phenomena, the development of Super-FEPs and assessment cases is given and the conclusions are drawn:

- The key safety-relevant phenomena and their related uncertainties represent the integrated scientific understanding of the disposal system and its performance, i.e. they capture the scientific view.
- The Super-FEPs and their alternative realisations represent an abstraction of the integrated scientific understanding of the disposal system and its performance and were derived for the purpose of quantitative assessment; i.e. they capture the view of the safety assessment modeller. Additional information on Super-FEPs is presented related to associated uncertainties and design / system options, significance of uncertainties, safety-relevant aspects that are affected by uncertainties and design / system options and their treatment in assessment cases.
- Because of the different focus there is not a one-to-one correspondence between key safety-relevant phenomena and Super-FEPs. The performed map shows that all key safety-relevant phenomena are covered by one or several Super-FEPs, with the exception of a small number of phenomena that can be excluded from further (quantitative) consideration on the basis of (i) scientific evidence, (ii) quantitative analyses performed outside the main stream of safety assessment or (iii) qualitative arguments. It has also been shown that for each Super-FEP, at least one key safety-relevant phenomenon exists, thus justifying the inclusion of that particular Super-FEP in the modelling approach.
- The performed completeness audits and checks show that:

i) each OPA FEP not screened out previously (see Tab. A2.1.1) is properly included within one or more of the key safety-relevant phenomena and their uncertainties, with the exception of a small number considered not to be safety-relevant (justifications are given in Chapters 4 and 5 of Nagra 2002a), and

ii) each safety-relevant OPA FEP is either included within one or several Super-FEPs and assessment cases or is shown, by scientific evidence, quantitative analysis or qualitative arguments, to have an insignificant effect on safety.

5 Audit of assessment code capabilities

This chapter summarises the stages of FEP management related to the assessment of the capability of assessment codes and the audit of these codes against the Super-FEPs and assessment cases for the evaluation of which the codes are used. This corresponds to processes (h) to (j) as set out in Section 2.3.

5.1 Audit of the codes against the Super-FEPs

5.1.1 Purpose of the audit

The assessment codes are described in detail in Appendix 1 of Nagra (2002b). They comprise the *Reference Model Chain (RMC)* codes, together with the general-purpose transport code, FRAC3DVS, and the Gas Model. The RMC includes:

- the STMAN family of codes for modelling the release of radionuclides from the waste forms, transport through the engineered barriers and release to the geosphere, comprising:
  - SPENT, which is applicable to directly disposed spent fuel (SF);
  - STRENG, which is applicable to vitrified high-level waste (HLW); and
  - STALLION, which is applicable to long-lived intermediate-level waste (ILW);
- the PICNIC geosphere transport code; and
- the TAME biosphere code.

Phenomena that are explicitly included in these codes are summarised in Appendix 7.

The following sections describe the audit of these codes against the Super-FEPs. Some of these Super-FEPs have several safety-relevant aspects (features and processes, many of which are subject to uncertainty or may have alternative realisations depending on the design / system options that are chosen), and each of these must be taken into account in selecting and applying the codes for assessment calculations. This does not mean that a code must explicitly represent a Super-FEP, with all its safety-relevant aspects. It may be sufficient to represent the FEP implicitly via, for example, a conservative model simplification. In practice, the RMC is adequate for most of the assessment cases. Where, however, a code cannot treat a safety-relevant aspect of a Super-FEP, the need can arise to replace one or more codes in the RMC with alternatives for the assessment cases that are affected, most commonly either FRAC3DVS replacing PICNIC or the Gas Model replacing the entire RMC.

5.1.2 Summary of the audit

The audit is summarised in Tab. 5.1-1. The Super-FEPs, organised according to Tab. A5.2.1, are listed in the first column of the table. Each of the Super-FEPs has associated with it certain safety-relevant aspects (e.g. the timing or likelihood of an event, the rate of a process, the magnitude of a feature) that must be taken into account in modelling the Super-FEP. These are listed in the third column of Tab. 5.1-1, with identification labels for these aspects (e.g. SF1) in the second column. Safety-relevant aspects of the Super-FEPs can be addressed in a number of different ways, as shown using the following symbols used in Tab. 5.1-1:

✓ *A safety-relevant aspect of a Super-FEP is fully represented by a code*: either a process is modelled explicitly, or the magnitude, timing, rate or spatial extent of a process, or the performance of a feature, directly determines one or more input parameters.

- ✓ *A safety-relevant aspect of a Super-FEP is only partially represented by a code*: either only some limited aspect of a feature is modelled explicitly, or assumptions regarding the (non-negligible) impact of a process on the properties of the system are built into the code, but no parameter values are directly affected that can be used to vary these assumptions.
- ○ *A safety-relevant aspect of a Super-FEP is not represented by a code, but gives rise to time-dependent system properties that can be treated indirectly*: parameter sets can be chosen that represent steady-state system properties corresponding, for example, to the end-state of the system once the process is complete or to one of a number of possible transient states.

Shading indicates where a Super-FEP is irrelevant to the domain modelled by the code (see Appendix 1 of Nagra 2002b).

Where a code of the RMC cannot fully treat a safety-relevant aspect of a Super-FEP, but an alternative code exists that can treat this aspect quantitatively, this is indicated using the symbol ► in the table. The symbol appears:

- in the STMAN and PICNIC columns, where safety relevant aspects concern gas production and migration and radionuclides that can be transported as volatile species – these aspects are addressed by replacing the RMC with the Gas Model;
- in the PICNIC column, where safety relevant aspects concern the transient effects on groundwater movement of, for example, ice loading / unloading during glacial periods – these aspects are addressed using FRAC3DVS in place of PICNIC, and
- in the TAME column, where safety relevant aspects concern drinking water extraction from the Malm aquifer – these aspects are addressed using a simple analytical approach to calculate dose in place of TAME.

Where no qualified code exists, this is indicated using the symbol ●.

5.1.3 Key findings of the audit

The audit confirms that the RMC is adequate to represent most of the Super-FEPs and their safety-relevant aspects. The audit highlights safety-relevant aspects of Super-FEPs that cannot be handled by the RMC, but can be treated using alternative codes. For a few of the Super-FEPs or specific safety-relevant aspects of Super-FEPs, no qualified radionuclide transport code (and / or corresponding database) exists. This is true for:

- criticality;
- the distribution of breaching times for SF / HLW canisters;
- the extent of sorption on canister corrosion products;
- the effects on solubility limitation of the natural concentrations of isotopes;
- the magnitude and time-dependence of transport resistances within the waste matrix or of breached canisters in the SF / HLW near field; and
- immobilisation processes in the Opalinus Clay and confining units.

In all these case, however, significant effects can be ruled out by supplementary studies (e.g. for criticality), effects are intrinsically favourable to safety and can be conservatively neglected (e.g. transport resistances within the waste matrix or of failed canisters in the SF / HLW near field, immobilisation processes), or parameters (e.g. canister breaching time) can be chosen to ensure that calculations err on the side of pessimism.

Tables in Appendix 8 explain in more detail the allocation of symbols in Tab. 5.1-1. These tables address each code in turn, and indicate the features of the code affected by the various aspects of the Super-FEPs.

Tab. 5.1-1: The representation of Super-FEPs and their safety-relevant aspects in safety assessment computer codes

The Super-FEPs are organised according to Tab. 6.8-1 in the Safety Report (Nagra 2002a). The symbols are explained in Section 5.1.2.

Super-FEPs	**Safety-relevant aspects represented by models**		**Reference Model Chain**					**Alternative codes**	
			STMAN codes						
			SPENT	**STRENG**	**STALLION**	**PICNIC**	**TAME**	**FRAC3DVS**	**Gas Model**
			SF						
Quantities and burnup of fuel and associated radio-nuclide inventories, including the instant release fraction (IRF)	SF1	Waste inventory in a single package and number of packages	✔						✓
	SF2	Partitioning between fuel matrix, cladding and IRF	✔						✓
	SF3	^{14}C in organic and inorganic form upon release	✔						✓
	SF4	Proportion of organic ^{14}C in volatile form upon release	►						✔
Corrosion of cladding	SF5	Corrosion rate	✔						✓
Breaching of cladding	SF6	Timing	✓						
Dissolution of fuel matrix	SF7	Dissolution rate	✔						✔
Criticality	SF8	None – ruled out by design and supporting calculations	●						
			HLW						
Quantities of glass and associated radio-nuclide inventories	HL1	Waste inventory in a single package and number of packages		✔					✓
Dissolution rate of glass	HL2	Dissolution rate		✔					
			SF / HLW canisters						
Breaching of steel canisters	CN1	Distribution of breaching times	●	●					
	CN2	Time of occurrence of breaching	✔	✔					✔
Gas generation by steel canister corrosion	CN3	Gas generation rate for SF / HLW	►	►					✔
Canister material	CN4	Time of occurrence of breaching (time of occurrence affected by canister material)	✔	✔					
	CN5	Presence of initial defects (likelihood affected by canister material)	✔	✔					

Tab. 5.1-1: (Cont.)

Super-FEPs	Safety-relevant aspects represented by models		Reference Model Chain					Alternative codes	
			STMAN codes						
			SPENT	STRENG	STALLION	PICNIC	TAME	FRAC3DVS	Gas Model
SF / HLW near field									
The long resaturation time of the repository and its surroundings	NF1	The rate of the resaturation process	✓	✓					✓
Geochemical immobilisation and retardation in the near field	NF2	Solubility limitation (reservoir)	✔	✔					
	NF3	Solubility limitation (buffer)	✔	✔					
	NF4	Linear, equilibrium sorption	✔	✔				✔	
	NF5	Colloid filtration by bentonite	✓	✓					
	NF6	The extent of co-precipitation with secondary minerals	✓	✓					
	NF7	The extent of sorption on canister corrosion products	●	●					
	NF8	The effects on solubility limitation of the natural concentrations of isotopes	●	●					
Migration of radiolytic oxidants generated at SF surfaces into bentonite buffer	NF9	Proportion of the buffer affected and the magnitude of the effects on geochemical immobilisation	○						
Thermal alteration of the bentonite buffer adjacent to the SF / HLW canisters	NF10	Proportion of the buffer affected and the magnitude of the effects on buffer transport properties	○	○					
Transport resistances provided by internal spaces (fractures) within the waste forms, by the breached SF / HLW canisters and by corrosion products	NF11	The magnitude of transport resistance of initial defects	✔	✔					
	NF12	The magnitude and time-dependence of other transport resistances	●	●					
Tunnel liner	NF13	Requirement for a liner	○	○					
Hydraulic transport characteristics of bentonite	NF14	Stationary flow						✔	
	NF15	Transient flow						✔	
	NF16	Advection / dispersion						✔	
	NF17	Aqueous diffusion	✔	✔				✔	
	NF18	Effective flow rate at outer boundary	✔	✔					
	NF19	Compaction of bentonite by tunnel convergence	○	○					
Gas transport characteristics of bentonite	NF20	Gas-induced release of dissolved radionuclides	○						
	NF21	Dilatant gas pathway formation (SF / HLW near field)	►	►					✓
	NF22	Gas dissolution and diffusion	►	►					✔

Tab. 5.1-1 (Cont.)

Super-FEPs		Safety-relevant aspects represented by models	Reference Model Chain					Alternative codes	
			STMAN codes						
			SPENT	STRENG	STALLION	PICNIC	TAME	FRAC3DVS	Gas Model
ILW									
Quantities of waste and associated radionuclide inventories	IL1	Waste inventory in a single package and number of packages			✓				✓
Breaching of ILW steel drums and emplacement containers	IL2	Time of occurrence of breaching			✓				
Corrosion / dissolution of ILW	IL3	Corrosion rate of metallic components			✓				
	IL4	Corrosion / dissolution rate of remaining ILW components			●				
Immobilisation and retardation in the ILW near field	IL5	Linear, equilibrium sorption and solubility limitation			✓				
Gas generation	IL6	Gas generation rates for ILW			▶				✓
Hydraulic and gas transport character-istics of the ILW near field	IL7	Effective flow rate at outer boundary			✓				
	IL8	Gas dissolution and diffusion			▶				✓
	IL9	Porewater displacement by gas			▶ or ○				✓
Compaction of waste / mortar	IL10	Timing of convergence aris-ing from void reduction of breached, corroded canisters			○				
The long resaturation time of the ILW tunnels	IL11	The rate of the resaturation process			✓				
Tunnels / ramp / shaft and seals									
Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)	TS1	Transport paths provided by the tunnels / ramp / shaft				✓			
	TS2	Stationary flow				✓			
	TS3	Transient flow				○			
	TS4	Advection / dispersion				✓			
	TS5	Aqueous diffusion				✓			
The seals and the surrounding rock	TS6	Formation of dilatant gas pathways through the sealing zone							✓
	TS7	Transport resistance of the seals and the surrounding rock				✓			

Tab. 5.1-1: (Cont.)

Super-FEPs	Safety-relevant aspects represented by models		Reference Model Chain: STMAN codes: SPENT	STRENG	STALLION	PICNIC	TAME	Alternative codes: FRAC3DVS	Gas Model
Opalinus Clay and confining units									
Low groundwater flow rate through undisturbed Opalinus Clay	OP1	Stationary flow				✓		✓	
	OP2	Transient flow				► or ○		✓	
	OP3	Advection / dispersion				✓		✓	
	OP4	Aqueous diffusion				✓		✓	
	OP5	Long-term changes (e.g. due to erosion of overburden)				○		○	
Length of vertical transport path from emplacement tunnels to overlying and underlying formations	OP6	Transport paths provided by the Opalinus Clay and confining units				✓		✓	✓
Geochemical immobilisation and retardation in the Opalinus Clay and confining units	OP7	Linear, equilibrium sorption				✓		✓	
	OP8	Immobilisation processes				●		●	
Homogeneity	OP9	Transport paths provided by transmissive discontinuities, faults and repository-induced fractures in the clay				✓		✓	
Migration of high pH plume from ILW backfill into Opalinus Clay	OP10	The depth of migration, and associated physical and chemical changes in the clay				○			
Radionuclide transport through the confining units and regional aquifers	OP11	Transport paths provided by the confining units and regional aquifers				✓			
The barrier system (general)									
The migration of repository induced gas	BS1	Gas dissolution and diffusion in the Opalinus Clay (incl. tunnel EDZs)				►			✓
	BS2	Capillary leakage in the Opalinus Clay				►			✓
	BS3	Pathway dilation in the Opalinus Clay				►			✓
	BS4	Porewater displacement in the Wedelsandstein				►			✓
	BS5	Gas dissolution and diffusion in the low-permeability upper confining units				►			✓
	BS6	Capillary leakage through low-permeability upper confining units				►			✓

Tab. 5.1-1: (Cont.)

Super-FEPs	Safety-relevant aspects represented by models		Reference Model Chain					Alternative codes	
			STMAN codes						
			SPENT	STRENG	STALLION	PICNIC	TAME	FRAC3DVS	Gas Model
The barrier system (general)									
Future human actions	BS7	Borehole penetration of the repository	○	○	○		○		
	BS8	Drinking water extraction from the Malm aquifer					►		
	BS9	Abandonment of repository before backfilling / sealing				○			
The surface environment									
Climatic evolution	SE1	The nature and timing of climate change					○		
Geomorphological evolution	SE2	Properties of the exfiltration area for groundwater conveying radionuclides					○		

5.2 Selection of codes to represent the assessment cases

Having audited the codes against the Super-FEPs, the next step is to select an appropriate code, or code combination (model chain), to evaluate each assessment case. In order to do this, information from Appendix 5 on the significance and treatment in assessment cases of uncertainties and design / system options associated with specific Super-FEPs (Tab. A5.2.1) and information from this chapter on the qualification of codes to represent safety-relevant aspects of the Super-FEPs that can be affected by these uncertainties and design / system options must be brought together. The result is the overview table given in Appendix 9.

As shown by Tab. A9.1.1 in Appendix 9, the choice of the codes used to model the assessment cases depends on the uncertainties or design / system options that the cases address and on safety-relevant aspects of the Super-FEPs that these affect. The Reference Case is modelled using the RMC. If the uncertainties or design / system options that are addressed by an alternative case affect safety-relevant aspects of the Super-FEPs that the RMC can treat in some way (other than always simply assuming negligible impact), then the RMC is generally also used. In practice, this means that the RMC is used for virtually all cases. In a small number of cases, however, an uncertainty is addressed that affects a safety-relevant aspect that cannot adequately be treated using the RMC, and either one or more of the codes in the RMC must be replaced with an alternative code or analytical calculation.

Tab. 5.2-1 gives a summary of the resulting treatment of the assessment cases by codes in the safety assessment.

Tab. 5.2-1: Summary of the treatment of assessment cases by the codes

Corresponds to Tab. 2.2-1 in Nagra (2002b).

Alternative scenarios addressing scenario uncertainty	Alternative conceptualisations addressing conceptual uncertainty	Parameter variations addressing parameter uncertainty	Codes applied							
			SPENT	STRENG	STALLION	PICNIC	TAME	FRAC3DVS	Gas Model	Analytical calculations
1. Reference Scenario Release of dissolved radionuclides (7.4)	1.1 Reference conceptualisation	1.1a Reference Case (RC)	x	x	x	x	x			
		1.1b Variability in canister inventory	x	x		x	x			
		1.1c Reduced canister lifetime	x	x		x	x			
		1.1d Pessimistic near field geochemical dataset	x	x	x	x	x			
		1.1e Increased glass dissolution rate in HLW		x		x	x			
		1.1f Increased water flow rate in geosphere (10-fold increase)	x	x	x	x	x			
		1.1g Decreased water flow rate in geosphere (10-fold decrease)	x	x	x	x	x			
		1.1h Pessimistic geosphere sorption constants	x	x	x	x	x			
		1.1i Pessimistic near-field and geosphere geochemical dataset	x	x	x	x	x			
		1.1j Pessimistic geosphere diffusion constants	x	x	x	x	x			
		1.1k Pessimistic treatment of ^{14}C (organic) in SF	x			x	x			
	1.2 Solubility-limited dissolution of SF	1.2a Base Case only	x			x	x			
	1.3 Bentonite thermal alteration	1.3a Base Case only	x	x		x	x			
	1.4 Glacially-induced flow in the Opalinus Clay	1.4a Base Case only	x				x	x		
	1.5 Additional barrier provided by confining units	1.5a Vertical transport through confining units	x	x	x	x	x			
		1.5b Horizontal transport in local aquifers	x	x	x	x	x			
	1.6 Radionuclide release affected by ramp / shaft	1.6a Base Case	x	x	x	x	x			
		1.6b Increased hydraulic conductivity of EDZ (100-fold increase)	x	x	x	x	x			
	1.7 Convergence-induced release affected by ramp (ILW)	1.7a Steady-state hydraulics			x	x	x			
		1.7b Water pulse			x		x	x		
	1.8 Gas-induced release of dissolved radionuclides affected by ramp / shaft	1.8a Base Case	x		x	x	x			
		1.8b Increased water flow rate in ILW			x	x	x			

Tab. 5.2-1: (Cont.)

Alternative scenarios addressing scenario uncertainty	Alternative conceptualisations addressing conceptual uncertainty	Parameter variations addressing parameter uncertainty	Codes applied							
			SPENT	**STRENG**	**STALLION**	**PICNIC**	**TAME**	**FRAC3DVS**	**Gas Model**	**Analytical calculations**
2. Alternative Scenario 1 Release of volatile radionuclides along gas pathways (7.5)	2.1 Release of ^{14}C from SF and ILW as volatile species in the gas phase not affected by ramp / shaft ("tight seals")	2.1a-c Three different gas permeability values							x	
	2.2 Release of ^{14}C from SF and ILW as volatile species in the gas phase affected by ramp / shaft ("leaky seals")	2.2a-c Three different gas permeability values							x	
3. Alternative Scenario 2 Release of radionuclides affected by human actions (7.6)	3.1 Borehole penetration	3.1a-d Penetration of SF/HLW/ILW emplacement tunnel (parameter variations related to the water flow rate through the borehole and the number of canisters affected)	x	x	x		x			
		3.1e-g Direct hit of a SF canister (parameter variations related to the water flow rate through the borehole)	x				x			
	3.2 Deep groundwater extraction from Malm aquifer (production of well as dilution)	3.2a/b Two different degrees of plume capture efficiency (10 %, 100 %)	x	x	x	x				x
	3.3 Abandoned repository	3.3a Base Case only	x	x	x	x	x			
4. "What if" cases to investigate robustness of the disposal system (7.7)	4.1 High water flow rate	4.1a Increased water flow rate in geosphere (100-fold increase)	x	x	x	x	x			
	4.2 Transport along transmissive discontinuities	4.2a/b Number of SF/HLW canisters affected ($T = 10^{-10}$ m^2 s^{-1})	x	x		x	x			
		4.2c ILW ($T = 10^{-10}$ m^2 s^{-1})			x	x	x			
		4.2d/e Number of SF/HLW canisters affected ($T = 10^{-9}$ m^2 s^{-1})	x	x		x	x			
		4.2f ILW ($T = 10^{-9}$ m^2 s^{-1})			x	x	x			
	4.3 SF: Increased fuel dissolution rate	4.3a 10-fold increase with respect to RC	x			x	x			
		4.3b 100-fold increase with respect to RC	x			x	x			
	4.4 Redox front (SF/ILW compacted hulls)	4.4a Base Case only	x		x	x	x			
	4.5 ILW: Gas-induced release of dissolved radionuclides through the ramp only	4.5a/b Two different water flow rates			x	x	x			

Tab. 5.2-1: (Cont.)

Alternative scenarios addressing scenario uncertainty	Alternative conceptualisations addressing conceptual uncertainty	Parameter variations addressing parameter uncertainty	Codes applied							
			SPENT	**STRENG**	**STALLION**	**PICNIC**	**TAME**	**FRAC3DVS**	**Gas Model**	**Analytical calculations**
	4.6 Unretarded transport of ^{14}C released as volatile species through host rock; retardation in confining units taken into account	4.6a-c Three different gas permeability values							x	
	4.7 Poor near field and pessimistic near-field / geosphere geochemical dataset	4.7a RC flow rate	x	x	x	x	x			
		4.7b 10-fold increase of flow rate	x	x	x	x	x			
		4.7c 100-fold increase of flow rate	x	x	x	x	x			
	4.8 No advection in geosphere (diffusive transport only)	4.8a Base Case only	x	x	x	x	x			
	4.9 SF: Increased cladding corrosion rate	4.9a 10-fold increase with respect to RC	x			x	x			
	4.10 K_d(I) for NF and geosphere = 0	4.10a Base Case only	x	x	x	x	x			
	4.11 Decreased transport distance in Opalinus Clay (30 m)	4.11a Base Case only	x	x	x	x	x			
5. Design and system options (7.8)	5.1 Increased waste arisings (300 GWa(e))	5.1a Base Case only	x			x	x			
	5.2 ILW high force compacted waste option	5.2a Base Case only			x	x	x			
	5.3 SF canister with Cu shell	5.3a Canister breaching at 10^5 years	x			x	x			
		5.3b Initial defect (small initial pinhole, full breaching at 10^5 years)	x			x	x			
		5.3c Initial defect (large initial pinhole, full breaching at 10^5 years)	x			x	x			
6. Illustration of effects of biosphere uncertainty (7.9)	6.1 Reference and alternative geomorphology	6.1a Reference area (RC)	x	x	x	x	x			
		6.1b Sedimentation area	x	x	x	x	x			
		6.1c Wetland	x	x	x	x	x			
		6.1d Exfiltration to spring located at valley side	x	x	x	x				x
	6.2 Reference and alternative climates	6.2a Present-day climate (RC)	x	x	x	x	x			
		6.2b Drier / warmer than present-day climate	x	x	x	x	x			
		6.2c Wetter / warmer than present-day climate	x	x	x	x	x			
		6.2d Periglacial climate	x	x	x	x				x

5.3 Confirmation of the representation of Super-FEPs by cases and codes

5.3.1 Purpose

The model or model chain used to evaluate the cases should include the code or codes that are qualified to address the safety-relevant aspects affected by the uncertainties or design / system options under consideration. This is checked via Tab. 5.3-1.

5.3.2 Summary of the check

The first three columns of Tab. 5.3-1 list the Super-FEPs, associated uncertainties and design / system options and the safety-relevant aspects of the Super-FEPs that these affect. These are equivalent to columns 1, 2 and 4 of Tab. A5.2.1 of Appendix 5, but, for conciseness, only the identifiers (B.1.1, SF1, etc.) are given, rather than full descriptions. The fourth column gives the alternative assessment cases that address the uncertainties and design / system options. These are taken from the right-most column of Tab. A5.2.1. The fifth column shows the code or codes that are qualified to represent the safety-relevant aspects of the Super-FEPs, i.e. the codes for which a large or small tick or the symbol ○ appears in Tab. 5.1-1 (qualified codes that are not used for a particular case are shown in parentheses in the fifth column). The model or model chain used to evaluate the cases are indicated in the right-most column.

5.3.3 Findings

Tab. 5.3-1 confirms that the models or model chains used to evaluate the assessment cases do indeed include the code or codes that are qualified to address the safety-relevant aspects affected by the uncertainties or design / system options under consideration. Case 5.1a, for example, addresses the possibility for increased nuclear power production (B.1.1.1). This affects safety-relevant aspect SF1, namely the waste inventory in a single package and number of packages. SPENT is qualified to represent this aspect (see Tab. 5.1-1). The RMC is used to evaluate case 5.1a, and this chain includes SPENT (the spent fuel code within the STMAN family of near field codes).

Tab. 5.3-1: The significance and treatment in assessment cases of uncertainties and design / system options associated with specific Super-FEPs, and qualified codes used to evaluate the cases

The numbering scheme for Super-FEPs and associated uncertainties and design / system options corresponds to that of Tab. A5.2.1.

Super-FEP	**Associated uncertainties and design / system options**	**Safety-relevant aspects that are affected by uncertainties and design / system options**	**Alternative cases addressing uncertainties and design / system options**	**Codes qualified to address safety-relevant aspects (see Tab. 5.1-1)**	**Model or model chain used to evaluate cases (see Tab. 5.2-1)**
SF					
B.1.1	B.1.1.1	SF1	5.1a	SPENT (Gas Model)	RMC
	B.1.1.2	SF1	1.1b	SPENT (Gas Model)	RMC
		SF2		SPENT (Gas Model)	
	B.1.1.2a	SF3	1.1k	SPENT (Gas Model)	RMC
	B.1.1.3	SF2	See above (1.1b)		
B.1.2	-	SF5	4.9a	SPENT (Gas Model)	RMC
B.1.3	-	SF6	No alternative cases defined		
B.1.4	B.1.4.1	SF7	1.2a	SPENT (Gas Model)	RMC
	B.1.4.2	SF7	4.3a-b	SPENT (Gas Model)	RMC
B.1.5	-	SF8	None (supplementary arguments for omission)		
HLW					
B.2.1	-	HL1	No alternative cases defined		
B.2.2	-	HL2	1.1e	STRENG	RMC
SF / HLW canisters					
B.3.5	B.3.5.1	CN2	1.1c	SPENT STRENG (Gas Model)	RMC
	B.3.5.2	CN2	None – see, however, B.3.7 ("Canister material")		
	B.3.5.3	CN1	No alternative cases defined		
B.3.6	-	CN3	See B.7.1.1 ("The creation of gas pathways")		
B.3.7	-	CN4	5.3a-c	SPENT STRENG	RMC
		CN5		SPENT STRENG	

Tab. 5.3-1: (Cont.)

Super-FEP	Associated uncertainties and design / system options	Safety-relevant aspects that are affected by uncertainties and design / system options	Alternative cases addressing uncertainties and design / system options	Codes qualified to address safety-relevant aspects (see Tab. 5.1-1)	Model or model chain used to evaluate cases (see Tab. 5.2-1)
SF / HLW near field					
B.4.1	-	NF1	No alternative cases defined		
B.4.2	B.4.2.1	NF2	1.1d 1.1i	SPENT STRENG	RMC
		NF3		SPENT STRENG	
		NF4		SPENT STRENG (FRAC3DVS)	
	B.4.2.1a	NF5	No alternative cases defined		
	B.4.2.2	NF6	No alternative cases defined		
	B.4.2.3	NF7	No alternative cases defined		
	B.4.2.4	NF8	No alternative cases defined		
B.4.3	-	NF9	4.4a	SPENT	RMC
B.4.4	-	NF10	1.3a	SPENT STRENG	RMC
B.4.5	-	NF11	No alternative cases defined		
		NF12			
B.4.6	-	NF13	None (supplementary arguments for omission)		
B.4.7	-	NF19	No alternative cases defined		
B.4.7.1	-	NF20	1.8a	SPENT	RMC
ILW					
B.3.1	-	IL1	5.2a	STALLION	RMC
B.3.2	-	IL2	No alternative cases defined		
B.3.3	-	IL3	No alternative cases defined		
		IL4			
B.3.3.2	-	IL5	1.1d 1.1i 4.4a	STALLION	RMC
B.3.4	-	IL6	None – see, however, B.3.7 ("Canister material")		
B.4.8	-	IL9	1.8b	STALLION (Gas Model)	RMC

Tab. 5.3-1: (Cont.)

Super-FEP	Associated uncertainties and design / system options	Safety-relevant aspects that are affected by uncertainties and design / system options	Alternative cases addressing uncertainties and design / system options	Codes qualified to address safety-relevant aspects (see Tab. 5.1-1)	Model or model chain used to evaluate cases (see Tab. 5.2-1)
ILW					
B.3.3.1	-	IL10	1.7a-b	STALLION	1.7a: RMC 1.7b: STALLION → FRAC3DVS → TAME (see also B.5.1.2, below)
B.3.3.3	-	IL11	No alternative cases defined		
Tunnels / ramp / shaft and seals					
B.5.1	B.5.1.1	TS1	1.6a-b	PICNIC	RMC
		TS2		PICNIC	
	B.5.1.2	TS3	1.7a-b	PICNIC	1.7a: RMC 1.7b: STALLION → FRAC3DVS → TAME
		OP2		PICNIC or FRAC3DVS	
	B.5.1.3	TS3	1.8a-b	PICNIC	RMC
		OP2		PICNIC or FRAC3DVS	
B.5.2	-	TS7	4.5a-b	PICNIC	RMC
Opalinus Clay and confining units					
B.6.1	B.6.1.1	OP1	1.1f-g, 4.1a, 4.7a-c, 4.8a	PICNIC (FRAC3DVS)	RMC
	B.6.1.2	OP2	1.4a	PICNIC or FRAC3DVS	SPENT → FRAC3DVS → TAME
	B.6.1.3	OP5	No alternative cases defined		
B.6.1a	-	OP6	4.11a	PICNIC (FRAC3DVS) (Gas Model)	RMC
B.6.2	B.6.2.1	OP7	1.1h-j, 4.10a	PICNIC (FRAC3DVS)	RMC
	B.6.2.2	OP8	No alternative cases defined		

Tab. 5.3-1: (Cont.)

Super-FEP	Associated uncertainties and design / system options	Safety-relevant aspects that are affected by uncertain-ties and design / system options	Alternative cases addressing uncertain-ties and design / system options	Codes qualified to address safety-relevant aspects (see Tab. 5.1-1)	Model or model chain used to evaluate cases (see Tab. 5.2-1)
Opalinus Clay and confining units					
B.6.3	B.6.3.1	OP9	4.2a-c	PICNIC (FRAC3DVS)	RMC
	B.6.3.2	OP9	4.2d-f	PICNIC (FRAC3DVS)	RMC
B.6.4	-	OP10	No alternative cases defined		
B.6.5	-	OP11	1.5a-b	PICNIC	RMC
The barrier system (general)					
B.7.1	B.7.1.1	SF4	2.1a-c	Gas Model	Gas Model
		NF21		Gas Model	
		IL8		Gas Model	
		BS1-6		Gas Model	
	B.7.1.2	TS6	2.2a-c	Gas Model	Gas Model
	B.7.1.3	CN3	No alternative cases defined		
	B.7.1.4	BS6	4.4a-c	Gas Model	Gas Model
	B.7.1.5	IL6	No alternative cases defined		
	B.7.1.6	SF2	No alternative cases defined		
B.7.2	B.7.2.1	BS7	3.1a-g	STMAN codes TAME	STMAN → TAME
	B.7.2.2	BS8	3.2a-b	None	STMAN → PICNIC → Analytical calculations
	B.7.2.3	BS9	3.3a	PICNIC	RMC
The surface environment					
B.8	-	SE1	6.2a-d	TAME	6.2a-c: RMC 6.2d: STMAN → PICNIC → Analytical calculations
B.9	-	SE2	6.1a-d	TAME	6.1a-c: RMC 6.1d: STMAN → PICNIC → Analytical calculations

6 Conclusions and final remarks

This chapter makes concluding remarks on the FEP management process and its contribution to the overall confidence in the safety assessment.

As outlined in Section 1.3.2, the aims of the FEP management process documented in this report are:

- **Compilation of a complete set of information in the format of FEPs (the OPA FEP Database)** – The OPA FEP Database serves as a basis for a number of audits and checks (see Figs. 2.1-1, 2.2-1). Completeness of the OPA FEP Database is ensured by auditing it against other FEP databases (NEA International FEP Database and NEA FEPCAT Catalogue for Argillaceous Media). Completeness is also ensured by comparing the OPA FEP Database (or, more precisely, the safety-relevant FEPs, which are a sub-set of the OPA FEP Database) with an independently developed list of key safety-relevant phenomena.
- **Adequate treatment of information / no inadvertent loss of information** – To ensure that the information is adequately treated and that no information is accidentally discarded without reason, on the one hand it is checked which of the safety-relevant FEPs is reflected in which of the assessment cases. For those safety-relevant FEPs that are not included in any of the cases, it is ensured that an adequate justification is available. On the other hand, a similar procedure is conducted for the independently developed list of key safety-relevant phenomena, which are mapped onto Super-FEPs, which are then checked for their incorporation in the assessment cases.
- **Availability of adequate tools for quantitative assessment / use of suitable tools for assessment cases** – The FEP management process has to ensure that adequate tools are available for the quantitative assessment and that for the individual assessment cases suitable tools are used.
- **Assessment and documentation of the bias introduced in the different assessment cases –** Qualification of the assessment cases in terms of the bias introduced in their evaluation allows a better appreciation of the corresponding calculated results. Although this is regarded as a part of the FEP management process, the corresponding tables are not included in the present report, but are given in the Models, Codes and Data report (Nagra 2002b).

To fulfil these aims a complex process of auditing, checking and mapping of information has been applied. This process is strongly iterative; i.e. the tables shown in this report have gone through a number of cycles before they were fixed in the present form. It is felt that as a result of this process confidence in completeness of the OPA FEP Database, in adequate treatment of information and thus, ultimately, that an adequately broad range of assessment cases has been analysed with adequate tools, is at a sufficient level. This provides an additional qualitative argument supporting the quantitative results of the safety assessment.

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Appendix 1: International FEP Lists

A1.1 The NEA International FEP List

The NEA International FEP List is a list of factors relevant to the assessment of long-term safety of solid radioactive waste repositories, that attempts to be comprehensive within defined bounds. This forms a master list and classification scheme by which to examine the project-specific FEP database entries (NEA 2000a). The list consists of 134 generically described factors organised according to a scheme of categories and subcategories illustrated in Fig. A1.1.1.

Tab. A1.1.1 (following pages) shows the complete listing of NEA International FEPs in category scheme order.

- Category headings are indicated by **BOLD CAPITAL TEXT.**
- Subcategory headings are indicated by CAPITAL TEXT.

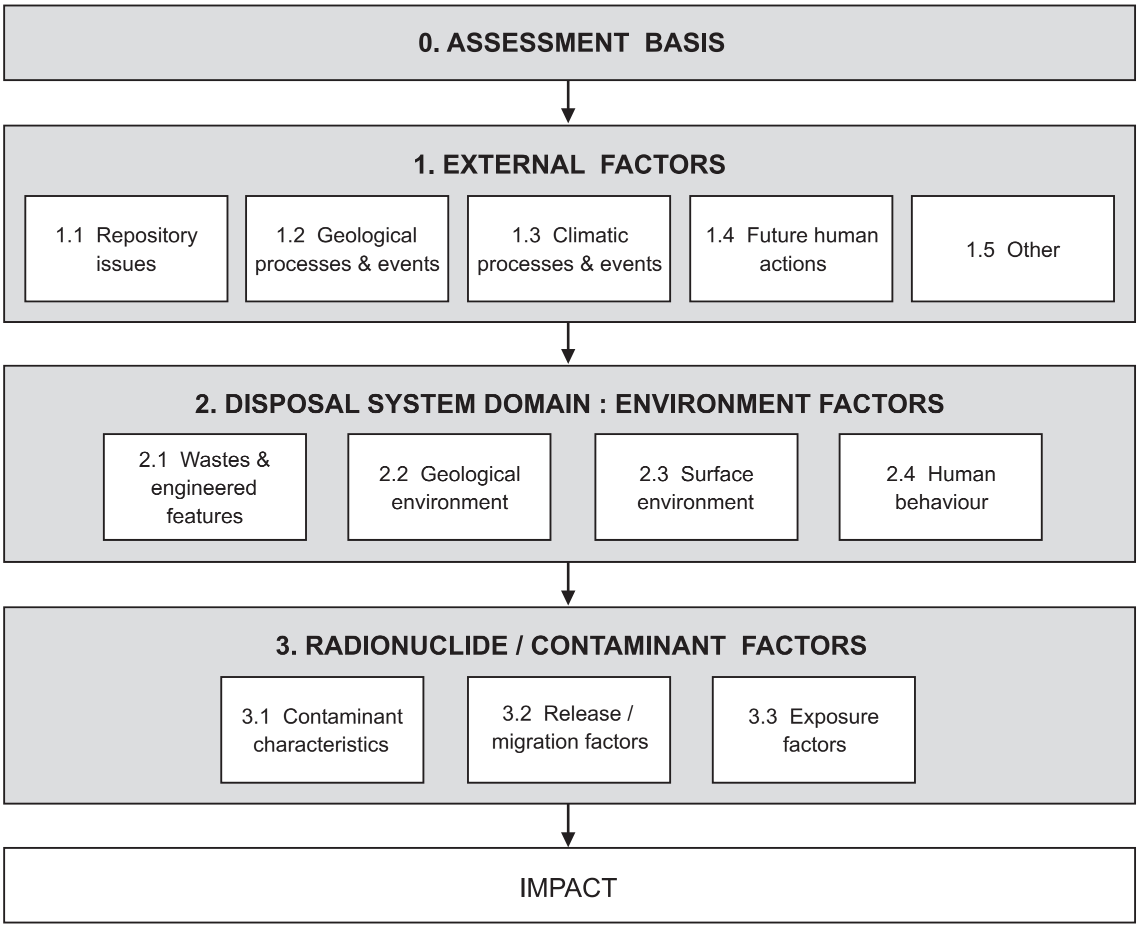

Fig. A1.1.1: The classification scheme used in deriving the International FEP List

Tab. A1.1.1: The NEA International FEP List

0 ASSESSMENT BASIS

0.01 Impacts of concern
0.02 Timescales of concern
0.03 Spatial domain of concern
0.04 Repository assumptions
0.05 Future human action assumptions
0.06 Future human behaviour (target group) assumptions
0.07 Dose response assumptions
0.08 Aims of the assessment
0.09 Regulatory requirements and exclusions
0.10 Model and data issues

1 EXTERNAL FACTORS

1.1 REPOSITORY ISSUES

1.1.01 Site investigation
1.1.02 Excavation / construction
1.1.03 Emplacement of wastes and backfilling
1.1.04 Closure and repository sealing
1.1.05 Records and markers, repository
1.1.06 Waste allocation
1.1.07 Repository design
1.1.08 Quality control
1.1.09 Schedule and planning
1.1.10 Administrative control, repository site
1.1.11 Monitoring of repository
1.1.12 Accidents and unplanned events
1.1.13 Retrievability

1.2 GEOLOGICAL PROCESSES AND EFFECTS

1.2.01 Tectonic movements and orogeny
1.2.02 Deformation, elastic, plastic or brittle
1.2.03 Seismicity
1.2.04 Volcanic and magmatic activity
1.2.05 Metamorphism
1.2.06 Hydrothermal activity
1.2.07 Erosion and sedimentation
1.2.08 Diagenesis
1.2.09 Salt diapirism and dissolution
1.2.10 Hydrological / hydrogeological response to geological changes

1.3 CLIMATIC PROCESSES AND EFFECTS

1.3.01 Climate change, global
1.3.02 Climate change, regional and local
1.3.03 Sea level change
1.3.04 Periglacial effects

1.3.05 Glacial and ice sheet effects, local
1.3.06 Warm climate effects (tropical and desert)
1.3.07 Hydrological / hydrogeological response to climate changes
1.3.08 Ecological response to climate changes
1.3.09 Human response to climate changes

1.4 FUTURE HUMAN ACTIONS

1.4.01 Human influences on climate
1.4.02 Motivation and knowledge issues (inadvertent / deliberate human actions)
1.4.03 Un-intrusive site investigation
1.4.04 Drilling activities (human intrusion)
1.4.05 Mining and other underground activities (human intrusion)
1.4.06 Surface environment, human activities
1.4.07 Water management (wells, reservoirs, dams)
1.4.08 Social and institutional developments
1.4.09 Technological developments
1.4.10 Remedial actions
1.4.11 Explosions and crashes

1.5 OTHER

1.5.01 Meteorite impact
1.5.02 Species evolution
1.5.03 Miscellaneous and FEPs of uncertain relevance

2 DISPOSAL SYSTEM DOMAIN: ENVIRONMENTAL FACTORS

2.1 WASTES AND ENGINEERED FEATURES

2.1.01 Inventory, radionuclide and other material
2.1.02 Waste form materials and characteristics
2.1.03 Container materials and characteristics
2.1.04 Buffer / backfill materials and characteristics
2.1.05 Seals, cavern / tunnel / shaft
2.1.06 Other engineered features materials and characteristics
2.1.07 Mechanical processes and conditions (in wastes and EBS)
2.1.08 Hydraulic / hydrogeological processes and conditions (in wastes and EBS)
2.1.09 Chemical / geochemical processes and conditions (in wastes and EBS)
2.1.10 Biological / biochemical processes and conditions (in wastes and EBS)
2.1.11 Thermal processes and conditions (in wastes and EBS)
2.1.12 Gas sources and effects (in wastes and EBS)
2.1.13 Radiation effects (in wastes and EBS)
2.1.14 Nuclear criticality

2.2 GEOLOGICAL ENVIRONMENT

2.2.01 Excavation disturbed zone, host rock
2.2.02 Host rock
2.2.03 Geological units, other
2.2.04 Discontinuities, large scale (in geosphere)
2.2.05 Contaminant transport path characteristics (in geosphere)
2.2.06 Mechanical processes and conditions (in geosphere)

2.2.07 Hydraulic / hydrogeological processes and conditions (in geosphere)
2.2.08 Chemical / geochemical processes and conditions (in geosphere)
2.2.09 Biological / biochemical processes and conditions (in geosphere)
2.2.10 Thermal processes and conditions (in geosphere)
2.2.11 Gas sources and effects (in geosphere)
2.2.12 Undetected features (in geosphere)
2.2.13 Geological resources

2.3 SURFACE ENVIRONMENT

2.3.01 Topography and morphology
2.3.02 Soil and sediment
2.3.03 Aquifers and water-bearing features, near surface
2.3.04 Lakes, rivers, streams and springs
2.3.05 Coastal features
2.3.06 Marine features
2.3.07 Atmosphere
2.3.08 Vegetation
2.3.09 Animal populations
2.3.10 Meteorology
2.3.11 Hydrological regime and water balance (near-surface)
2.3.12 Erosion and deposition
2.3.13 Ecological / biological / microbial systems

2.4 HUMAN BEHAVIOUR

2.4.01 Human characteristics (physiology, metabolism)
2.4.02 Adults, children, infants and other variations
2.4.03 Diet and fluid intake
2.4.04 Habits (non-diet-related behaviour)
2.4.05 Community characteristics
2.4.06 Food and water processing and preparation
2.4.07 Dwellings
2.4.08 Wild and natural land and water use
2.4.09 Rural and agricultural land and water use (incl. fisheries)
2.4.10 Urban and industrial land and water use
2.4.11 Leisure and other uses of environment

3 RADIONUCLIDE / CONTAMINANT FACTORS

3.1 CONTAMINANT CHARACTERISTICS

3.1.01 Radioactive decay and in-growth
3.1.02 Chemical / organic toxin stability
3.1.03 Inorganic solids / solutes
3.1.04 Volatiles and potential for volatility
3.1.05 Organics and potential for organic forms
3.1.06 Noble gases

3.2 CONTAMINANT RELEASE / MIGRATION FACTORS

3.2.01 Dissolution, precipitation and crystallisation, contaminant
3.2.02 Speciation and solubility, contaminant
3.2.03 Sorption / desorption processes, contaminant
3.2.04 Colloids, contaminant interactions and transport with
3.2.05 Chemical / complexing agents, effects on contaminant speciation / transport
3.2.06 Microbial / biological / plant-mediated processes, contaminant
3.2.07 Water-mediated transport of contaminants
3.2.08 Solid-mediated transport of contaminants
3.2.09 Gas-mediated transport of contaminants
3.2.10 Atmospheric transport of contaminants
3.2.11 Animal, plant and microbe mediated transport of contaminants
3.2.12 Human-action-mediated transport of contaminants
3.2.13 Foodchains, uptake of contaminants in

3.3 EXPOSURE FACTORS

3.3.01 Drinking water, foodstuffs and drugs, contaminant concentrations in
3.3.02 Environmental media, contaminant concentrations in
3.3.03 Non-food products, contaminant concentrations in
3.3.04 Exposure modes
3.3.05 Dosimetry
3.3.06 Radiological toxicity / effects
3.3.07 Non-radiological toxicity / effects
3.3.08 Radon and radon daughter exposure

A1.2 The NEA FEPCAT List

The NEA FEPCAT project aims at providing, for each included so-called FEP[13], a critical overview of conclusions and key references related to its current understanding and its potential impact on long-term performance of the geosphere. Experimental information (field, laboratory, numeric) provided by the participating organizations is the primary source of data.

The final NEA FEPCAT Report was not available at the time of finalising the safety assessment for Project "Entsorgungsnachweis", but the available FEP List was already in its final form, and the audit was performed using this final FEP List (Mazurek at al. 2002). The FEPCAT List consists of a structured list of 59 FEPs that are generally relevant to the assessment of underground disposal of solid radioactive waste in argillaceous host rocks (Tab. A1.2.1).

[13] The FEPCAT Database reflects the scientific view and includes arguments and independent evidence that may be used to support conceptual assumptions and model simplifications and to derive input data in the safety assessment. The FEPCAT Database can thus be viewed to be more closely related to the list of key safety-relevant phenomena, discussed in Section 4.1 and Appendix 4, than to FEPs in the usual sense of the word.

Tab. A1.2.1: The NEA FEPCAT List

FEP		Structured FEP classification	Related FEPs
No.	**Hierarchy**		
	A	UNDISTURBED SYSTEM	
	A1	**Transport mechanisms**	
1	A1.1	Advection / dispersion	
2	*A1.1.1*	*Size and geometry of the host rock and of surrounding units, migration pathlength*	
3	*A1.1.2*	*Migration pathways, including heterogeneity and anatomy*	
4	*A1.1.3*	*Undetected geological features*	
5	*A1.1.4*	*Hydraulic potentials and gradients in the host rock, including boundary conditions*	
6	*A1.1.5*	*Hydraulic properties of the host rock*	
7	*A1.1.6*	*Units over- and underlying the host formation: local and regional hydrogeologic framework*	
	A1.2	Diffusion	A2.1
8	*A1.2.1*	*Diffusivity*	*A2.1.1*
9	*A1.2.2*	*Connected matrix porosity*	*A2.1.2*
10	*A1.2.3*	*Ion exclusion*	*A2.1.4*
11	*A1.2.4*	*Surface diffusion*	*A2.1.5*
12	A1.3	Colloid formation, transport and filtration	
	A2	**Retardation mechanisms**	
	A2.1	Matrix diffusion	A1.2
8	*A2.1.1*	*Diffusivity*	*A1.2.1*
9	*A2.1.2*	*Connected matrix porosity*	*A1.2.2*
13	*A2.1.3*	*Flow-wetted surface and accessibility of matrix*	
10	*A2.1.4*	*Ion exclusion*	*A1.2.3*
11	*A2.1.5*	*Surface diffusion*	*A1.2.4*
	A2.2	Sorption (broad definition)	
14	*A2.2.1*	*Lithology, mineralogy of rocks and fracture infills*	
15	*A2.2.2*	*Natural organics, complexation*	
16	*A2.2.3*	*Mineral-surface area*	
17	*A2.2.4*	*Pore- and fracture water composition*	
18	*A2.2.5*	*Dissolution / precipitation of solid phases*	
19	*A2.2.6*	*Solid solutions / co-precipitation*	
20	*A2.2.7*	*Ion exchange*	
21	*A2.2.8*	*Surface complexation*	
22	*A2.2.9*	*Thermodynamic and kinetic modelling data*	

Tab. A1.2.1: (Cont.)

FEP		Structured FEP classification	Related FEPs
No.	Hierarchy		
	A3	**System understanding and independent methods / tools to build confidence in predictive models**	
23	A3.1	Palaeo-hydrogeology of the host formation and of embedding units	*C1.1.1*
24	A3.2	Evolution of pore-fluid (water and gas) chemistry and mineralogy in the host formation and in embedding units	*C1.1.2*
25	A3.3	Water residence times in the host formation	
	B	REPOSITORY-INDUCED PERTURBATIONS	
	B1	**Chemical perturbations**	
26	B1.1	Oxidation of the host rock	
27	*B1.1.1*	*Redox buffering capacity of the host rock*	
28	B1.2	Effects of repository components on pore-water chemistry in the host rock	
29	*B1.2.1*	*Interactions of hyperalkaline fluids and host rock*	
30	*B1.2.2*	*Organics from waste and their effect on transport properties of the host rock*	
	B2	**Thermal perturbations**	
31	B2.1	Thermal effects on mineral stability and pore-water composition	
32	B2.2	Thermal rock properties	
33	B2.3	Thermally induced consolidation of the host rock	
	B3	**Geomechanical perturbations**	
34	B3.1	Geomechanical stability	
35	B3.2	Size and structure of the EDZ	
36	B3.3	Effects of bentonite swelling on the host rock	
37	B3.4	Geomechanical rock properties	
	B4	**Hydraulic perturbations**	
38	B4.1	Hydraulic properties of the EDZ	
39	B4.2	State of saturation of the EDZ and desiccation cracking	
	B5	**Perturbations from coupled processes**	
40	B5.1	Coupled thermo-hydro-mechanic processes	
41	B5.2	Swelling	C2.3
42	B5.3	Self-sealing	C2.4
43	B5.4	Off-diagonal Onsager processes except chemical osmosis	
44	B5.5	Chemical osmosis	

Tab. A1.2.1: (Cont.)

FEP No.	FEP Hierarchy	Structured FEP classification	Related FEPs
	B6	**Perturbations from waste-derived gas**	
45	B6.1	Gas dissolution and chemical interactions between gas and pore water	
46	B6.2	Gas migration through the primary porosity (matrix, natural fractures)	
47	B6.3	Gas migration through stress-induced porosity (gas fracs, pathway dilation)	
48	B6.4	Gas-induced transport in water	
49	**B7**	**Microbiological perturbations**	
	C	LONG-TERM EVOLUTION	
	C1	**Diagenesis**	
	C1.1	Past basin evolution	
23	*C1.1.1*	*Palaeo-hydrogeology of the host formation and of the embedding units*	A3.1
24	*C1.1.2*	*Evolution of pore-fluid (water and gas) chemistry and mineralogy in the host formation and in embedding units*	A3.2
50	*C1.1.3*	*Past burial history*	
	C1.2	Ongoing and future processes	
51	*C1.2.1*	*Present and future geothermal regime and related processes*	
52	*C1.2.2*	*Future changes in hydrochemistry of the host rock and of surrounding formations (e.g. due to out-diffusion, water-rock interactions, uplift)*	
	C2	**Deformation events**	
53	C2.1	Past deformation events	
54	C2.2	Future fault (re)activation, changes in migration pathways; changes of hydraulic parameters; flow events	
41	C2.3	Swelling	B5.2
42	C2.4	Self-sealing	B5.3
55	C2.5	Present-day stress regime	
56	C2.6	Future stress regime	
	C3	**Erosion and burial**	
57	C3.1	Geomechanical effects of erosion / unloading	
58	C3.2	Consolidation due to burial	
59	C3.3	Future evolution of hydraulic potentials and gradients (e.g. due to erosion or burial)	

Appendix 2: The Opalinus Clay FEP List and Database

A2.1 Introduction

The Opalinus Clay FEP List (OPA FEP List) consists of 482 FEPs organised in a structure of 18 categories and 52 sub-categories, see Section 3.2 and Tab. 3.2-1 in the main text.

The 482 FEPs and the 52 sub-categories are each included as a record in an electronic database which thus contains a total of 534 records. Each FEP is identified by a name and a two part unique number of the form "m.n / o.pq", where "m.n" indicates the category, "o" indicates the sub-category and "pq" indicates the individual FEP number within the sub-category.

Tab. A2.1.1 shows the complete listing of OPA FEPs in category scheme order, but giving the OPA FEP titles only. For many purposes, this will be adequate. However, those readers who would like to view the description of a specific OPA FEP should consult Tab. A2.1.2, which repeats Tab. A2.1.1, but gives in addition a short description of each OPA FEP. As discussed in Section 3.2, these descriptions were compiled for internal purposes. They were needed to better define what was meant by the relatively short FEP names; however, they were never intended to reflect the detailed scientific basis of Project *Entsorgungsnachweis* (the scientific basis is documented in numerous reference reports, see Fig. 1.1-1). This process resulted in FEP descriptions that are rather heterogeneous: they have been written by different authors at different project stages and do not always reflect the current understanding. The structuring of the list was also progressively refined so that the final structure is as shown in the overview table Tab. 3.2-1. Gaps in the numbering are due to modifications of the structure during its iterative development.

Tab. A2.1.1: Listing of OPA FEPs in category scheme order, incl. screened FEPs (titles only)

Screened out FEPs are indicated by *italic text* and a "qualifier" giving additional information on why the FEP was sreened out:

Category headings are indicated by **bold text**.

Subcategory headings are indicated by CAPITAL TEXT.

NA not applicable (see Tab. 3.4-1 for generic reasons for screening)

SRn not quantitatively analysed, but discussed in Chapter *n* of the Safety Report (Nagra 2002a)

I not explicitly analysed, but implicitly included in all assessment cases

0. Assessment basis

1. SITE AND DISPOSAL CONCEPT
1.01 Waste form and packaging
1.02 Waste emplacement and repository
1.03 Host geology
1.04 Local and regional surface environment
1.05 Geographical location
1.06 Appropriate repository design and closure

0.5 Common FEPs

1.01 Radioactive decay
1.02 Speciation
1.03 Gaseous and volatile isotopes

1. Siting and design

1. SITING
1.01 Repository site
1.02 Host rock / geology – regional character
1.03 Host rock / geology – at repository location
1.04 Surface environment

2. WASTE
2.01 Overall waste inventory
2.02 HLW reference inventory
2.03 SF reference inventory
2.04 ILW reference inventory
2.05 Alternative inventory / waste allocation assumptions

3. FACILITY, DESIGN & OPERATION
3.01 Repository layout/constraints
3.02 SF / HLW emplacement panels – reference design
3.03 SF / HLW emplacement panels – alternative design *SR4*
3.04 ILW emplacement tunnels – reference design
3.05 ILW emplacement tunnels – alternative design *NA*
3.06 Operations/excavation/emplacement schedule
3.07 Closure and sealing
3.08 Effect of construction and operation phase
3.09 Retrievability *SR2*
3.10 Monitoring (part of design basis)

2.1 Vitrified HLW

1. FEATURES AND CHARACTERISTICS (HLW)
1.01 Typical waste unit – vitrified HLW
1.02 Waste form (glass)
1.03 Stainless steel fabrication flask (incl.void space)
1.04 Glass cracking and surface area
1.05 Heat output (RN decay heat)

2. ENVIRONMENTAL PROCESSES (HLW)
2.01 Glass recrystallisation
2.02 Phase separation
2.03 Temperature evolution
2.04 Radiation damage
2.05 Glass alteration / dissolution
2.06 Rate of glass dissolution
2.07 Congruent dissolution
2.08 Selective leaching
2.09 Iron corrosion products / clay minerals and glass dissolution
2.10 Precipitation of silicates / silica gel and glass dissolution
2.11 Radiolysis
2.12 He gas production
2.13 Microbial activity and effects

3. RADIONUCLIDE PROCESSES (HLW)
3.01 Radionuclide release from glass
3.02 Elemental (and RN) solubility limits
3.03 Co-precipitates / solid solutions (of RNs)
3.05 Colloid formation (RN bearing)
3.06 Solute transport resistance

4. SPECIAL ISSUES (HLW)
4.01 Quality control
4.02 Handling accidents *NA*
4.03 Fuel mixing at reprocessing – variant specification
4.04 Nuclear criticality

2.2 Spent fuel

1. FEATURES AND CHARACTERISTICS (SF)
1.01 Typical waste unit – spent fuel
1.02 UO_2 fuel matrix
1.03 Zircaloy cladding and structural elements
1.04 Filling material and voids
1.05 Heat output (RN decay heat)
1.06 Distribution of radionuclides in spent fuel
1.07 Chemically toxic contaminants *NA*
1.08 Fuel cracking and surface area

2. ENVIRONMENTAL PROCESSES (SF)
2.01 Temperature evolution
2.02 Saturation / water content
2.03 Gas generation in intact canister
2.03.1 Fuel matrix dissolution
2.04 Zircaloy corrosion
2.05 Cladding integrity

2.06 Galvanic effects
2.07 Alpha-radiolysis – production of oxidants and hydrogen, and recombination
2.08 Beta / gamma-radiolysis effects
2.09 Radiation damage
2.10 Fuel alteration product formation
2.11 Canister corrosion products
2.11.1 Volume expansion
2.12 Microbial activity and effects
2.13 Zircaloy corrosion / hydrogen gas production

3. RADIONUCLIDE PROCESSES (SF)
3.01 Radionuclide release from fuel
3.02 Radionuclide release from cladding and structural materials
3.03 Radionuclide elemental solubilities and precipitation
3.05 Co-precipitation of radionuclides
3.06 Sorption of radionuclides inside canister
3.07 Complexation of radionuclides
3.08 Formation of radionuclide-bearing colloids
3.09 Gaseous radionuclide release

4. SPECIAL ISSUES (SF)
4.01 Quality control of the inventory of fuel in a canister
4.02 Handling accidents *NA*
4.03 Damaged fuel *I*
4.04 Nuclear criticality
4.05 Extreme temperature of cladding
4.06 Cracking of fuel pellets by He buildup

2.3 ILW waste and packages

1. FEATURES AND CHARACTERISTICS (ILW)
1.01 ILW waste types
1.01.1 ILW waste groups
1.02 Typical waste package / emplacement containers
1.03 Chemically toxic components *NA*
1.04 Compacted waste (hulls / ends)
1.05 Conditioning materials
1.06 Waste packages
1.06.1 Backfill
1.06.2 Voids
1.07 Heat output
1.08 Organics
1.09 Extraneous materials (including microbes / biological materials)

2. ENVIRONMENTAL PROCESSES (ILW)
2.01 Resaturation of repository
2.01.1 Host rock creep: effect on near field (tunnel convergence)
2.02 Temperature evolution of near field
2.03 Chemical evolution – pH
2.04 Chemical evolution – redox
2.04.1 Galvanic effects
2.04.2 Degradation of backfill
2.05 Radiolysis
2.05.1 Alpha-radiolysis

2.05.2 Beta / gamma-radiolysis
2.06 Corrosion of metallic components
2.06.1 Volume expansion
2.07 Degradation / failure of disposal containers and emplacement packages
2.08 Gas generation and transport
2.09 Effect of temperature on chemical processes
2.10 Microbial activity and effects

3. RADIONUCLIDE PROCESSES (ILW)
3.00 RN Transport
3.00.1 Diffusive transport
3.00.2 Flow and advective transport
3.01 Radionuclide release through waste form degradation
3.02 Instant release fraction
3.03 Release of volatile radionuclides over gas pathway
3.03.1 Gas dissolution in porewater
3.03.2 Sorption on cement materials
3.04 Sorption on and co-precipitation with corrosion products
3.05 Co-precipitation with calcite
3.05.1 Complexation
3.06 Colloid generation

4. SPECIAL ISSUES (ILW)
4.00.1 Quality control
4.00.2 Handling accidents *NA*
4.01 Effects of co-disposal with SF / HLW *NA*
4.03 Nuclear criticality *NA*

3.1 SF / HLW canister

1. FEATURES AND CHARACTERISTICS (SF / HLW canister)
1.01 Cast steel canister (vitrified waste)
1.01.1 Cast steel canister (spent fuel)
1.01.2 Cu / steel canister (spent fuel)
1.02 Canister thickness / specification (vitrified waste canister)
1.02.1 Canister thickness / specification (cast steel spent fuel canister)
1.02.2 Canister thickness / specification (Cu / steel canister)

2. ENVIRONMENTAL PROCESSES (Canister)
2.01 Canister temperature evolution (vitrified waste)
2.01.1 Canister temperature evolution (spent fuel)
2.02 Corrosion on wetting (steel canister – vitrified waste or spent fuel)
2.02.1 Corrosion on wetting (Cu / steel canister)
2.03 Oxic uniform corrosion (steel canister – vitrified waste / spent fuel)
2.03.1 Oxic uniform corrosion (Cu / steel canister – spent fuel)
2.04 Microbially-mediated corrosion (steel canister – vitrified waste / spent fuel)
2.04.1 Microbially-mediated corrosion (Cu / steel canister)
2.05 Anoxic corrosion (steel canister – vitrified waste / spent fuel)
2.05.1 Anoxic corrosion (Cu / steel canister)
2.06 Localised corrosion (steel canister – vitrified waste / spent fuel)
2.06.1 Localised corrosion (Cu / steel canister – spent fuel)
2.07 Total extent of corrosion (steel canister – vitrified waste / spent fuel)
2.07.1 Total corrosion (steel canister – spent fuel)
2.07.2 Total corrosion (Cu / steel canister – spent fuel)

2.08	Stress corrosion cracking (steel canister – vitrified waste / spent fuel)	
2.09	Other canister degradation processes (steel and Cu / steel canisters)	
2.10	Radiation shielding	
2.11	Canister breaching – reference (steel canister – vitrified waste / spent fuel)	
2.11.1	Canister breaching – reference (Cu / steel canister – spent fuel)	
2.13	Chemical buffering (canister corrosion products)	
2.14	Hydrogen production (steel canister – vitrified waste / spent fuel)	
2.14.1	Hydrogen production (Cu / steel canister – spent fuel)	
2.15	Effect of hydrogen on corrosion	
2.16	Corrosion products – physical effects (steel canister – vitrified waste/spent fuel)	
2.16.1	Corrosion products – physical effects (Cu / steel canister – spent fuel)	
3.	RADIONUCLIDE PROCESSES (Canister)	
3.01	Residual canister – crack / hole effects (vitrified waste)	
3.02	Residual canister – crack / hole effects (spent fuel)	
3.03	Radionuclide sorption on and co-precipitation with canister corrosion products	
4.	SPECIAL ISSUES (Canister)	
4.01	Quality control	
4.02	Mis-sealed canister	

4.1 Bentonite buffer

1.	FEATURES AND CHARACTERISTICS (Bentonite buffer)	
1.01	Bentonite emplacement and composition	
1.01.1	Pellets	
1.01.2	*Corrosion of structural elements in HCB blocks*	*SR5*
1.02	Bentonite swelling pressure	
1.03	Bentonite plasticity	
1.04	Buffer permeability	
1.05	Bentonite porewater chemistry	
1.06	Gas permeability	
1.07	Inhomogeneities (properties and evolution)	
2.	ENVIRONMENTAL PROCESSES (Bentonite buffer)	
2.01	Thermal evolution	
2.02	Bentonite saturation	
2.03	Mineralogical alteration – short term	
2.04	Mineralogical alteration – long term	
2.05	Bentonite cementation	
2.06	Bentonite-iron interactions (canister)	
2.06.1	Bentonite – Cu interactions	
2.07	*Microbial activity*	*SR5*
2.08	Radiolysis	
2.09	*Bentonite erosion*	*NA*
2.10	Interaction with cement components	
2.11	Gas fracturing	
3.	RADIONUCLIDE PROCESSES (Bentonite buffer)	
3.01	Radionuclide transport through buffer	
3.02	Radionuclide retardation	
3.03	Elemental solubility / precipitation	
3.04	Colloid filtration	
3.05	Interaction and diffusion between canisters	

4. SPECIAL ISSUES
4.01 Quality Control
4.03 Organics / contamination of bentonite
4.04 Canister sinking

5.3 ILW backfill and liner

1. FEATURES AND CHARACTERISTICS (ILW backfill and liner)
1.01 Backfill material
1.02 Backfill emplacement
1.03 Hydraulic and gas permeability
1.04 Effects of initial (operating) conditions
1.05 Lining material
1.05.1 Drainage system *NA*
1.05.3 Seals
1.05.4 Cement additives
1.05.5 Organics
1.06 Rock bolts
1.07 Joints and cracks in backfill / liner
1.08 Voids in backfill / liner

2. ENVIRONMENTAL PROCESSES (ILW backfill and liner)
2.01 Cement hydration
2.02 Temperature evolution
2.03 Mechanical strength / stability
2.04 Mechanical evolution and external forces
2.04.1 Effect of liner on rock creep
2.05 Saturation / hydraulic evolution
2.06 Chemical Degradation
2.07 Degradation due to reaction with sulphate
2.08 Degradation due to reaction with magnesium
2.08.1 Degradation due to other reactions
2.09 Volume expanding materials
2.10 Pore-structure heterogeneity and evolution
2.10.1 Compaction
2.11 Formation of advective paths
2.12 Biofilms
2.13 Colloid formation through backfill degradation
2.14 Effects of temperature gradients
2.15 2-phase flow

3. RADIONUCLIDE PROCESSES (ILW backfill and liner)
3.01 Diffusive transport through backfill and liner
3.02 Flow and advective transport through backfill and liner
3.03 Radionuclide sorption in backfill and liner
3.04 Sorption / incorporation of radionuclides on colloids and microbes
3.05 Solubility
3.06 Co-precipitation (of RNs)
3.07 Complexation

4. SPECIAL ISSUES (ILW backfill and liner)
4.01 Quality control
4.02 Poor emplacement
4.03 Interfaces, cracks and slabbing
4.04 Seismic effects

6.1 Bentonite – host rock (HR) interface

1.	FEATURES AND CHARACTERISTICS (Bentonite – HR interface)	
1.01	Excavation-disturbed zone (EDZ)	
1.01.1	*Rock bolts and mesh*	*SR5*
1.02	Open contact joints	
1.03	Effective hydraulic properties	
1.04	Mineralogy	
1.05	Groundwater composition	
1.06	Natural organics	
1.07	*Microbial activity*	*SR5*
1.08	Hydraulic gradient	
1.09	Water flow at bentonite – host rock interface	
2.	ENVIRONMENTAL PROCESSES (Bentonite – HR interface)	
2.01	Desaturation / resaturation of EDZ	
2.02	Thermal evolution	
2.03	Geomechanical processes	
2.04	Effect of bentonite swelling on EDZ	
2.05	Swelling of clay minerals in EDZ	
2.06	Compaction of EDZ	
2.07	Geochemical alteration	
2.08	Fluid and heat fluxes by coupled processes (Onsager)	
2.09	Gas transport	
2.10	Colloid production and effects	
3.	RADIONUCLIDE PROCESSES (Bentonite – HR interface)	
3.01	Radionuclide migration pathways	
3.02	Radionuclide sorption	
3.03	Elemental solubility	
3.04	Advective / dispersive / diffusive transport	
3.05	Matrix diffusion	
3.06	Gas-induced transport	
3.07	Colloid-facilitated transport	
3.08	Convergence-induced transport	
3.09	Transport by coupled processes (Onsager)	
4.	SPECIAL ISSUES (Bentonite – HR interface)	

6.3 Concrete – HR interface (ILW)

1.	FEATURES AND CHARACTERISTICS (Concrete – HR interface)	
1.01	Excavation-disturbed zone (EDZ)	
1.01.1	*Rock bolts*	*NA*
1.03	Effective hydraulic properties	
1.04	Mineralogy	
1.05	Groundwater composition	
1.06	Natural organics	
1.07	*Microbial activity*	*NA*
1.08	Hydraulic gradient	
1.09	Water flow at concrete – host rock interface	

2. ENVIRONMENTAL PROCESSES (Concrete – HR interface)
2.01 Desaturation / resaturation of EDZ
2.02 Thermal evolution
2.03 Geomechanical processes
2.05 Swelling of clay minerals in EDZ
2.06 Compaction of EDZ
2.07 Geochemical alteration
2.08 Fluid and heat fluxes by coupled processes (Onsager)
2.09 Gas transport
2.10 Colloid production and effects

3. RADIONUCLIDE PROCESSES (Concrete – HR interface)
3.01 Radionuclide migration pathways
3.02 Radionuclide sorption
3.03 Elemental solubility
3.04 Advective / dispersive / diffusive transport
3.05 Matrix diffusion
3.06 Gas-induced transport
3.07 Colloid-facilitated transport
3.08 Convergence-induced transport
3.09 Transport by coupled processes (Onsager)

4. SPECIAL ISSUES (Concrete – HR interface)

7. Opalinus Clay (OPA) host rock

1. FEATURES AND CHARACTERISTICS (OPA host rock)
1.01 Discontinuities
1.02 OPA matrix
1.03 Effective hydraulic properties
1.04 Mineralogy
1.05 Groundwater composition
1.06 Natural organics
1.07 Stress regime
1.08 Hydraulic gradient
1.09 Heterogeneity within OPA
1.10 Calcite veins *NA*
1.11 Overpressures

2. ENVIRONMENTAL PROCESSES (OPA host rock)
2.01 Thermal effects
2.03 Swelling of clay
2.04 Geochemical alteration
2.05 Microbial activity *SR4*
2.06 Effects of gas on OPA
2.07 Groundwater flow
2.08 Gas transport
2.09 Colloid transport
2.10 Effect of colloids on OPA properties
2.11 Density-driven groundwater flow (thermal and saline)
2.12 Fluid fluxes by coupled processes (Onsager)

3.	RADIONUCLIDE PROCESSES (OPA host rock)	
3.01	Radionuclide migration pathways	
3.02	Elemental solubility	
3.03	Advective / dispersive / diffusive transport	
3.04	Matrix diffusion	
3.05	Radionuclide sorption	
3.06	Dilution of radionuclides	
3.07	Colloid-facilitated transport	
3.08	Gas-induced transport	
3.10	Transport by coupled processes (Onsager)	
4.	SPECIAL ISSUES (OPA host rock)	
4.01	Exploratory boreholes	
4.03	Influx of oxidising water	
4.04	*Intrusion of saline groundwater*	*NA*
4.05	Chemical plume from ILW	

8. Tunnels & shafts

1.	FEATURES AND CHARACTERISTICS (Tunnels & shafts)	
1.01	Access tunnels, ramp and shaft	
1.02	Tunnel, ramp and shaft seals	
1.03	Effective hydraulic properties	
1.04	Hydraulic gradient	
2.	ENVIRONMENTAL PROCESSES (Tunnels & shafts)	
2.01	Seal performance (during and after swelling)	
2.02	Tunnel backfill performance	
2.03	Drainage of water	
2.04	Preferential flow of water	
2.05	Colloid transport	
2.06	Gas transport	
2.07	Fluid fluxes by coupled processes (Onsager)	
2.08	Density-driven groundwater flow (thermal and saline)	
3.	RADIONUCLIDE PROCESSES (Tunnels & shafts)	
3.01	Radionuclide migration pathways	
3.02	*Elemental solubility*	*NA*
3.03	Advective / dispersive / diffusive transport	
3.04	Matrix diffusion	
3.05	Radionuclide sorption	
3.06	Dilution of radionuclides	
3.07	Colloid-facilitated transport	
3.08	Gas-induced transport (of RNs)	
3.09	Convergence-induced transport	
3.10	Transport by coupled processes (Onsager)	
4.	SPECIAL ISSUES (Tunnels & shafts)	
4.01	*Oil or organic fluid spill*	*NA*
4.02	Influx of oxidising water	
4.03	*Intrusion of saline groundwater*	*NA*
4.04	*Chemical plume from ILW*	*NA*
4.05	Alteration of backfill by liner of access tunnels	

9. Geology & hydrology

1. GEOLOGY
1.01 Lithostratigraphy
1.02 Geological formation / history
1.03.1 Sedimentology, mineralogy etc. – overlying formations
1.03.3 Sedimentology, mineralogy etc. – underlying formations
1.05 Regional stress regime
1.06 Faults, distribution and properties
1.07 Groundwater composition
1.08 Natural resources

2. HYDROGEOLOGIC MODEL(S)
2.01 Hydrogeological units
2.02 Effective hydraulic properties
2.03 Recharge / discharge zones
2.04 Hydraulic gradient
2.05 Groundwater flowpaths
2.06 Density-driven groundwater flow (thermal and saline)

3. RADIONUCLIDE MIGRATION (Geology & hydrology)
3.01 Radionuclide migration pathways
3.02 Dilution of radionuclides
3.03 Sorption / retardation

10. Biosphere

1. FEATURES AND CHARACTERISTICS (Biosphere)
1.01 Topography and geomorphology
1.02 Geosphere-biosphere interface
1.03 Soils
1.04 Aquifers
1.05 Surface water bodies
1.06 Atmosphere
1.07 Animals
1.08 Vegetation
1.09 Climate
1.10 Present-day biosphere
1.11 Agricultural practices
1.12 Natural and semi-natural environments
1.13 Hunter / gathering lifestyle

2. ENVIRONMENTAL PROCESSES (Biosphere)
2.01 Exfiltration to a biosphere aquifer
2.02 Exfiltration to surface waters
2.03 Water resource exploitation
2.04 Filtration *NA*
2.05 Surface water flow
2.06 Groundwater flow
2.07 Erosion / deposition
2.08 Sedimentation
2.09 Soil formation
2.10 Interface effects
2.11 Precipitation
2.12 Evapotranspiration

2.13	Capillary rise	
2.14	Percolation	
2.15	Irrigation	
2.16	Surface run-off	
2.17	Bioturbation	
2.18	Suspended sediment transport	
2.19	Earthworks (human actions, dredging, etc.)	
2.20	Ploughing	
2.21	Exfiltration to spring	
3.	RADIONUCLIDE MIGRATION PROCESSES (Biosphere)	
3.01	Radionuclide accumulation in sediments	
3.02	Radionuclide accumulation in soils	
3.03	Radionuclide transport as solute	
3.04	Radionuclide transport with solid material	
3.05	Radionuclide sorption	
3.06	Speciation and solubility	
3.07	Diffusion / dispersion	
3.08	Radionuclide volatilisation / aerosol / dust production	
3.09	Dilution of radionuclides in surface water (aquifer, river, lake etc.)	
3.11	Uptake by crops	
3.12	Uptake by livestock	
3.13	Uptake in fish	
3.15	Foodchain equilibrium	
3.16	Secular equilibrium of radionuclide chains	
3.17	Removal mechanisms	
3.18	Food and water processing	
3.2	RADIONUCLIDE EXPOSURE PROCESSES (Biosphere)	
3.21	Exposure pathways	
3.22	Age groups	
3.23	Dosimetry	
3.24	Human lifestyle	
3.25	Contaminated products (non-food)	
3.26	Consumption of uncontaminated products	
3.27	Radon pathways and doses	
4.	SPECIAL ISSUES (Biosphere)	
4.01	Future biosphere conditions	
4.02	*Non-radiological effects*	*NA*
4.03	*Radiological effects on non-human biota*	*NA*

11. Geological processes and events

2.	ENVIRONMENTAL PROCESSES (Geological P&E)	
2.01	Regional vertical movements	
2.02	Regional horizontal movements	
2.03	Compaction of Opalinus Clay	
2.04	Erosion	
2.05	Evolution of regional stress regime	
2.06	Neo-tectonic activity	
2.07	Self-sealing of faults	
2.08	Seismic activity	
2.09	Magmatic activity (volcanism and plutonism)	
2.10	*Hydrothermal activity*	*NA*

12. Climatic processes and events

1.	FEATURES AND CHARACTERISTICS (Climatic P & E)
1.01	Present-day climatic conditions
1.02	Future climatic conditions
1.03	Glacial climate
1.04	Permafrost
1.05	Tundra climate
1.06	Dry climate
1.07	Warm seasonal humid climate
1.08	Warm equable humid climate
1.09	Seasonality of climate
2.	ENVIRONMENTAL PROCESSES (Climatic P & E)
2.02	Fluvial erosion / sedimentation
2.03	Glacial erosion / sedimentation
2.04	Glacial-fluvial erosion / sedimentation
2.05	Ice sheet effects (loading, melt water recharge)
2.06	Effective moisture (recharge)
2.09	Greenhouse effect

13. Future human actions

1.	FUTURE HUMAN ACTIONS (Future human actions)	
1.01	Exploratory drilling	
1.02	Resource exploitation through boreholes	
1.03	Mining activities	
1.04	Geothermal exploitation	
1.05	Deep groundwater extraction	
1.06	Liquid waste injection	
2.01	Human-induced climate change	
2.02	*Surface pollution (soils, rivers)*	*NA*
2.03	*Groundwater pollution*	*NA*
2.04	Water management schemes	
3.01	*Intentional intrusion*	*NA*
3.02	Inadvertent intrusion	
3.03	*Repository records, markers*	*NA*
3.04	*Planning restrictions*	*NA*
3.05	Abandonment of repository	

Tab. A2.1.2: Listing of OPA FEPs in category scheme order, incl. a brief description of each OPA FEP

0. Assessment basis

1. SITE AND DISPOSAL CONCEPT

1.01 Waste form and packaging

The repository will contain well-characterised spent UO_2 and mixed-oxide fuel (SF), vitrified high-level waste from the reprocessing of spent fuel (HLW) and long-lived intermediate-level waste (ILW) in amounts that are defined, and in packages the characteristics of which are well known.

1.02 Waste emplacement and repository

The wastes will be emplaced in a deep geological repository (depth approx. 650 m) in a subhorizontal claystone formation. In the proposed repository, carbon steel canisters containing either SF or HLW are emplaced coaxially within a system of parallel tunnels that are constructed in the centre of the formation and aligned along the dip direction. The tunnels are backfilled with compacted bentonite. ILW is emplaced in larger-diameter concrete-lined tunnels, with a cementitious backfill.

1.03 Host geology

The host geology consists of layered sedimentary rocks overlying the crystalline basement at the northern edge of the Molasse Basin. The host rock itself, the Opalinus Clay, is a moderately over-consolidated claystone which forms a layer somewhat more than 100 m thick and dips to the south-east at about 5º. The siting area is located at the edge of the zone influenced by the Alps. Tectonically, it is subject to a slight compressive stress but is not significantly deformed. It also lies within one of the seismically quiet areas of Switzerland, with a small uplift and erosion rate and average heat flow.

1.04 Local and regional surface environment

The topography of the Rhine valley is characterised today by relatively gently sloping valley bottoms, with river terraces developed over gravels laid down in the Quaternary period. The present-day climate is described as cool temperate and is representative of interglacial conditions.

1.05 Geographical location

The potential site of the SF/HLW/ILW repository is located in the Zürcher Weinland (northern Switzerland), close to the Rhine river section between Neuhausen and Rheinau.

1.06 Appropriate repository design and closure

The repository is designed to provide a robust system of multiple passive safety barriers. A range of well-understood features ensure that long-term safety can be demonstrated, while taking full account of any sources of uncertainty and detrimental phenomena. The design allows for the possibility of an extended monitoring period prior to final repository closure ("Kontrollierte geologische Langzeitlagerung").

0.5 Common FEPs

1.01 Radioactive decay

Radionuclides decay to form products (stable or radioactive) at characteristic rates (decay rates).

1.02 Speciation

The behaviour of a radionuclide is determined by the physical and chemical characteristics of the element of which it is an isotope and, in particular,

- the way in which the element interacts with, or is incorporated in, solid materials, and
- the speciation of the element in the aqueous phase.

1.03 Gaseous and volatile isotopes

Some radionuclides are isotopes of elements that are either gaseous or form volatile compounds at relevant temperatures and pressures. Gaseous elements, e.g. Kr, will be lost from HLW during vitrification. Of the fission products and activation products, only carbon is expected to be capable of forming (organic) volatile compounds. Isotopes of radon will be produced by radioactive ingrowth over the course of time.

1. Siting and design

1. SITING

1.01 Repository site

The potential site of the SF/HLW/ILW repository is in the Zürcher Weinland of northern Switzerland, close to the Rhine river section between Neuhausen and Rheinau. The repository is located in the Opalinus Clay (reference depth of the repository 650 m below ground). Separate emplacement tunnels for SF/HLW and ILW are constructed in the centre of the clay layer and aligned along the dip direction. The design includes the main repository, a pilot repository for monitoring purposes and a test facility (rock laboratory). Access to the system of tunnels is provided, during construction and operation, by a spiral ramp. A vertical ventilation shaft is also foreseen.

1.02 Host rock/geology – regional character

The host rock, the Opalinus Clay (which also includes the so-called Murchisonae beds), is a moderately over-consolidated claystone which forms a layer somewhat more than 100 m thick and dips to the south-east at about 5º. The siting area is located at the edge of the zone influenced by the Alps. Tectonically, it is subject to a slight compressive stress but is not significantly deformed. It also lies within one of the seismically quiet areas of Switzerland, with a small uplift and erosion rate and average heat flow. The formations above and below the Opalinus Clay (upper and lower confining units) mostly have a low hydraulic conductivity and form a supplementary geological barrier between the host rock and the regional aquifers, strengthening the barrier function of the host rock. Because of its almost constant thickness, lateral extent and lithological continuity, the host rock offers a large element of flexibility in locating a repository.

1.03 Host rock/geology – at repository location

At the repository location, the host rock is at a depth of 600 to 750 m. There are no detectable faults in the 3D seismic survey (resolution a few metres). The geological environment corresponds the situation described in 1./1.02.

1.04 Surface environment

The main discharge feature in the potential siting region is the Rhine river. The surface elevation is between 300 and 700 m above sea level and the topography of the Rhine valley is characterised today by relatively gently sloping valley bottoms, with river terraces developed over gravels laid down in the Quaternary period. The present-day climate is described as cool temperate and is representative of interglacial conditions.

2. WASTE

2.01 Overall waste inventory

The waste inventory is based on the assumption that the existing Swiss nuclear power plants will all operate for 60 years and includes a specified inventory of SF, HLW and ILW.

2.02 HLW reference inventory

The radionuclide inventory of each HLW glass type (i.e. COGEMA glass and BNFL glass) is considered in the assessment calculations.

2.03 SF reference inventory

The inventory of safety-relevant radionuclides in spent fuel of various burnups and types is described, including the uncertainties.

2.04 ILW reference inventory

Radionuclide inventories in all ILW waste types are described, including allocation of waste inventories to ILW-1 and ILW-2.

2.05 Alternative inventory/waste allocation assumptions

Alternative repository design and waste arisings are defined for the 300 GWa(e) scenario. The possibility of higher burnup fuel is also considered.

3. FACILITY, DESIGN & OPERATION

3.01 Repository layout/constraints

The emplacement tunnels are constructed in the centre plane of the Opalinus Clay, providing a layer of about 50 m of Opalinus Clay above and below the tunnels. SF and HLW tunnels are 40 m apart. The emplacement tunnels for ILW are located far from the SF/HLW tunnels, to ensure minimal interaction between the two sections of the repository.

3.02 SF/HLW emplacement panels – reference design

The array of parallel SF/HLW emplacement tunnels, with a 40 m separation between tunnels, forms a single emplacement "panel" in the centre plane of the Opalinus Clay.

3.03 SF/HLW emplacement panels – alternative design

Not applicable, i.e. alternative not considered.

3.04 ILW emplacement tunnels – reference design

ILW is emplaced in tunnels with a cross-section of about 7 m wide by 9 m high that have a concrete liner.

3.05 ILW emplacement tunnels – alternative design

Not applicable.

3.06 Operations/excavation/emplacement schedule

Only the end result of the schedule for excavation, emplacement and sealing is considered in developing the safety assessment approach.

3.07 Closure and sealing

Bulkheads and seals are required at the ends of emplacement tunnels. Similarly, low permeability seals are required for the verticals shaft and the access ramp. A bentonite/sand mixture will be used to backfill operations tunnels and the ramp. The seals consist of compacted bentonite.

3.08 Effect of construction and operation phase

During the construction and operation phases, the repository tunnel system is ventilated and the host rock is exposed to air. This can result in a number of processes that may affect long-term safety, including:

- formation of an unsaturated zone around the tunnels,
- potential oxidation of sulphides (pyrite) and organic carbon in the adjacent rock,
- microbial activity under aerobic conditions,
- evaporation of porewater and consequent accumulation of solutes (salt),
- carbonation of cement (access and ILW tunnels) by atmospheric carbon dioxide,
- trapping of oxygen after backfilling potentially leading to aerobic corrosion of metals.

3.09 Retrievability

Retrievability is the capability to partially or completely remove any waste emplaced in a repository. Before repository closure the wastes can be easily retrieved. After closure retrieval is possible in principal by means of mining techniques, but at significantly higher effort. Impacts of retrieval on safety are considered to be outside of the scope of the assessment, and are thus not considered further.

3.10 Monitoring (part of design basis)

Monitoring is an intrinsic feature of the envisaged concept of monitored long-term geological disposal. The monitoring activity will be focused on the pilot repository, containing real waste and full-scale engineered barriers. After repository closure, no monitoring in the underground is foreseen.

2.1 Vitrified HLW

1. FEATURES AND CHARACTERISTICS (HLW)

1.01 Typical waste unit – vitrified HLW

A typical HLW unit is a flask containing 0.15 m^3 or 412 kg of glass. The glass can be either of the two types considered in the assessment (i.e. COGEMA glass and BNFL glass).

1.02 Waste form (glass)

The HLW glass considered is produced from highly active liquor resulting from nuclear fuel reprocessing. This contains most of the radionuclides from the irradiated fuel but is significantly depleted of uranium and plutonium, which are separated for re-use, and volatile components such as iodine. The highly active liquor, incorporating the radionuclides, is solidified in borosilicate glass. HLW glass is produced by COGEMA and BNFL.

1.03 Stainless steel fabrication flask (including void space)

The vitrified waste (glass) is contained by a thin stainless steel container which acts as a mould for the molten glass. It is not be relied upon to provide any physical barrier function. Each flask contains 150 l of glass. The glass does not completely fill the container so that an air void space is present.

1.04 Glass cracking and surface area

Cracking of the glass on cooling and as a result of any handling accident means that the surface area of the glass is greater than the surface of a monolithic block. The glass may break into a few large fragments plus a large number of smaller shards. The estimated surface area of a cracked glass block depends on the size of fragments that are considered. Very small fragments can be neglected because they have small volume and hence small radionuclide content.

1.05 Heat output (RN decay heat)

Waste containers produce significant heat at the time of emplacement, although the rate of heat production decreases over time. The heat output of COGEMA and BNFL reference waste containers is considered in developing the repository layout, in assessing the evolution and performance of engineered barriers and in developing data for solubility and sorption.

2. ENVIRONMENTAL PROCESSES (HLW)

2.01 Glass recrystallisation

Glass recrystallisation could occur and would lead to a less dissolution resistant waste matrix. However, crystallisation is a very slow process and only possible if a high glass temperature is maintained over a prolonged period. It is unlikely to occur below 400 °C and, therefore, considering a maximum glass temperature of 195 °C at disposal, it is assumed not to occur.

2.02 Phase separation

Improper heat treatment of glass can produce macroscopic phase separation, which could lead to a reduction of the chemical resistance of the glass. In particular, this process would favour the selective leaching of Cs and Sr. This should be avoided by quality control procedures for vitrification.

2.03 Temperature evolution

The time-dependent temperature of the glass is considered in assessing its dissolution rate and the heat generated by HLW is considered in terms of its wider effects on the engineered barrier system. In particular, heat output is considered in repository design in order to ensure that thermal criteria, especially for bentonite, are met.

2.04 Radiation damage

Alpha radiation damage leads to slight changes in the properties of the glass over time.

2.05 Glass alteration/dissolution

The glass matrix is thermodynamically unstable in contact with water, and thus begins to alter and to dissolve.

2.06 Rate of glass dissolution

The long term dissolution rate of the glass depends on its composition (BNFL or COGEMA glass), temperature and solution composition (in particular pH and Si concentration). It is derived from lab experiments. The rate may be influenced by clays (bentonite) and iron corrosion products (see also 2.1/2.09).

2.07 Congruent dissolution

It is usually assumed that all the glass constituents including radionuclides dissolve congruently, i.e. the glass components go into solution according to their proportional content in the glass, although some elements are partially fixed in alteration products.

2.08 Selective leaching

Selective leaching of specific alkali and alkali-earth ions from the glass may occur. However, this is a short-term effect which is only significant before alteration layers build up.

2.09 Iron corrosion products/clay minerals and glass dissolution

The glass dissolution rate depends on aqueous silica concentration. In the presence of iron corrosion products and clays (bentonite), dissolution is often faster than in their absence, and this is attributed to silica sorption or precipitation of iron silicates.

2.10 Precipitation of silicates/silica gel and glass dissolution

Since glass dissolution rates depend on Si concentration in solution (see 2.1/2.06) the precipitation of silicates may influence the rates if silicate precipitation rates are similar (not much smaller) to the dissolution rates. There is experimental evidence that these rates may be comparable in the long term. This process is included implicitly in the glass corrosion rates, see also 2.1/2.06.

2.11 Radiolysis

No significant radiolysis of water around the HLW canisters occurs prior to canister breaching, because of the shielding effects of the canisters. Following breaching and ingress of water into the canisters, radioloytic decomposition of water close to the glass will occur, giving rise to hydrogen and a range of other radiolysis products.

2.12 He gas production

Helium will be produced from alpha decay of HLW and, following canister breaching and ingress of water, will dissolve and be transported into the buffer and thence into the surrounding rock.

2.13 Microbial activity and effects

Microbial activity may affect glass dissolution processes, result in selective leaching of some species, and affect solubilities. The level of microbial activity is expected to be low in the nutrient deficient conditions within the engineered barriers.

3. RADIONUCLIDE PROCESSES (HLW)

3.01 Radionuclide release from glass

Radionuclides are released into solution from the glass fragments by congruent dissolution at a rate dependent on the glass dissolution rate and the glass surface area.

3.02 Elemental (and RN) solubility limits

The concentration of many radionuclides in aqueous solution adjacent to the glass will be limited by the solubilities of radionuclide-bearing solids formed by the interaction of glass and bentonite pore fluid containing complexants. In addition, radionuclides may be sorbed or co-precipitated with these secondary glass phases and iron corrosion products. The solubility limits are determined for a porewater conditioned by the presence of bentonite and iron corrosion products.

3.03 Co-precipitates/solid solutions (of RNs)

Secondary products from glass dissolution/canister corrosion and solid solutions will form which will incorporate many of the waste nuclides as a result of coprecipitation. Radionuclides may also be sorbed on the glass secondary products. These processes are currently still difficult to treat quantitatively. Precipitation of pure phases is covered in 2.1/3.02.

3.05 Colloid formation (RN bearing)

Colloids containing radionuclides may be produced as the glass degrades/dissolves. These are prevented from being transported away from the glass by the filtration properties of the bentonite buffer and the Opalinus Clay.

3.06 Solute transport resistance

The limited dimension of cracks in the glass blocks is expected to lead to a resistance to radionuclide (and silica) diffusion/transport. The process has been discussed for spent fuel in SKB-91; the effectiveness depends on other resistances in the system. This is conservatively neglected in Project Entsorgungsnachweis safety assessment modelling.

4. SPECIAL ISSUES (HLW)

4.01 Quality control

Strict quality control is applied during the manufacture of the glass resulting in a homogenous and well characterised product. The temperature and gamma-ray spectrum of each flask can be monitored prior to loading into the overpack. Application of quality control is implicit in the assumed glass characteristics.

4.02 Handling accidents

Handling accidents, e.g. a dropped canister, could result in damage to the stainless steel fabrication flask and/or additional cracking of the glass. Moderate cracking of the glass is, in any case, assumed.

4.03 Fuel mixing at reprocessing – variant specification

The inventory of radionuclides in each flask is limited by the BNFL and COGEMA specifications. The different dissolution rates of BNFL and COGEMA glasses and different radionuclide inventories are considered in safety assessment calculations.

4.04 Nuclear criticality

Fissile material may become critical if sufficiently high concentrations are reached in the presence of a moderator. The potential for the process to occur in the repository is assumed to be negligible for HLW because of low fissile material content.

2.2 Spent fuel

1. FEATURES AND CHARACTERISTICS (SF)

1.01 Typical waste unit – spent fuel

The typical waste unit is a BWR or PWR fuel element, consisting of numerous fuel rods. The fuel rods themselves consist of the Zircaloy cladding containing the UO_2 fuel pellets. Radionuclides are contained in both the fuel pellets and the cladding. A small fraction (~7 %) of the spent fuel inventory consists of Mixed-Oxide (MOX) fuel. The fuel elements have an average burnup of ~48 GWd/tIHM.

1.02 UO_2 fuel matrix

The spent fuel waste form consists of UO_2 fuel pellets contained in Zircaloy sheaths. The UO_2 fuel provides a matrix which contains the largest proportion of the total radionuclide inventory associated with this waste type.

1.03 Zircaloy cladding and structural elements

A typical fuel element consists of UO_2 fuel rods (Zircaloy cladding containing the fuel pellets), the rods being held together with additional structural materials. Some of the radionuclide inventory in a fuel element is contained in the Zircaloy and structural materials, as a consequence of neutron activation.

1.04 Filling material and voids

The reference spent fuel canister would contain four PWR or nine BWR fuel elements, which would be placed in channels in a cast steel canister or canister insert. A residual void volume remains, because of the clearance required for placement of the fuel elements into the canister. This volume may become water filled following canister breaching, and provides a reservoir in which radionuclides released from the fuel are dissolved or precipitated. The volume of water is considered in criticality calculations.

1.05 Heat output (RN decay heat)

The heat output of the various types of SF (BWR and PWR types of UO_2, and also MOX) as a function of burnup varies considerably. Canisters may contain UO_2 fuel (e.g. 4 BWR or 9 PWR) or may contain 1 MOX assembly and 3 UO_2 assemblies. The number, type and age of assemblies, as well as the burnup, which averages 48 GWd/t, determine the heat output of a canister. Administrative controls on the mixing of fuels (including mixing MOX fuel elements with UO_2 fuel elements) and the age of the fuel at disposal will ensure that the average heat output of a canister does not exceed 1500 W. Heat output is considered in repository design in order to ensure that thermal criteria, especially for bentonite, are met.

1.06 Distribution of radionuclides in spent fuel

Radionuclides are not distributed uniformly throughout the spent fuel matrix and throughout the cladding. Some radionuclides are partially segregated to the fuel-sheath gap and grain boundaries. This can have a significant influence on the rate of release from UO_2 and MOX spent fuel.

1.07 Chemically toxic contaminants

There are a number of chemically toxic contaminants (metals) present in the fuel which may be released upon fuel dissolution.

1.08 Fuel cracking and surface area

Spent fuel cracks may form during in-reactor irradiation, increasing the surface area of fuel that will be exposed to groundwater. This may influence dissolution.

2. ENVIRONMENTAL PROCESSES (SF)

2.01 Temperature evolution

The temperature of the spent fuel and the surrounding materials will increase after emplacement of the canisters. The temperature increase will affect many physical and chemical processes.

2.02 Saturation/water content

Unsaturated conditions may exist for a long time after canister failure because water inflow will be slow and the void volume of a SF canister is large. The fuel may thus be exposed to unsaturated conditions.

2.03 Gas generation in intact canister

A gas pressure may be generated in a sealed canister. This could arise from fission gas and He release. It is assumed that no water is present in spent fuel rods at the time of sealing in canisters, because fuel assemblies will have been in dry storage for decades prior to emplacement in disposal canisters.

2.03.1 Fuel matrix dissolution

Radionuclides are contained in the matrix of spent fuel and are released at the rate that the fuel matrix dissolves. The rate of matrix dissolution is expected to be determined by the rate of supply of oxidants, which may be influenced by hydrogen buildup, or, alternatively, by the solubility limitation of U(IV).

2.04 Zircaloy corrosion

The integrity of Zircaloy fuel cladding will be affected by uniform corrosion and possibly by localised corrosion processes. Zircaloy also has an oxide film present from in-reactor corrosion, which is considered in relation to radionuclide release.

2.05 Cladding integrity

The Zircaloy fuel cladding is corrosion resistant, and may provide a barrier preventing access of water to the fuel matrix even after the canister is breached. Its integrity may be affected by corrosion and hydrogen-induced cracking.

2.06 Galvanic effects

Galvanic coupling of metals in the canister may affect steel or Zircaloy corrosion rates. Effects are not considered as cladding is assumed to have no containment function in safety assessment.

2.07 Alpha-radiolysis – production of oxidants and hydrogen, and recombination

No significant radiolysis of water around the SF canisters occurs prior to canister breaching, because of the shielding effects of the canisters. Following breaching and ingress of water into the canisters, radioloytic decomposition of water close to the fuel matrix will occur, giving rise to a range of radiolysis products, although some recombination of radiolytic oxidants and reductants may occur. Radiolysis produces oxidants that may influence the rate of fuel matrix dissolution. Furthermore, it produces hydrogen gas that may also influence matrix dissolution, as well as the transport of radionuclides that form volatile species.

2.08 Beta/gamma-radiolysis effects

Beta/gamma-radiolysis products may influence the dissolution rate of SF by producing radiolytic oxidants. The rapid decay of beta/gamma fields makes such effects small.

2.09 Radiation damage

Radiation damage from fission and alpha decay may affect Zircaloy and fuel materials, influencing their chemical stability.

2.10 Fuel alteration product formation

Alteration products may precipitate as spent fuel dissolves. The precipitates may fill fractures in the fuel as well as the fuel/sheath gap. Actinides could be incorporated in these precipitates and cause alpha radiolysis of the porewater.

2.11 Canister corrosion products

Canister corrosion products such as magnetite will form as the canister corrodes, influencing the dissolution rate of the fuel and/or the migration of radiolytic oxidants formed near the fuel surfaces, as well as the chemical conditions in the porewater.

2.11.1 Volume expansion

Conversion of spent fuel to higher oxides of uranium results in a volume expansion that will partially fill voids in the canisters. Formation of higher oxides is expected to be limited because of reducing conditions. Even if some are formed, the void volume inside the canisters is sufficiently large that complete filling of the voids and the buildup of stresses inside the canister are not considered likely. The process is eliminated from further consideration in the safety assessment.

2.12 Microbial activity and effects

Microbial activity may affect spent fuel dissolution processes and could affect solubilities. The level of microbial activity is expected to be negligible in compacted bentonite, thus there is expected to be no effect on spent fuel dissolution.

2.13 Zircaloy corrosion/hydrogen gas production

Corrosion of Zircaloy produces H_2 which may accumulate in the near field influencing mass transport and affecting fuel dissolution. The production is small relative to that from steel corrosion.

3. RADIONUCLIDE PROCESSES (SF)

3.01 Radionuclide release from fuel

Radionuclides incorporated in the fuel matrix are released congruently with matrix dissolution following canister breaching. Radionuclides that are partially segregated to the fuel-sheath gap and grain boundaries are released more rapidly upon breaching.

3.02 Radionuclide release from cladding and structural materials

Radionuclides incorporated in the Zircaloy cladding and structural materials are released congruently with the corrosion of these materials following canister breaching. The oxide film formed on these materials while they are in the reactor may also affect radionuclide release.

3.03 Radionuclide elemental solubilities and precipitation

The concentration of many radionuclides in aqueous solution adjacent to the fuel will be limited by the solubilities of radionuclide-bearing solids formed by the interaction of fuel and bentonite pore fluid. In addition, radionuclides may be sorbed or co-precipitated with these secondary phases and iron corrosion products. The solubility limits are determined for a porewater conditioned by the presence of bentonite and iron corrosion products.

3.05 Co-precipitation of radionuclides

Secondary products from fuel matrix dissolution/cladding and canister corrosion and solid solutions will form which will incorporate many of the waste nuclides as a result of co-precipitation. These processes are generally difficult to treat quantitatively. Precipitation of pure phases is covered in 2.2/3.03.

3.06 Sorption of radionuclides inside canister

Radionuclides released from spent fuel may be sorbed by corrosion products in the canister, limiting their release from the canister.

3.07 Complexation of radionuclides

The solubilities of radionuclides released from spent fuel will be influenced by the presence of complexants in the porewater.

3.08 Formation of radionuclide-bearing colloids

Any radionuclide-bearing colloids that are formed around the fuel are expected to be filtered by the bentonite buffer. Such colloids can potentially have a negative impact if the bentonite colloid filtration function is lost, although the host rock is also an efficient colloid filter.

3.09 Gaseous radionuclide release

Some radionuclides in spent fuel are in gaseous form or may be converted to volatile form upon dissolution of the fuel. The only gaseous radionuclide released in significant quantities is the very short-lived Kr-85 (half-life: 10.8 a). C-14 is a potentially volatile radionuclide that is an important component of the instant release fraction. Studies of C-14 release from fuel cladding suggest an organic form that may be converted to a volatile form. Tritium is also very short-lived (half-life: 12.3 a) and thus not relevant.

4. SPECIAL ISSUES (SF)

4.01 Quality control of the inventory of fuel in a canister

The radionuclide inventory and associated heat output of a spent fuel canister is determined by the fuel type (BWR and PWR types of UO_2, and also MOX) and burnup. Either 4 PWR or 9 BWR fuel elements will be placed in a canister and the average burnup is required to be less than 48 GWd/tIHM in order to remain below the 1500 W per canister thermal constraint for assumed average storage times of 40 years. In the case of MOX fuel, it is necessary to combine 1 MOX PWR element with 3 UO_2 PWR fuel elements in a canister. To ensure that the maximum heat output of 1500 W per canister is not exceeded, strict quality control procedures will be required.

4.02 Handling accidents

Handling accidents, such as dropping a fuel assembly before loading into a canister, or dropping a loaded canister, may occur. This may affect the integrity of the fuel. Such events are expected to be rare, furthermore, no credit is given to Zircaloy cladding as a post-canister breaching containment barrier, so a significant impact on radionuclide releases calculated in the safety assessment is not expected.

4.03 Damaged fuel

Some fuel may be damaged (e.g., cladding failures) prior to placing it in canisters. Such damaged cladding would result in radionuclide release immediately upon canister failure. No credit is given to the cladding as a post-canister breaching containment barrier, so this is eliminated from further consideration.

4.04 Nuclear criticality

Fissile material may become critical if sufficiently high concentrations are reached in the presence of a moderator. The potential for the process to occur in the repository has been examined using calculations and reasoned arguments.

4.05 Extreme temperature of cladding

Cladding temperature should be below ~400 °C to avoid failure by creep rupture.

4.06 Cracking of fuel pellets by He buildup

Fuel may crack as a consequence of He buildup from actinide decay. The cracking would change the surface area, influencing the dissolution rate. This is assumed not to occur, as pressures in fission gas bubbles in fuel are already extremely high and do not cause cracking.

2.3 ILW waste and packages

1. FEATURES AND CHARACTERISTICS (ILW)

1.01 ILW waste types

ILW waste types considered in this safety assessment are long-lived intermediate-level wastes from reprocessing at COGEMA and BNFL (sludges/concentrates, hulls and ends, centrifuge slurry, etc.). There are no liquid wastes.

1.01.1 ILW waste groups

Some components of some waste types (complexants, oxidants, etc.) may have adverse effects on the performance of the repository. Potentially problematic waste will be emplaced separately; this is referred to as waste group ILW-2. Other waste is referred to as ILW-1.

1.02 Typical waste package/emplacement containers

Containers are combined into concrete emplacement containers.

1.03 Chemically toxic components

The waste packages may contain toxic chemicals.

1.04 Compacted waste (hulls/ends)

Currently, hulls and ends and some technological wastes are expected to be compacted and packed into steel flasks.

1.05 Conditioning materials

The COGEMA waste type WA-COG-2 is conditioned with bitumen. All other waste types are conditioned with cement grouts.

1.06 Waste packages

Waste is enclosed within stainless-steel drums or flasks, with a variety of dimensions. Depending on their dimensions, 4 to 18 packages are placed in a concrete emplacement container. The containers are backfilled with gas permeable mortar to provide venting of internally generated gas, to avoid overpressurisation and structural damage.

1.06.1 Backfill

Gas permeable mortars are foreseen to backfill the ILW tunnels.

1.06.2 Voids

Usually waste packages have voids. In the long term these voids may contribute to convergence of the ILW tunnels.

1.07 Heat output

Heat will be generated by cement hydration in the grout and by radionuclide decay in the wastes. Heat production is very limited leading to only small temperature increases.

1.08 Organics

Organic material, in particular cellulose, degrades under alkaline conditions. Among the degradation products, there are potent complexants for radioelements, in particular isosaccharinic acid (ISA) may increase the mobility of some radionuclides under alkaline conditions. Since not all the cellulose is available for degradation and since ISA sorbs strongly on cement, the effects on radionuclide mobility are limited. Since cellulose contents in ILW wastes are low, only small effects on long term safety are expected. Problematic wastes containing complexants are segregated into ILW-2.

1.09 Extraneous materials (including microbes/biological materials)

The organic matter in the groundwater consists partially of humic substances which bind to radioelements and may therefore enhance their mobility (increased solubility, decreased sorption). Since concentrations of humic substances in relevant groundwaters are low, only insignificant effects are expected.

2. ENVIRONMENTAL PROCESSES (ILW)

2.01 Resaturation of repository
Following closure, groundwater will migrate inwards from the host rock and saturate the void spaces within the repository near field. It may also resaturate through water inflow along the backfilled access tunnel system and shaft and / or their EDZs.

2.01.1 Host rock creep: effect on near field (tunnel convergence)
Waste packages may be corroded and mechanically compacted due to host rock creep. In particular, voids originally present in the packages may collapse.

2.02 Temperature evolution of near field
The distribution of temperature in the near field may be affected by exothermic reactions (hydration reactions of cement, corrosion of Al), radiogenic heating, etc.

2.03 Chemical evolution – pH
An initially very high-pH (>13) and high ionic-strength environment results from the degradation of the cementitious near-field materials (dissolution of alkali hydroxides into cement porewater). In a second stage, a high pH (approx. 12.5) is expected, dominated by portlandite.

2.04 Chemical evolution – redox
In the absence of dissolved oxygen (which will be rapidly consumed by reaction with metallic materials and, possibly, organic material in the waste), near-field redox conditions will be determined by the equilibrium between the iron in the system and all its corrosion products but may be influenced by radiolysis (see 2.3/2.05) or by nitrate present in the waste. In the very long-term, the Eh will tend towards that of the infiltrating groundwater.

2.04.1 Galvanic effects
Galvanic coupling of different metals may occur in waste containers. High corrosion rates for Al and Zn are considered, thus they would corrode rapidly. After this, galvanic effects would be unimportant.

2.04.2 Degradation of backfill
Cementitious material is not stable in contact with the groundwater of the host rock. It therefore slowly degrades as the groundwater enters the near field (diffusive or advective transport).

2.05 Radiolysis
Radiolysis will give rise to the production of radiolytic reductants (including hydrogen) and oxidants. These may affect redox conditions near to the waste, see 2.3/2.05.1 and 2.05.2.

2.05.1 Alpha-radiolysis
Alpha-radiolysis, particularly in the wastes containing hulls and ends, will produce oxidants and reductants that may influence near field redox chemistry.

2.05.2 Beta/gamma-radiolysis
Beta/gamma emitters are present but decay away very rapidly.

2.06 Corrosion of metallic components
Anaerobic corrosion of metallic components will give rise to the production of hydrogen.

2.06.1 Volume expansion
Not important as cracking of porous backfill would not influence mass transport, because a low flow environment is provided by the host rock. See 5.3/2.09.

2.07 Degradation/failure of disposal containers and emplacement packages
In the long term steel drums may corrode and concrete containers may crack losing their physical retention capability.

2.08 Gas generation and transport

Gas will be generated in the repository due to corrosion of metals (e.g. reinforcing steel, waste containers), due to radiolysis and due to degradation of organics by microbial activity. Gas may build up and migrate outwards via a number of different processes.

2.09 Effect of temperature on chemical processes

All chemical processes are temperature dependent. In particular, the kinetics and equilibrium position of chemical reactions and the different phases that may exist can be affected by temperature. If high temperatures exist (> 80 °C) for a period during the evolution of the repository, high-temperature cementitious phases may form, which give rise to uncertainty in the behaviour of the repository at later times. Based on modelling results, temperatures are expected to be well below 80 °C at all times.

2.10 Microbial activity and effects

Although microbes may survive under alkaline conditions, their activity is low under these harsh conditions. Nevertheless, due to inhomogeneous waste, areas of enhanced microbial activity may develop. It is very unlikely that products with more adverse properties than those of isosaccharinic acid (see 2.3/1.08) will form. However, at a high organic load in the waste, the carbon dioxide produced may degrade the cement and reduce the retention properties of the near field.

3. RADIONUCLIDE PROCESSES (ILW)

3.00 RN Transport

The transport of radionuclides is most likely to be mediated by the porewater within and around the waste packages. Radionuclides are either dissolved in this porewater or are attached to (or incorporated within) colloids. The possibility of transport in the gas phase must also be considered.

3.00.1 Diffusive transport

Radionuclides are transported in solution through the pore structure of the backfill and container walls. Provided flow is negligible in the host rock (as is expected to be the case), transport in the near field will also be dominated by aqueous diffusion.

3.00.2 Flow and advective transport

The hydraulic conductivity of the near field is such that porewater flow and advective transport could, in principle, occur in response to a sufficient driving force. A driving force is provided by the (low) ambient hydraulic gradient in the host rock, but the low hydraulic conductivity of the rock means that the resulting flow into and out of the near field is likely to be small. The driving force provided by gas pressure build up must, however, be taken into account.

3.01 Radionuclide release through waste form degradation

Radionuclides are released to solution when water enters the waste containers and the conditioning materials begin to degrade.

3.02 Instant release fraction

A part of the radionuclide inventory may be released instantaneously upon breaching of the waste containers.

3.03 Release of volatile radionuclides over gas pathway

Radionuclides that exist as volatile species may become mixed with gases generated by, for example, corrosion of metals and subsequently transported with these gases.

3.03.1 Gas dissolution in porewater

Hydrogen gas, methane and carbon dioxide will be produced and will dissolve in the porewater until their solubilities are reached.

3.03.2 Sorption on cement materials

Sorption of many radionuclides is favoured by the high pH environment that results from the presence of cementitious materials. For a given system, there exists only a limited number of sorption sites. Different radionuclides, and also stable isotopes, may compete for the same sorption sites.

3.04 Sorption on and co-precipitation with corrosion products

Secondary products from corrosion of metals and solid solutions will form which will incorporate many of the radionuclides as a result of co-precipitation.

3.05 Co-precipitation with calcite

During the evolution of a cementitious repository, calcite will be precipitated. The precipitating calcite will incorporate some elements into its structure. In some cases, this effectively removes radionuclides from solution.

3.05.1 Complexation

Molecules (organic and inorganic) which can bind radioelements are usually termed complexants. Often the resulting complexes are water soluble, in which case the radioelement concentration in the porewater is increased, i.e. the solubility is increased and its sorption properties are decreased. Examples of complexants are:

- ISA (cellulose degradation product) in cement porewater,
- cement additives,
- carbonate in the groundwater,
- humic substances in the groundwater,
- cyanide or sulphides from the waste.

3.06 Colloid generation

Degradation of waste and chemical condensation (e.g. formation of Pu(IV) polymer) may give rise to colloids incorporating radionuclides. In cement water colloids are not stable (coagulation) and therefore low concentrations are expected.

4. SPECIAL ISSUES (ILW)

4.00.1 Quality control

Quality control on ILW waste packages, radionuclide inventories and waste container fabrication is provided by COGEMA and BNFL quality assurance requirements.

4.00.2 Handling accidents

Waste packages may be damaged during handling and emplacement.

4.01 Effects of co-disposal with SF/HLW

Spent fuel and high-level waste will be emplaced in the same repository as ILW and each waste form may, in principle, influence the evolution of the other. Of particular concern is the possibility that cement water may adversely affect bentonite. The distance and the presence of seals between SF/HLW on one hand and ILW on the other hand is expected to prevent significant interactions.

4.03 Nuclear criticality

Fissile material such as Pu-239 is present in some of the ILW wastes, in particular in the hulls and ends containers. The quantities are small and considered insufficient to lead to criticality.

3.1 SF/HLW canister

1. FEATURES AND CHARACTERISTICS (SF/HLW canister)

1.01 Cast steel canister (vitrified waste)

The design criteria placed on the cast steel canister include a maximum acceptable dose at the canister surface for the operational period and the requirement that the canister should remain unbreached for at least 1000 years after repository closure. The canister design for HLW is the same as that considered in the Kristallin-I study.

1.01.1 Cast steel canister (spent fuel)

The design criteria are the same as for the canister for vitrified waste. The canister is constructed from cast steel and has either 4 or 9 channels to hold PWR (UO_2 and MOX) or BWR fuel elements.

1.01.2 Cu/steel canister (spent fuel)

The design criteria are the same as for the cast steel canister, except for the requirement that the canister should remain unbreached for at least 100 000 a. The design is similar to that of the Swedish SR 97 study.

1.02 Canister thickness/specification (vitrified waste canister)

A wall thickness of 250 mm is specified to give the required strength for repository conditions.

1.02.1 Canister thickness/specification (cast steel spent fuel canister)

The minimum wall thickness is ~150 mm. The design is expected to have a collapse pressure of > 80 MPa (see below - Cu/steel canister).

1.02.2 Canister thickness/specification (Cu/steel canister)

The Cu outer shell would have a wall thickness of 50 mm, to give a minimum corrosion barrier lifetime of 100 000 a. The steel insert has a collapse pressure of 80 MPa, well in excess of the 30 MPa pressure expected in the repository.

2. ENVIRONMENTAL PROCESSES (Canister)

2.01 Canister temperature evolution (vitrified waste)

Canister temperature will be determined mainly by the radiogenic heat output of the glass, the thermal conductivity of the bentonite backfill and the host rock, and the ambient rock temperature. Canister surface temperatures are expected to be ~150 °C at a few years after emplacement, declining to ~80 °C after 100 a. The canister temperature will affect corrosion rates and will influence the moisture content of the bentonite.

2.01.1 Canister temperature evolution (spent fuel)

Canister surface temperatures are expected to be ~160 °C at a few years after emplacement, declining to ~80 °C after 1000 a. The temperature effects are considered in evaluating the corrosion allowance.

2.02 Corrosion on wetting (steel canister – vitrified waste or spent fuel)

Corrosion of the canister would be negligible in the absence of water but will proceed in the presence of water in liquid or vapour form.

2.02.1 Corrosion on wetting (Cu/steel canister)

Corrosion of Cu would occur in the presence of aerated water or water vapour but would essentially cease once oxygen is consumed. The extent of corrosion occurring during the aerated phase (whether unsaturated or not) is accounted for in establishing the corrosion allowance.

2.03 Oxic uniform corrosion (steel canister – vitrified waste/spent fuel)

After canister emplacement, oxygen in trapped air will be consumed by oxic uniform corrosion of the canister surface.

2.03.1 Oxic uniform corrosion (Cu/steel canister – spent fuel)

Oxic corrosion of copper will occur immediately after canister emplacement and will continue until oxygen is consumed.

2.04 Microbially-mediated corrosion (steel canister – vitrified waste/spent fuel)

Microbial activity may catalyse corrosion by otherwise kinetically hindered oxidising agents. The most likely process is microbial reduction of groundwater sulphates to sulphides, and reaction of iron with dissolved sulphides. The potential for microbial corrosion is extremely small because of lack of viability of microbes in bentonite.

2.04.1 Microbially-mediated corrosion (Cu/steel canister)

Microbial reduction of sulphate to sulphide may occur, which may cause corrosion of copper, but microbial activity is considered non-viable in compacted bentonite (see 3.1/2.04).

2.05 Anoxic corrosion (steel canister – vitrified waste/spent fuel)

After exhaustion of oxygen and other oxidants, the iron canister will corrode anoxically with the associated production of hydrogen gas and magnetite.

2.05.1 Anoxic corrosion (Cu/steel canister)

Under anoxic conditions, sulphide produced by microbial reduction of sulphate may cause corrosion of Cu, but the rate would be limited by slow mass transport through the buffer.

2.06 Localised corrosion (steel canister – vitrified waste/spent fuel)

Corrosion of large surfaces is generally uneven, mainly due to differences in surface composition or slight local variations in the corrosive medium. In addition, localised corrosion (pitting corrosion) may occur during the short period of time after repository closure in which oxygen is present in the repository.

2.06.1 Localised corrosion (Cu/steel canister – spent fuel)

Pitting corrosion of copper would only be expected to occur during the aerated phase.

2.07 Total extent of corrosion (steel canister – vitrified waste/spent fuel)

The maximum extent of corrosion of a canister over the design lifetime represents the sum of various corrosion processes, including oxic uniform and non-uniform corrosion, microbial corrosion and anoxic corrosion.

2.07.1 Total corrosion (steel canister – spent fuel)

The maximum extent of corrosion from all processes occurring within the design lifetime is estimated in determining the corrosion allowance and establishing canister wall thickness.

2.07.2 Total corrosion (Cu/steel canister – spent fuel)

The maximum extent of corrosion from all mechanisms is considered in determining the corrosion allowance.

2.08 Stress corrosion cracking (steel canister – vitrified waste/spent fuel)

Stress corrosion cracking (SCC) is a possible mechanism for more rapid corrosion in areas with high residual stresses, e.g. due to welding. The SCC process requires a certain minimum stress level before it can occur.

2.09 Other canister degradation processes (steel and Cu/steel canisters)

The effects on the canister of corrosion by radiolysis products (production negligible due to thickness of canister wall), as well as high-temperature creep and hydrogen embrittlement are considered in evaluating canister performance.

2.10 Radiation shielding

The canister acts as a radiation shield so that radiolysis outside the canister prior to canister breaching will be negligible.

2.11 Canister breaching – reference (steel canister – vitrified waste/spent fuel)

The canisters will eventually be breached as a result of corrosion and mechanical loads, exposing the vitrified waste and spent fuel to groundwater.

2.11.1 Canister breaching – reference (Cu/steel canister – spent fuel)

A design lifetime of 100 000 a is adopted for the Cu/steel canister variant.

2.13 Chemical buffering (canister corrosion products)

Continuing corrosion of unreacted iron of the canister and redox buffering by corrosion products may lower the oxidation potential of porewaters around the waste and within the bentonite.

2.14 Hydrogen production (steel canister – vitrified waste/spent fuel)

Corrosion of the steel canister under anoxic conditions will result in hydrogen gas production. The hydrogen produced may accumulate and influence various processes in the repository, including spent fuel dissolution, groundwater movement and radionuclide transport in bentonite and in surrounding rock.

2.14.1 Hydrogen production (Cu/steel canister – spent fuel)

Corrosion of the copper shell of the Cu/steel canister would produce no hydrogen. Hydrogen production would commence only after canister breaching, with the exposure of the steel to water (only occurs for defective canister or after the design lifetime of 100 000 years).

2.15 Effect of hydrogen on corrosion

The formation of a gas phase within and around the canister may reduce or prevent contact of liquid water with steel . Water vapour will, nevertheless, be present at steel surfaces and so corrosion will continue. The corrosion rate may also decrease as hydrogen partial pressure increases.

2.16 Corrosion products – physical effects (steel canister – vitrified waste/spent fuel)

Corrosion products will build up on the canister surface, influencing the corrosion rate. In addition, the formation of magnetite from iron causes a doubling of the volume, which has the effect of potentially increasing stresses in the bentonite and increasing the load on the canister.

2.16.1 Corrosion products – physical effects (Cu/steel canister – spent fuel)

Corrosion of Cu is very limited under anoxic conditions, thus there are no physical effects expected prior to canister breaching. After canister breaching, corrosion of the iron insert will produce magnetite, and the volume increase may influence the size of the failure hole in the copper, by plugging it or forcing it open.

3. RADIONUCLIDE PROCESSES (Canister)

3.01 Residual canister – crack/hole effects (vitrified waste)

Even after the canister has been breached, its physical presence will restrict access of water to the glass and restrict the rate of radionuclide release. The size and shape of any holes/cracks will affect water ingress and the radionuclide release rate.

3.02 Residual canister – crack/hole effects (spent fuel)

Even after the canister has been breached, its physical presence will restrict access of water to the spent fuel and restrict the rate of radionuclide release. The size and shape of any holes/cracks will affect water ingress and radionuclide release rate.

3.03 Radionuclide sorption on and co-precipitation with canister corrosion products

Radionuclides may be sorbed on, or co-precipitated with, the canister corrosion products. There is good evidence of such processes from natural analogue studies, especially at redox front traps.

4. SPECIAL ISSUES (Canister)

4.01 Quality control

Quality control will be exercised on canister manufacture, sealing and inspection. Quality control is implicit in assumed canister characteristics.

4.02 Mis-sealed canister

If canisters are welded then, in principle, it is possible that welds could be incomplete or faulty.

4.1 Bentonite buffer

1. FEATURES AND CHARACTERISTICS (Bentonite buffer)

1.01 Bentonite emplacement and composition

The canisters are emplaced horizontally along the axis of the repository tunnels on pre-compacted bentonite blocks having a dry density of ~1750 kg m^{-3}. The remaining void around the canisters is filled with granular bentonite backfill having a dry density of ~1500 kg m^{-3}, the granules themselves having a density of ~2100 - 2200 kg m^{-3}.

1.01.1 Pellets

Most of the bentonite buffer will be made of high density pellets that will swell upon contact with water.

1.01.2 Corrosion of structural elements in HCB blocks

The concept for emplacement of highly compacted bentonite (HCB) blocks involves a steel framework on which the blocks are placed. Corrosion of this structure would produce planes of iron oxide corrosion products through the bentonite. The structure is designed so that steel components do not extend from the canister to the Opalinus Clay, to ensure that fast transport paths across the bentonite are not created.

1.02 Bentonite swelling pressure

The saturation of the bentonite creates a swelling pressure on the host rock and waste canister. The precompacted blocks beneath the canisters, which have a dry density of 1650 to 1750 kg m^{-3}, will develop a swelling pressure in the order of 4 to 18 MPa. The granular bentonite filling the remaining region around the canisters will have a swelling pressure of ~2 to 4 MPa. Maintenance of a significant swelling pressure assures that bentonite has a low hydraulic conductivity.

1.03 Bentonite plasticity

The plastic properties of the saturated bentonite ensure that the bentonite will form a homogeneous mass, closing gaps between individual blocks, around the canister and at the tunnel walls. The plasticity of the bentonite is also expected to reduce possible shear forces on the canisters.

1.04 Buffer permeability

The very low hydraulic conductivity of bentonite prevents groundwater flow in the vicinity of the canister. This means that, once water saturation is reached, any solute transport can only occur by diffusion.

1.05 Bentonite porewater chemistry

The bentonite porewater chemistry is buffered by ion exchange reactions, mineral equilibria and dissolution of some mineral components of the bentonite. Key features are near neutral pH and reducing conditions (due to canister corrosion products / Fe(II) minerals in bentonite).

1.06 Gas permeability

Hydrogen is produced by anoxic corrosion of steel and the effects must be considered in evaluating the behaviour of the bentonite buffer. Some of the gas produced may dissolve in the porewater, but the gas may also exceed the solubility under repository conditions and be transported through gas channels or capillaries into the surrounding rock.

1.07 Inhomogeneities (properties and evolution)

Uncertainty and variability in source material may produce variable physical/chemical characteristics. This may influence subsequent evolution of physical, hydraulic and chemical characteristics. Such effects are considered unimportant due to bentonite plasticity.

2. ENVIRONMENTAL PROCESSES (Bentonite buffer)

2.01 Thermal evolution

After reaching a maximum within the first ten years, the temperature declines over the next few hundred years for vitrified waste and several thousand years for spent fuel. Many of the processes occurring within the engineered barriers are temperature dependent. Elevated temperatures may affect various aspects of repository performance.

2.02 Bentonite saturation

After emplacement, groundwater will slowly penetrate the bentonite, which will swell so that a homogenous mass is formed. The time taken for bentonite to saturate depends on the hydraulic and thermal properties of both the bentonite and the surrounding rock.

2.03 Mineralogical alteration – short term

Alteration of bentonite minerals could potentially lead to a reduction of bentonite swelling properties and/or plasticity. Short-term processes that must be considered include thermally induced shrinkage cracking, alteration and reduction in swelling capacity during the unsaturated phase and illitisation during the high temperature period (the first few hundred years). However, these processes have no effect on long-term safety.

2.04 Mineralogical alteration – long term

The long-term stability of bentonite at repository temperatures may be influenced by illitisation and cementation processes, which could reduce the swelling capacity and alter the cation-exchange capacity of the buffer.

2.05 Bentonite cementation

Interaction of water vapour with bentonite during the unsaturated phase may cause cementation, with relatively rapid loss of some swelling capacity. This may also influence the hydraulic properties of the buffer.

2.06 Bentonite-iron interactions (canister)

Corrosion of the steel canister under anaerobic conditions produces magnetite. This may result in interactions with the bentonite that modify the swelling capacity and hydraulic conductivity of bentonite near the canister surface. Volume changes would also occur (3.1/2.16). The porewater is defined by assessing the interaction of porewater from Opalinus Clay with the bentonite, taking into account the presence of iron corrosion products.

2.06.1 Bentonite-Cu interactions

Interactions between the Cu canister and bentonite may influence the swelling, sorption and hydraulic properties of the buffer. Effects are considered negligible.

2.07 Microbial activity

Microbes are considered non-viable in highly compacted bentonite.

2.08 Radiolysis

Radiation can cause disassociation of molecules, e.g. water, leading to a change in chemical conditions and gas production. Radiolysis may influence redox conditions, thus affecting solubilities and sorption in the buffer.

2.09 Bentonite erosion

Bentonite can be eroded as a result of groundwater movement. For sodium bentonite, the calculated critical velocity for the onset of erosion is about 10^{-4} m s^{-1}, thus this is irrelevant for a repository with Opalinus Clay as host rock.

2.10 Interaction with cement components

The beneficial properties of bentonite as a buffer material (swelling, low permeability and good sorption properties) may be significantly affected by reactions with cement. Such reactions, even if they occur, cannot be significant in the Swiss SF/HLW repository because there would be only very limited quantities of cementitious material in the SF/HLW panels. Furthermore, design measures (placement of ILW at a distance from SF/HLW, presence of seals) ensure that influences from the ILW repository part with large amounts of cement on the SF/HLW part are negligible.

2.11 Gas fracturing

Gas entry in bentonite may involve passage through microcracks or through a capillary network. The impact of such processes on buffer integrity and radionuclide transport requires evaluation.

3. RADIONUCLIDE PROCESSES (Bentonite buffer)

3.01 Radionuclide transport through buffer

Radionuclides will migrate through the buffer by aqueous diffusion. In addition, they may be retarded by sorption. Transport of some radionuclides as volatile species by repository-generated gas must also be considered.

3.02 Radionuclide retardation

Cation exchange and surface complexation cause retardation of many diffusing nuclides in the bentonite buffer.

3.03 Elemental solubility/precipitation

Radionuclide concentrations in aqueous solution in the buffer will be constrained by elemental solubility limits.

3.04 Colloid filtration

Colloids associated with radionuclides may be produced, for example, as the glass or spent fuel dissolve. The transport of these colloids through the bentonite is, however, prevented by its fine pore structure (filtration).

3.05 Interaction and diffusion between canisters

Radionuclides not only diffuse radially away from the canisters, but also in the axial direction between canisters. Radionuclides may also diffuse back into the buffer having earlier migrated into the host rock or tunnel EDZ. Not considered significant.

4. SPECIAL ISSUES

4.01 Quality Control

Production of compacted bentonite blocks and granular bentonite will require quality control to produce a product with satisfactory physical and chemical properties. Quality of emplacement will also require monitoring.

4.03 Organics/contamination of bentonite

The source of the bentonite will be carefully selected and quality checked. Oil-spills in the tunnel could be a potential source of localised contamination. The effect could be a reduction in sorption of radionuclides in the bentonite buffer. It is expected that significant contamination or oil-spills can be detected and remedied, so that only a very small fraction of the bentonite would be affected.

4.04 Canister sinking

If the bentonite is to be effective as a safety barrier, retarding solute transport and preventing the movement of colloids, it must continue to completely surround the steel canister over a long period of time. If the canister were able to sink through the bentonite due to creep, then the effectiveness of the bentonite barrier would be reduced.

5.3 ILW backfill and liner

1. FEATURES AND CHARACTERISTICS (ILW backfill and liner)

1.01 Backfill material

Mortar is selected as a backfill material to fill the void spaces both within the concrete emplacement containers (between the waste packages in the emplacement containers, and between the waste packages and the container walls) and between the emplacement containers and the tunnel lining. The mortars are assumed to be gas permeable.

1.02 Backfill emplacement

After the waste containers are emplaced the tunnels will be backfilled as soon as possible.

1.03 Hydraulic and gas permeability

The backfill is formulated to have a suitable gas permeability (see 5.3/1.01). It therefore has also a high hydraulic permeability.

1.04 Effects of initial (operating) conditions

The operational phase of a cementitious repository (open and ventilated tunnels) may influence safety relevant properties of some repository components. This is minimised by sealing immediately after waste emplacement.

1.05 Lining material

Shotcrete (ca. 40 cm thickness) is selected as the lining material for ILW tunnels.

1.05.1 Drainage system

Due to the low water flux a drainage system is not necessary in Opalinus Clay host rock. Eliminated from further consideration.

1.05.3 Seals

A concrete plug is placed at the exit of the ILW disposal tunnels. Bentonite seals in the adjacent tunnel are described in 8./1.02.

1.05.4 Cement additives

Like the degradation products of cellulose (see 5.3/1.05.5) cement additives may be potent complexants for radioelements and may increase the mobility of some radionuclides. However, due to the strong sorption of these additives on cement, their effects on radionuclide mobility are limited.

1.05.5 Organics

Organic material, in particular cellulose, degrades under alkaline conditions. Among the degradation products, there are potent complexants for radioelements, in particular iso-saccharinic acid (ISA) may increase the mobility of some radionuclides under alkaline conditions. Since not all the cellulose is available for degradation and since ISA sorbes strongly on cement, the effects on radionuclide mobility are limited. Since cellulose contents in ILW wastes are low, only small effects on long term safety are expected.

1.06 Rock bolts

Steel rock bolts will be used to support the tunnel, together with shotcrete. These will corrode producing hydrogen.

1.07 Joints and cracks in backfill/liner

Any cracks in the liner are not considered to be relevant to long-term safety since the backfill is, in any case, a more important transport barrier. Cracks in the backfill could form a significant transport path if there is flowing porewater and advective radionuclide transport, reducing the effectiveness of this barrier. The low hydraulic conductivity of the host rock will lead to a diffusion dominated system in which cracks are not relevant.

1.08 Voids in backfill/liner

The backfill is assumed to be placed without macroscopic voids.

2. ENVIRONMENTAL PROCESSES (ILW backfill and liner)

2.01 Cement hydration

Cement hydration is an exothermic chemical reaction that can release heat over a short period. This will dissipate rapidly.

2.02 Temperature evolution

Temperature increases due to radioactive decay and cement hydration may affect backfill and liner integrity. Based on the results of calculations, only a small temperature rise is expected.

2.03 Mechanical strength/stability

The liner material is selected to give mechanical strength and stability during the operating phase. The waste containers and mortar are expected to completely fill the void space in the tunnel and remain mechanically stable at least until metal waste containers corrode.

2.04 Mechanical evolution and external forces

The liner and backfill will experience mechanical loads (including rock creep) from the surrounding rock.

2.04.1 Effect of liner on rock creep

The concrete ILW tunnel liner will prevent significant rock creep and tunnel convergence in the short term (operational phase).

2.05 Saturation/hydraulic evolution

See 2.3/2.01 (saturation) and 5.3/2.10 (hydraulic evolution).

2.06 Chemical degradation

Cementitious material is not stable in contact with the groundwater of the host rock. It therefore slowly degrades as the groundwater enters the near field. See also 2.3/2.04.2

2.07 Degradation due to reaction with sulphate

Chemical interaction of cement paste with sulphate from the groundwater, incl. pyrite oxidation products, has an impact on the calcium aluminate phases of the hydrated cement system (ettringite and calcium aluminate mono-sulphate (AFm) formation). Due to volume increase the concrete may be disrupted. However, volume changes are not expected to be significant.

2.08 Degradation due to reaction with magnesium

Magnesium strongly reacts with portlandite to form brucite-like phases ($Mg(OH)_2$). This process is very slow and not considered important.

2.08.1 Degradation due to other reactions

Waste components like ammonium salts, mercury and zinc chloride and chromates may be corrosive for cement. However, such compounds are only present in the waste in small amounts; their influence can thus be neglected.

2.09 Volume expanding materials

Products from the corrosion of steel reinforcement, rock bolts and volume-expanding ettringite/monosulphate (see 5.3/2.07) or Friedel salts (chlorides) may form within the backfill. Due to volume increase the concrete may be disrupted. This would not affect mass transport significantly.

2.10 Pore-structure heterogeneity and evolution

The pore structure of the backfill and liner may be affected by the degradation of cement, by damage due rock movements, by volume expansion due to corrosion of reinforcements and rock bolts, or become clogged due to microbial activity and the precipitation of cementitious components and calcite. Such effects are neglected, as they would have a small impact on mass transport.

2.10.1 Compaction

In the long term, voids in the waste packages and the backfill, as well as voids caused by cement dissolution, will close due to plastic deformation of the surrounding Opalinus Clay, leading to convergence of the ILW tunnels.

2.11 Formation of advective paths

Cracking of the liner and backfill is likely and could lead to the formation of connected paths through the liner and the backfill. However, the low hydraulic conductivity of the surrounding host rock is expected to prevent advective transport along these paths.

2.12 Biofilms

Aerobic growth of microbes during the operational phase may lead to biofilms. Decomposition by cement water may produce complexing compounds (like ISA).

2.13 Colloid formation through backfill degradation

Degradation of the backfill may give rise to colloids that incorporate released radionuclides. In cement water colloids are not stable (coagulation) and therefore low concentrations are expected; furthermore colloids will be filtered effectively by the surrounding Opalinus Clay.

2.14 Effects of temperature gradients

Temperature gradients in the ILW tunnels are too small to give rise to significant convective flow.

2.15 2-phase flow

After a period of gas-pressure build-up, the gas pressure may exceed the capillary pressure in the larger cement pores, water will be forced out and 2-phase flow may take place.

3. RADIONUCLIDE PROCESSES (ILW backfill and liner)

3.01 Diffusive transport through backfill and liner

Radionuclides are transported by diffusion in solution through the pore structure of the backfill and liner, due to the low hydraulic conductivity of the host rock, which is expected to prevent significant advective flow.

3.02 Flow and advective transport through backfill and liner

Transport through the backfill and liner may be influenced by advection. Preferential flowpaths through the backfill may arise either (i), due to built-in heterogeneity (e.g. relatively permeable backfill between much less permeable waste containers), or (ii), due to uneven near-field degradation (e.g. cracking of backfill/liner). Preferential flowpaths through the liner may arise from cracking of this material. However, the low hydraulic conductivity of the host rock is expected to prevent significant advective flow.

3.03 Radionuclide sorption in backfill and liner

Sorption of many radionuclides is favoured by the high pH environment that results from the presence of cementitious materials (principally the backfill). For a given system, there exists only a limited number of sorption sites. Different radionuclides, and also stable isotopes, may compete for the same sorption sites.

3.04 Sorption/incorporation of radionuclides on colloids and microbes

Colloids or microbes may incorporate radionuclides, e.g. through the processes lumped together as "sorption". In cement water colloids are not stable (coagulation) and therefore low concentrations are expected, and they could not be transported through Opalinus Clay (filtration).

3.05 Solubility

Solubility is a property of a chemical element, and not of the radioisotope. Several elements have limited solubilities in the chemical environment that will exist in the backfill. The presence of stable isotopes will affect the concentration of radioactive isotopes of the same element (isotopic dilution). The presence of chemically similar elements can also affect solubility.

3.06 Co-precipitation (of RNs)

Chemical processes in the backfill may lead to co-precipitation (see 2.3/3.04 and 2.3/3.05).

3.07 Complexation

Molecules (organic and inorganic) which can bind radioelements are usually termed complexants. Often the resulting complexes are water soluble, in which case the radioelement concentration in the porewater is increased, i.e. the solubility of the radioelement concerned is increased and its sorption properties are decreased. Examples of complexants are:

- ISA (cellulose degradation product) in cement porewater,
- cement additives,
- carbonate in the groundwater,
- humic substances in the groundwater,
- cyanide an sulphides from the waste,
- Complexants increase solubility limits and reduce sorption of the radioelement concerned.

4. SPECIAL ISSUES (ILW backfill and liner)

4.01 Quality control

A concrete liner will be used to provide tunnel support and a grout backfill will be used to fill all voids in the tunnel. Good quality control measures will need to be adopted to reduce the possibility of large voids.

4.02 Poor emplacement

Poor emplacement of liner and backfill could create voids that would result in increased tunnel convergence when the ILW near field resaturates.

4.03 Interfaces, cracks and slabbing

Cracks and voids in the liner may, in principle, lead to enhanced groundwater flow. However, groundwater flow is expected to be limited due to the low hydraulic conductivity of the surrounding host rock.

4.04 Seismic effects

Seismic events may crack and weaken the ILW backfill and liner. Not relevant as further cracking will not influence mass transport.

6.1 Bentonite-host rock (HR) interface

1. FEATURES AND CHARACTERISTICS (Bentonite-HR interface)

1.01 Excavation-disturbed zone (EDZ)

There is a disturbed host rock zone in the vicinity of tunnels and shafts due to excavation process (increased porosity, hydraulic conductivity and diffusivity).

1.01.1 Rock bolts and mesh

Rock bolts and mesh will be used to support the tunnel, thus no tunnel liner is required. These metallic components may generate gas as they corrode, but the amount of gas is likely to be small compared to that generated by canister corrosion.

1.02 Open contact joints

Voidage at the interface between the bentonite and EDZ would lead to a connected transport path along the contact region. Any such voidage is, however, likely to close due to the plasticity of the Opalinus Clay and the swelling of the bentonite, and seals are designed to prevent flow and advective transport along any such path.

1.03 Effective hydraulic properties

The movement of groundwater and advection of radionuclides along the interface between bentonite and the host rock will be determined by the overall porosity and hydraulic conductivity of the region, the degree of heterogeneity and the driving force for flow (hydraulic gradient and/or gas pressure).

1.04 Mineralogy

Sorption properties not only depend on the radioelement and the porewater chemistry, but also on the mineral composition of the solid (bentonite, host rock). It is assumed that the sorption property of a solid is the sum of the sorption properties of the single minerals although one mineral type usually dominates. Clay minerals sorb radioelements via cation exchange or surface complexation mechanisms.

1.05 Groundwater composition

Sorption properties not only depend on the radioelement and mineral composition, but also on the porewater composition. The most relevant properties of the porewater are pH, inorganic carbon content (carbonato complexes), redox potential and salinity.

1.06 Natural organics

Natural organics, in particular compounds lumped together under the name "humics", can form strong complexes with some radioelements. Complexation may decrease sorption and increase solubility of the radioelements concerned.

1.07 Microbial activity

Metabolites of microbes may form complexes with some radioelements. Dissolved in the porewater these metabolites may therefore decrease sorption and increase solubility of the radioelements concerned. Microbial activity in clay rocks is usually restricted. Microbial activity is not considered any further (second order effect).

1.08 Hydraulic gradient

The hydraulic gradient at the bentonite-HR interface depends on:

- the magnitude and direction of the regional hydraulic gradient,
- anomalous pore pressures within the Opalinus Clay,
- the distribution of hydraulic conductivity within and around the repository tunnels, and
- processes occurring within the repository that affect pore pressure, including tunnel convergence, gas generation and heat generation.

1.09 Water flow at bentonite – host rock interface

Axial and radial water flow may be driven by hydraulic/thermal/chemical gradients, consolidation of Opalinus Clay, tunnel convergence and gas generation.

2. ENVIRONMENTAL PROCESSES (Bentonite-HR interface)

2.01 Desaturation/resaturation of EDZ

Desaturation of EDZ occurs due to i) ventilation and degassing during the operational phase and ii) gas generation and suction exerted by bentonite during the post-closure phase. Resaturation of EDZ occurs due to the presence of a hydraulic gradient and due to gas dissolution. The duration of the desaturation and saturation periods may have significant effects on other safety-relevant processes (canister corrosion, waste dissolution, etc.).

2.02 Thermal evolution

Radiogenic heat production will lead to a temperature increase in the near field, followed by a slow decreases, which will influence the hydraulic and mechanical properties of the EDZ. Temperatures will not exceed ~95 °C and effects are not considered important.

2.03 Geomechanical processes

After sealing of the emplacement tunnels, the host rock may creep and converge, increasing the load on the bentonite.

2.04 Effect of bentonite swelling on EDZ

Self-sealing of excavation-induced fractures in the Opalinus Clay may be accelerated by the swelling pressure that develops as the bentonite backfill saturates.

2.05 Swelling of clay minerals in EDZ

Self-sealing of excavation-induced fractures may occur due to disintegration and swelling of the smectite fraction naturally present in the Opalinus Clay and due to the swelling pressure of the bentonite (6.1/2.04).

2.06 Compaction of EDZ

Compaction and decompaction of the Opalinus Clay may occur due to glaciations and sedimentation/erosion. This may affect hydraulic and mechanical properties of the EDZ and may displace porewater axially along tunnels and shafts in the EDZ.

2.07 Geochemical alteration

Geochemical reactions due to changed redox conditions (atmospheric oxygen, redox front migration, etc.), pH plume (cement dissolution) etc. can lead to changes in porewater composition and in mineral composition (dissolution, secondary minerals) and can therefore change sorption and solubility properties for the radioelements.

2.08 Fluid and heat fluxes by coupled processes (Onsager)

Fluid, heat, current, or solute fluxes can, in principle, be driven by hydraulic, thermal, electrical or chemical gradients. The off-diagonal processes in the matrix showing these fluxes vs. the driving gradients are collectively termed coupled (Onsager) processes.

2.09 Gas transport

A number of processes induced by gas buildup may occur at the interface between bentonite and Opalinus Clay, including gas dissolution, formation of new water-conducting / gas conducting features (pathway dilation), and porewater displacement by gas.

2.10 Colloid production and effects

Bentonite may be a source of colloidal particles to which radionuclides may become attached (sorption, incorporation). These colloids are likely to be immobile in the fine pore structure of the undisturbed Opalinus Clay (filtration), and may lead to clogging of Opalinus Clay pores. Colloids may be transported by diffusion and (if there is groundwater flow) advection in fractures in the EDZ or at the bentonite-HR interface.

3. RADIONUCLIDE PROCESSES (Bentonite-HR interface)

3.01 Radionuclide migration pathways

Transport of radionuclides may take place i) vertically through the host rock or ii) axially within the tunnel and ramp/shaft backfill, along the backfill-rock interface (voids) and through the associated EDZs.

3.02 Radionuclide sorption

Radioelements sorb on clay minerals via cation exchange or surface complexation mechanisms.

3.03 Elemental solubility

At the interface bentonite/host rock, the concentrations of most radioelements in the porewater are too low for solubility limits to be exceeded. On the other hand, radioelements may form solid solutions with minerals.

3.04 Advective/dispersive/diffusive transport

Transport of dissolved radionuclides is driven by pressure gradients (advection) and concentration gradients (diffusion). Dispersion takes place due to heterogeneities, which can occur over a wide range of scales along the migration pathways.

3.05 Matrix diffusion

Radionuclides that are advected along fractures or connected void spaces at or near the bentonite-HR interface may also diffuse into stagnant porewater in the adjacent rock matrix. This retardation process is termed matrix diffusion.

3.06 Gas-induced transport

Gas-induced transport is taken to include:

- the displacement by gas pressure of porewater containing dissolved radionuclides, and
- transport of radionuclides as volatile species with repository-generated gases.

3.07 Colloid-facilitated transport

Radionuclide transport can be influenced if radionuclides are sorbed reversibly or irreversibly on colloids, or if intrinsic colloids (i.e. colloids consisting primarily of precipitated radionuclides) are formed.

3.08 Convergence-induced transport
Transport of dissolved radionuclides can be influenced by porewater displacement induced by tunnel convergence.

3.09 Transport by coupled processes (Onsager)
See 6.1/2.08.

4. SPECIAL ISSUES (Bentonite-HR interface)
No special issues have been identified.

6.3 Concrete-HR interface (ILW)

1. FEATURES AND CHARACTERISTICS (Concrete-HR interface)

1.01 Excavation-disturbed zone (EDZ)
There is a disturbed host rock zone adjacent to the ILW liner. The zone has an increased porosity, hydraulic conductivity and diffusivity and there may be chemical alteration due to the interaction with the concrete liner. This is not considered important because the hydraulic properties of the inside of the ILW tunnels (mortar, emplacement containers, waste) are significantly poorer than those of the EDZ.

1.01.1 Rock bolts
Rock bolts may be used to support the ILW tunnels. These metallic components may generate gas as they corrode, but the amount of gas is small compared to that generated by the waste packages.

1.03 Effective hydraulic properties
The interface may have an increased hydraulic conductivity relative to that of the host rock. This is not considered important because the hydraulic properties of the inside of the ILW tunnels (mortar, emplacement containers, waste) are significantly poorer than those of the EDZ.

1.04 Mineralogy
Concrete porewater may alter the mineralogy of the Opalinus Clay in contact with the liner. This may influence sorption and self-sealing.

1.05 Groundwater composition
See 6.2/1.04.

1.06 Natural organics
Natural organics, in particular compounds lumped together under the name "humics", can form strong complexes with some radioelements. Complexation may decrease sorption and increase solubility of the radioelements concerned.

1.07 Microbial activity
Metabolites of microbes may form complexes with some radioelements. Dissolved in the porewater these metabolites may therefore decrease sorption and increase solubility of the radioelements concerned. Microbial activity is not considered any further (second order effect).

1.08 Hydraulic gradient
The hydraulic gradient at the concrete-HR interface depends on:

- the magnitude and direction of the regional hydraulic gradient,
- anomalous pore pressures within the Opalinus Clay,
- the distribution of hydraulic conductivity within and around the repository tunnels, and
- processes occurring within the repository that affect pore pressure, including tunnel convergence and gas generation.

1.09 Water flow at concrete-host rock interface
Axial and radial water flow may be driven by hydraulic/thermal/chemical gradients, consolidation of OPA, tunnel convergence and gas generation.

2. ENVIRONMENTAL PROCESSES (Concrete-HR interface)

2.01 Desaturation/resaturation of EDZ

Desaturation of EDZ occurs due to i) ventilation and degassing during the operational phase and ii) gas generation during the post-closure phase. Resaturation of EDZ occurs due to the presence of a hydraulic gradient and gas dissolution. The duration of the desaturation and saturation periods may have significant effects on other safety-relevant processes (cement dissolution, waste dissolution, etc.).

2.02 Thermal evolution

Radiogenic and hydration heat production may influence the hydraulic and mechanical properties of the EDZ.

2.03 Geomechanical processes

Effect of orientation of layering of Opalinus Clay may affect the geomechanical stability of the EDZ and deformation may occur. See also 6.1/2.03.

2.05 Swelling of clay minerals in EDZ

Self-sealing of excavation-induced fractures may occur due to disintegration and swelling of clay minerals and plastic deformation of the clay.

2.06 Compaction of EDZ

Compaction and decompaction due to glaciations and sedimentation/erosion may influence the hydraulic and mechanical properties of the EDZ (effective porosity, hydraulic conductivity, elasticity, plasticity, etc.). Compaction may displace porewater axially along tunnels and shafts in EDZ.

2.07 Geochemical alteration

Geochemical reactions due to changed redox conditions (atmospheric oxygen, redox front migration, etc.), pH plume (cement dissolution) etc. can lead to changes in porewater composition and in mineral composition (dissolution, secondary minerals) and can therefore change sorption properties for the radioelements. See also 6.1/2.08.

2.08 Fluid and heat fluxes by coupled processes (Onsager)

See 6.1/2.08.

2.09 Gas transport

Gas production in excess of the solubility may lead to gas transport along the concrete-host rock interface by pathway dilation or displacement of porewater.

2.10 Colloid production and effects

The high chemical gradient at the concrete/host rock interface may be a source of colloidal particles to which radionuclides can become attached (sorption, incorporation). These colloids are likely to be immobile in the fine pore structure of the undisturbed Opalinus Clay (filtration), and may lead to clogging of Opalinus Clay pores.

3. RADIONUCLIDE PROCESSES (Concrete-HR interface)

3.01 Radionuclide migration pathways

Transport of radionuclides may take place i) vertically through the host rock or ii) axially within the tunnel and ramp/shaft backfill, along the backfill-rock interface (voids) and through the associated EDZs.

3.02 Radionuclide sorption

Radioelements sorb on clay and cement minerals via cation exchange or surface complexation mechanisms.

3.03 Elemental solubility

At the interface concrete/geosphere, the concentrations of most radioelements in the porewater are too low for solubility limits to be exceeded. Radioelements may form solid solutions with minerals.

3.04 Advective/dispersive/diffusive transport

Transport of dissolved radionuclides is driven by pressure gradients (advection) and concentration gradients (diffusion). Dispersion takes place due to heterogeneities, which can occur over a wide range of scales along the migration pathways.

3.05 Matrix diffusion

Radionuclides that are advected along fractures or connected void spaces at or near the backfill-HR interface may also diffuse into stagnant porewater in the adjacent rock matrix. This retardation process is termed matrix diffusion.

3.06 Gas-induced transport

Gas-induced transport is taken to include:

- the displacement by gas pressure of porewater containing dissolved radionuclides, and
- transport of radionuclides as volatile species with repository-generated gases.

3.07 Colloid-facilitated transport

Radionuclide transport can be influenced if radionuclides are sorbed reversibly or irreversibly on colloids, or if intrinsic colloids (i.e. colloids consisting primarily of precipitated radionuclides) are formed.

3.08 Convergence-induced transport

Transport of dissolved radionuclides can be influenced by porewater displacement induced by tunnel convergence.

3.09 Transport by coupled processes (Onsager)

See 6.1/2.08.

4. SPECIAL ISSUES (Concrete-HR interface)

No special issues have been identified.

7. Opalinus Clay (OPA) host rock

1. FEATURES AND CHARACTERISTICS (OPA host rock)

1.01 Discontinuities

The observed discontinuities in the Opalinus Clay are classified as follows:

- single fracture faults, consisting of a single fracture plane and with a lateral extent in the order of metres to decametres,
- localised deformation zones, consisting of bounding faults and a cataclastically deformed inner zone,
- composite deformation zones, consisting of a localised deformation zone, surrounded by a damage zone,
- joints.

1.02 OPA matrix

The unfractured Opalinus Clay matrix consists of a solid mineral fraction on one hand and bound and free water on the other hand.

1.03 Effective hydraulic properties

This is taken to include hydraulic conductivity and flow porosity.

1.04 Mineralogy

Sorption properties not only depend on the radioelement and the porewater chemistry, but also on the mineral composition of the solid. It is assumed that the sorption property of a solid is the sum of the sorption properties of the single minerals, although one mineral type usually dominates.

1.05 Groundwater composition

Sorption properties not only depend on the radioelement and mineral composition, but also on the porewater composition. The most relevant properties of the porewater are pH, inorganic carbon content (carbonato complexes), redox potential and salinity. The groundwater composition also affects the evolution of the engineered barrier system.

1.06 Natural organics

Natural organics, in particular compounds lumped together under the name "humics", can form strong complexes with some radioelements. Complexation may decrease sorption and increase solubility of the radioelements concerned.

1.07 Stress regime

Currently, a compressive stress field is observed at the potential repository site with the maximal component oriented horizontally approximately in the direction N-S.

1.08 Hydraulic gradient

The hydraulic gradient depends on the magnitude and direction of the regional hydraulic gradient, although anomalous pore pressures within the Opalinus Clay have also been observed (see also 7.1/1.11). Near the repository, the gradient can also be affected by:

- the distribution of hydraulic conductivity within and around the repository tunnels, and
- processes occurring within the repository that affect pore pressure, including tunnel convergence and gas generation.

1.09 Heterogeneity within OPA

The presence of discontinuities such as faults, deformation zones and layers with significant amount of materials with a low clay content (sand lenses, etc.) can influence the hydraulic, mechanical and radionuclide sorption properties of the host rock. In the extensive high-resolution 3D seismics campaign conducted in the potential siting region as part of the basis for this safety assessment, no previously undetected discontinuities that would have to be avoided when constructing the emplacement tunnels ("layout-determining features") were observed.

1.10 Calcite veins

Precipitated calcite coating is often observed within water-conducting features (calcite veins), affecting the hydraulic and geochemical properties of these features. Indeed, the presence of such a coating is evidence that the feature conducts (or has at some time conducted) flowing water. Only minor calcite precipitation was observed in the Opalinus Clay, giving strong palaeohydrogeological evidence for the long-lasting absence of flowing water.

1.11 Overpressures

Overpressures are anomalous pore pressures above hydrostatic pressure. In the region of interest, overpressures of up to 200 m were found in the Opalinus Clay.

2. ENVIRONMENTAL PROCESSES (OPA host rock)

2.01 Thermal effects

These include effects of radiogenic heat production on hydraulic, mineralogical and mechanical properties of Opalinus Clay (thermal degradation). The results of a thermal study show that temperatures in the Opalinus Clay due to the presence of heat-generating wastes will not exceed ~95 °C, which is only slightly above the maximal temperature the Opalinus Clay has experienced in the past (about 85 °C); thus thermal degradation is assumed to be negligible.

2.03 Swelling of clay

Swelling of clay means volume increase induced by water uptake. Swelling of Opalinus Clay contributes to self-sealing of fractures created during excavation or by gas generation, tunnel convergence and neo-tectonic activity.

2.04 Geochemical alteration

Geochemical reactions due to changed redox conditions (atmospheric oxygen, redox front migration, etc.), pH plume (cement dissolution) etc. can lead to changes in porewater composition and in mineral composition (dissolution, secondary minerals) and can therefore change sorption and solubility properties for the radioelements. These effects are expected to be negligible beyond a few metres into the host rock from the tunnel walls.

2.05 Microbial activity

Metabolites of microbes may form complexes with some radioelements. Solved in the porewater these metabolites may therefore decrease sorption and increase solubility of the radioelements concerned. Under anaerobic conditions the complexants excreted by micro-organisms are usually not very strong. Moreover, microbial activity in deep clay rocks is usually restricted. Microbial activity is not considered any further here (microbes are part of the chemical environment, and their effects are thus included in measurements).

2.06 Effects of gas on OPA

Gas generation in the repository may lead to pressure buildup and formation of new pathways (pathway dilation, gasfracs, hydrofracs). Gas dissolution or degassing of geogas may occur depending on temperature and pressure conditions at depth.

2.07 Groundwater flow
Very low groundwater flow rates are expected in the intact Opalinus Clay due to the very low hydraulic conductivity. Isotope profiles are indicative of a diffusion-dominated system; i.e. they are compatible with the assumption of negligible groundwater flow in the past.

2.08 Gas transport
This includes transport of free and dissolved gas via a number of different processes.

2.09 Colloid transport
Colloids are expected to be immobile in the Opalinus Clay matrix due to its fine pore structure (filtration). Colloids may, however, be transported through any water conducting features in the Opalinus Clay. The distance the colloids are transported depends on their stability and on a range of chemical and physical processes that may lead to filtration.

2.10 Effect of colloids on OPA properties
Colloid filtration during transport through water-conducting features may lead to flow porosity clogging.

2.11 Density-driven groundwater flow (thermal and saline)
Natural and radiogenic thermal gradients and salinity gradients may, in principle, influence groundwater flow in the host geology. However, due to the very low hydraulic conductivity of the host rock, these effects are considered negligible.

2.12 Fluid fluxes by coupled processes (Onsager)
See 6.1/2.08.

3. RADIONUCLIDE PROCESSES (OPA host rock)

3.01 Radionuclide migration pathways
Transport of radionuclides will most likely take place through the intact matrix, both upwards and downwards to local/regional aquifers. Transport in natural and / or repository-induced inhomogeneities is unlikely because of the efficient self-sealing capacity of the Opalinus Clay.

3.02 Elemental solubility
In the geosphere, the concentrations of most radioelements in the porewater are too low for solubility limits to be exceeded. Radioelements may form solid solutions with minerals.

3.03 Advective/dispersive/diffusive transport
Transport of dissolved radionuclides is driven by pressure gradients (advection) and concentration gradients (diffusion). Dispersion takes place due to heterogeneities, which can occur over a wide range of scales along the migration pathways.

3.04 Matrix diffusion
Radionuclides that are advected along discontinuities in the host rock may diffuse into stagnant porewater in the adjacent rock matrix. This retardation process is termed matrix diffusion.

3.05 Radionuclide sorption
Radioelements sorb on clay minerals, carbonates and other minerals in the Opalinus Clay via cation exchange or surface complexation mechanisms.

3.06 Dilution of radionuclides
Within the host rock itself, dilution is expected to be very limited due to the absence of any water-conducting features in the host rock in the potential siting area.

3.07 Colloid-facilitated transport
Radionuclide transport may be influenced by the presence of colloids if radionuclides are sorbed on or otherwise associated with colloids. In the absence of water-conducting features in the Opalinus Clay, colloid-facilitated transport is not relevant because colloids are immobile.

3.08 Gas-induced transport

Gas-induced transport is taken to include:

- the displacement by gas pressure of porewater containing dissolved radionuclides, and
- transport of radionuclides as volatile species with repository-generated gases.

3.10 Transport by coupled processes (Onsager)

See 6.1/2.08.

4. SPECIAL ISSUES (OPA host rock)

4.01 Exploratory boreholes

Exploratory boreholes drilled before or after the construction of the repository can lead to preferential radionuclide pathways, if they are not sealed properly.

4.03 Influx of oxidising water

Oxidising porewater may have an adverse effect on the retention of some radionuclides. In their oxidised form radionuclides may be better soluble and have lower sorption constants (examples: U, Tc). The pyrite in the host rock may be oxidised leading to higher sulphate concentrations in the porewater. The pH value may also decrease but Opalinus Clay is well buffered by its calcite content. The low hydraulic conductivity of Opalinus Clay and the strong buffering by pyrite and organic matter prevent oxidising water from entering from overlying or underlying rocks.

4.04 Intrusion of saline groundwater

An increase of salinity in the groundwater may decrease the sorption constant of some radioelements on the clay, in particular of those sorbing via the cation exchange mechanism (e.g. Cs). Such an increase of salinity in the future is ruled out based on the regional hydrogeological and hydrochemical situation.

4.05 Chemical plume from ILW

Geochemical reactions due to a high-pH plume from cement dissolution can lead to changes in porewater composition and in mineral composition (dissolution, secondary minerals) and can therefore change sorption and solubility properties for radioelements. Usually the porosity is also affected. The organic content of the ILW waste is too small to lead to an organic plume. The nitrate content of some waste types may be high enough to lead to a temporary plume, potentially leading to oxidising conditions (catalysed by microbes).

8. Tunnels & shafts

1. FEATURES AND CHARACTERISTICS (Tunnels & shafts)

1.01 Access tunnels, ramp and shaft

Access tunnels, ramp and ventilation shaft connect the various repository elements and require sealing after waste emplacement.

1.02 Tunnel, ramp and shaft seals

Seals are designed to hydraulically isolate different parts of the repository system. They are placed at various locations, including the ends of the waste emplacement tunnels.

1.03 Effective hydraulic properties

This includes hydraulic conductivity and flow porosity of backfill, seals and excavation disturbed zones.

1.04 Hydraulic gradient

The hydraulic gradients within the access tunnels, ramp and shaft depend on:

- the magnitude and direction of the regional hydraulic gradient,
- anomalous pore pressures within the Opalinus Clay,
- the distribution of hydraulic conductivity within and around the repository tunnels, including the access tunnels, ramp and shaft, and
- processes occurring within the repository that affect pore pressure, including tunnel convergence and heat and gas generation.

2. ENVIRONMENTAL PROCESSES (Tunnels & shafts)

2.01 Seal performance (during and after swelling)

The performance of seals is influenced by i) poor or incomplete emplacement of sealing material, ii) insufficient or heterogeneous swelling, iii) chemical degradation, iv) insufficient sealing of EDZ, v) damages induced by hydraulic overpressures (gas production, tunnel convergence) and geological events (neo-tectonic activity). Optionally, seals may be designed to be gas-permeable, in which case the effects of excessive pressure build-up due to gas generation would be mitigated.

2.02 Tunnel backfill performance

The tunnel backfill is designed to act as an efficient radionuclide transport barrier; this property can be compromised by i) open contact joints between backfill and EDZ, ii) chemical degradation and iii) channelling of flow in EDZ.

2.03 Drainage of water

Consolidation of Opalinus Clay may lead to water flowing along tunnels/ramp/shaft; relatively high flow velocities may occur due to drainage of many emplacement tunnels into a single access tunnel/ramp/shaft.

2.04 Preferential flow of water

Preferential flow may take place along the access tunnels/ramp/shaft, both into and out of the repository, depending on the performance of the seals.

2.05 Colloid transport

Colloids are expected to be immobile in the backfilled and sealed tunnels and shafts due to the fine pore structure of the backfill material and the seals (filtration). Colloids may, however, be transported through any connected void spaces along the interface with the host rock and also through any connected fractures in the EDZ. The distance the colloids are transported depends on their stability and on a range of chemical and physical processes that may lead to filtration.

2.06 Gas transport

This includes transport of free and dissolved gas via a number of different processes.

2.07 Fluid fluxes by coupled processes (Onsager)

See 6.1/2.08.

2.08 Density-driven groundwater flow (thermal and saline)

Natural and radiogenic thermal gradients and salinity gradients may influence groundwater flow in the access tunnels/ramp/shaft.

3. RADIONUCLIDE PROCESSES (Tunnels & shafts)

3.01 Radionuclide migration pathways

Potential radionuclide migration pathways include tunnels/ramp/shaft (including EDZ) and intersecting water-conducting features (if present).

3.02 Elemental solubility

In tunnels and shafts the concentrations of radioelements in the porewater are usually too low for solubility limits to be reached.

3.03 Advective/dispersive/diffusive transport

Transport of dissolved radionuclides is driven by pressure gradients (advection) and concentration gradients (diffusion). Dispersion takes place due to heterogeneities, which can occur over a wide range of scales along the migration pathways.

3.04 Matrix diffusion

Radionuclides that are advected along connected void spaces at the interface with the host rock or along connected fractures in the EDZ may also diffuse into stagnant porewater in the intact rock matrix. This retardation process is termed matrix diffusion.

3.05 Radionuclide sorption
Radioelements sorb on clay minerals contained in the bentonite of the bentonite-sand backfill and on cement minerals of the tunnel and shaft liners via cation exchange or surface complexation mechanisms.

3.06 Dilution of radionuclides
Radionuclide concentration may be lowered by mixing with inflowing water from overlying strata, from water-conducting features (if present) intersecting tunnels or shafts or by porewater squeezing by consolidation (see 8./2.03).

3.07 Colloid-facilitated transport
Radionuclide transport can be influenced if radionuclides are sorbed reversibly or irreversibly on colloids, or if intrinsic colloids (i.e. colloids consisting primarily of precipitated radionuclides) are formed.

3.08 Gas-induced transport (of RNs)
Gas-induced transport is taken to include:

- the displacement by gas pressure of porewater containing dissolved radionuclides, and
- transport of radionuclides as volatile species with repository-generated gases.

3.09 Convergence-induced transport
Radionuclide transport along tunnels/EDZ can be influenced by porewater displacement induced by tunnel convergence.

3.10 Transport by coupled processes (Onsager)
See 6.1/2.08.

4. SPECIAL ISSUES (Tunnels & shafts)

4.01 Oil or organic fluid spill
Oil spills in the tunnel could be a potential source of localised contamination. The effect could be a reduction in sorption of radionuclides in the backfill material and EDZ. It is expected that significant contamination or oil spills can be detected and remedied, so that only a very small fraction of the backfill material and EDZ would be affected. This is not considered any further (negligible effect).

4.02 Influx of oxidising water
Oxidising water flowing into the ramp or shaft from near the surface may have an adverse effect on radionuclide retention, due to oxidation of the host rock and backfill. Flow rates are expected to be low and pyrite and organic matter in the host rock will buffer the Eh. The pH value will not significantly decrease because Opalinus Clay and the backfill material are well buffered by their calcite content.

4.03 Intrusion of saline groundwater
An increase of salinity in the groundwater may decrease the sorption constant of some radioelements on the clay, in particular of those sorbing via the cation exchange mechanism (e.g. Cs). A very high salinity may also adversely affect the swelling property of bentonite seals and backfill. An intrusion of saline water from imperfectly sealed aquifers cannot be ruled out completely. However, the salinity of these groundwaters is similar to or lower than the salinity of the host rock pore water. Therefore no detrimental effects are expected.

4.04 Chemical plume from ILW
Geochemical reactions due to a high-pH plume from cement dissolution can lead to changes in porewater composition and in mineral composition (dissolution, secondary minerals) and can therefore change sorption and solubility properties for the radioelements. Usually the porosity is also affected. The organic content of the ILW waste is too small to lead to an organic plume. The nitrate content of some waste types may be high enough to lead to a temporary plume, potentially leading to oxidising conditions (catalysed by microbes). Since alkaline water may lead to cementation of bentonite seals and backfill, their swelling properties may be adversely affected. This is not considered any further because of the long flowpath (second order effect).

4.05 Alteration of backfill by liner of access tunnels
Geochemical reactions due to a high-pH plume from cement dissolution of the liner can lead to changes in porewater composition and in mineral composition (dissolution, secondary minerals) and can therefore change sorption and

solubility properties for the radioelements. Usually the porosity is also affected. Since alkaline water may lead to cementation of bentonite seals and backfill, their swelling properties may be adversely affected. Due to the small amount of cement used for the liners, the effects mentioned above are expected to be small.

9. Geology & hydrology

1. GEOLOGY

1.01 Lithostratigraphy

Stratigraphy in the region of interest (above crystalline basement): Muschelkalk and Keuper (both Triassic: limestones, dolomites, claystones, some evaporites); Lias, Dogger and Malm (all Jurassic: mainly claystones and limestones); Lower Freshwater Molasse (Tertiary: sandstones, marls); unconsolidated glacial and fluvial deposits (Quaternary).

1.02 Geological formation/history

The Opalinus Clay was deposited some 180 million years ago (Lower Dogger) by the sedimentation of fine clay particles in the Jurassic Sea. The Opalinus Clay was subjected to two successive stages of burial and uplift. It reached a maximum depth of ca. 1650 m below surface some 10 Ma b.p., i.e. at the time of Molasse sedimentation (clastic sediments from the uprising Alps). Since that time, ca. 1050 m of the overlying sediments were removed by uplift and erosion, which results in an average uplift rate of 0.1 mm/a over the last 10 Ma. Maximum temperatures in the Opalinus Clay were about 85 °C, i.e., the oil window has never been reached. Currently, an uplift/erosion rate of about 100 m per Ma is observed in the Zürcher Weinland.

1.03.1 Sedimentology, mineralogy etc. – overlying formations

Upper confining units (Wedelsandstein to Effinger Schichten): sequence of claystones with various silt/sand content and sandstones (minor part). Malm aquifer (Hornbuck-Schichten to Plattenkalke): limestones, some marly limestones. Tertiary (Lower Freshwater Molasse): sandstones and marls. Quaternary: unconsolidated sediments (gravel, sand, silt, peat).

1.03.3 Sedimentology, mineralogy etc. – underlying formations

Lower confining units (Lias and Keuper): sequence of claystones, sandstones, limestones and evaporitic rocks. Muschelkalk aquifer (Triassic): Limestones, dolomites.

1.05 Regional stress regime

An anisotropic compressive stress field is observed in the Zürcher Weinland, with a maximum horizontal stress of 23 MPa, a minimum horizontal stress of 15 MPa and a vertical stress of 16 MPa.

1.06 Faults, distribution and properties

The largest features found in the Zürcher Weinland are the Neuhausen fault (oriented NW-SE, maximum offset at Opalinus Clay level 40 m) and the Wildensbucher flexure (oriented W-E, maximum offset at Opalinus Clay level 20 m). Smaller scale features in the Opalinus Clay have been observed by the 3D seismic campaign but are found to be limited in extent with offsets smaller than a few m (no layout-determining faults).

1.07 Groundwater composition

Sorption properties not only depend on the radioelement and mineral composition but also on the porewater composition. The most relevant properties of the porewater are pH, inorganic carbon content (carbonate complexes), redox potential and salinity.

1.08 Natural resources

There are no indications of the presence of exploitable natural resources in the area of interest.

2. HYDROGEOLOGIC MODEL(S)

2.01 Hydrogeological units

Lithological units with rather uniform hydraulic properties: Quaternary, Tertiary, Malm aquifer, Malm-Dogger marls, Wedelsandstein, host rock (Opalinus Clay + Murchisonae Beds), argillaceous Lias, Arietenkalk, Lias-Keuper claystones, Sandsteinkeuper, Gipskeuper + Lettenkohle, Muschelkalk aquifer.

2.02 Effective hydraulic properties

The effective hydraulic properties include the hydraulic conductivity, the flow porosity, the lateral extent and connectivity of local aquifers.

2.03 Recharge/discharge zones

Groundwater flow modelling suggests that, for present conditions, discharge occurs predominantly

- into the Quaternary gravel along the Rhine south of the Rhine Falls (relevant for radionuclide release from the Opalinus Clay to the overlying Malm aquifer), and
- into the Quaternary gravel near the confluence of the Aare into the Rhine (relevant for radionuclide release from the Opalinus Clay to the underlying Muschelkalk aquifer).

2.04 Hydraulic gradient

The magnitude and direction of the hydraulic gradient in minor aquifers or water-conducting layers (Wedelsandstein, Sandsteinkeuper, Arietenkalk) and regional aquifers (Malm, Muschelkalk) influences radionuclide transport in these units.

2.05 Groundwater flowpaths

Groundwater flowpaths include the minor and regional aquifers above and below the Opalinus Clay up to the point of their exfiltration areas (biosphere model area).

2.06 Density-driven groundwater flow (thermal and saline)

Natural and radiogenic thermal gradients and salinity gradients may influence groundwater flow in the host geology.

3. RADIONUCLIDE MIGRATION (Geology & hydrology)

3.01 Radionuclide migration pathways

Potential advective radionuclide transport pathways from the Opalinus Clay to the exfiltration areas include:

- Regional aquifers (Malm, Muschelkalk),
- Minor aquifers (if laterally connected),
- Along non-sealed boreholes,
- Along access tunnels/ramp/shaft.

3.02 Dilution of radionuclides

Radionuclide concentration may be lowered by mixing with freshwater in regional aquifers (Malm and Muschelkalk), minor aquifers and surface water.

3.03 Sorption/retardation

The advective transport of radionuclides along the pathways identified in 9./3.01 is retarded by chemical processes which include cation exchange and surface complexation on clay minerals, carbonates and other minerals and are collectively termed "sorption" processes. Advective transport along fractures would also be retarded by matrix diffusion.

10. Biosphere

1. FEATURES AND CHARACTERISTICS (Biosphere)

1.01 Topography and geomorphology

This included the relief and shape of the surface environment and its evolution, landform (e.g. plains, hills, valleys) and the effects of river and glacial erosion thereon.

1.02 Geosphere-biosphere interface

This is the interface between the geosphere and the biosphere domains in a decoupled model. For northern Switzerland release into a biosphere aquifer is assumed; alternatives include release into a well, directly into a river, directly into soil, and into a spring located at a valley side.

1.03 Soils

The soil is the medium which forms the land surface and in which crops grow. Many different factors interact to determine soil type; e.g. geology, climate, vegetation, land-use, relief. Different soil types have characteristic horizons and properties. The top soil layer in agricultural areas is often relatively well mixed (uniform) up to the ploughing depth and is the zone with the highest density of crop roots.

1.04 Aquifers

Biosphere (local) aquifers are water-bearing features near the land surface with fast exchange between precipitation (infiltration) and exfiltration into surface water bodies, wells or springs.

1.05 Surface water bodies

Surface water bodies include lakes, rivers, streams and springs. The major surface water bodies in northern Switzerland are the rivers Rhine and Aare and side rivers. Under present-day conditions the rivers interact with the biosphere aquifers.

1.06 Atmosphere

The atmosphere is that part of the biosphere above the terrestrial and aquatic media (soil, surface water). Radionuclides may enter the atmosphere as gases (volatile radionuclides), aerosols or dust either because they have been transported from the geosphere in this form or they are generated within the biosphere.

1.07 Animals

Generally, all animals used for food production are considered (within agricultural, natural or semi-natural systems). For northern Switzerland cows (milk and meat), chicken (eggs) and fish are considered.

1.08 Vegetation

Plants and crops in agricultural, natural and semi-natural environments. For northern Switzerland agriculturally produced grain, green vegetables, root crops and fodder for cattle are considered.

1.09 Climate

The climate and its evolution is an important factor in estimating dose to exposed individuals.

1.10 Present-day biosphere

The biosphere relevant to the proposed repository in the Opalinus Clay of the Zürcher Weinland is that of the surface environment of the upper Rhine and Aare valleys.

1.11 Agricultural practices

The agricultural practices of a region depend on many interrelated factors including climate, geology, topography, human lifestyle and economics.

1.12 Natural and semi-natural environments

If intensive agricultural production ceases and there is no industrialisation or urbanisation, a natural or semi-natural environment may develop. Examples of such environments include meadows, moorland, woodlands. In these environments wild crops may be gathered and wild game hunted as food sources.

1.13 Hunter/gathering lifestyle

Hunter/gathering communities obtain their dietary requirements from the land by gathering those crops that are naturally available and hunting the wild game. These communities tend to be nomadic following the game and hence covering large areas. The population density is therefore very low. Communities that combine hunter/gathering activities with agriculture may also be considered.

2. ENVIRONMENTAL PROCESSES (Biosphere)

2.01 Exfiltration to a biosphere aquifer

Groundwater flow modelling suggests that, for present-day conditions, discharge potentially carrying radionuclides from the repository may occur

- into the Quaternary gravel along the Rhine south of the Rhine Falls for release of radionuclides from the Opalinus Clay to the overlying Malm aquifer,

- into the Quaternary gravel along the Rhine further downstream for the case of lateral transport in the Wedelsandstein,
- into the Klettgau aquifer for the case of lateral transport in the Sandsteinkeuper, and / or
- into the Quaternary gravel near the confluence of the Aare and the Rhine for release of radionuclides from the Opalinus Clay to the underlying Muschelkalk aquifer.

2.02 Exfiltration to surface waters
Exfiltrating contaminated groundwaters may flow directly into surface water systems.

2.03 Water resource exploitation
Contaminated groundwaters and surface waters may be abstracted for human use (e.g. drinking and bathing) and agricultural use (e.g. irrigation and animal watering).

2.04 Filtration
Abstracted groundwaters or surface waters are often filtered to remove suspended particulates and material which may have radionuclides associated with them prior to human consumption. This is not considered any further (filtration of drinking water is conservatively neglected – reserve FEP).

2.05 Surface water flow
The major surface water system in northern Switzerland consists of the Rhine, the Aare and their side rivers. The flow rate in the river affects the dilution of radionuclides as groundwater discharges from the alluvium into the stream channel, or directly into the stream channel. The flow rate is principally affected by climatic factors.

2.06 Groundwater flow
The flow rate in the biosphere aquifer depends on a number of factors, including interactions with surface water bodies (rivers, lakes), water flow from geosphere aquifers and infiltration. The groundwater flow rate affects the dilution of radionuclides released into the aquifer.

2.07 Erosion/deposition
Erosion/deposition (fluvial, glacial or glacio-fluvial) in the biosphere is affected by both geologic and climatic FEPs (see geologic and climatic domains). Erosion/deposition may influences the location, thickness and hydraulic properties of the biosphere aquifer and may significantly affect the radionuclide transport mechanisms in the biosphere over long timescales.

2.08 Sedimentation
Sedimentation of suspended sediment in rivers and lakes causes the build-up of bottom sediments in rivers and lakes. Sedimentation during flooding may cause (suspended) sediment build-up on soils.

2.09 Soil formation
River and lake sediments can accumulate to such an extent that the sediment turns into soil. Lowering the water level of a water body to expose sediments can have the same effect. Soil formation is also taking place continually due to weathering of parent and exposed rocks.

2.10 Interface effects
Within the biosphere and at the interface between the geosphere and the biosphere sharp changes in chemical and physical conditions may occur (e.g. boundary between reducing and oxidising environments, saline/freshwater boundaries, etc.). Radionuclide transport may be affected significantly as a consequence.

2.11 Precipitation
The amount of precipitation (rain and snow fall) depends on the climate. Precipitation may transport solutes as it flows downwards through soils or escapes as run-off.

2.12 Evapotranspiration
Evapotranspiration causes solutes to move upwards in the soil layers. It depends strongly on the climate.

2.13 Capillary rise
Capillary rise is a process by which solutes may move upwards through the soil profile from the water table (in the aquifer), under the following conditions: (1) evapotranspiration exceeds precipitation; (2) the storage capacity of the

soil is insufficient to match evapotranspiration minus precipitation; (3) the soil texture is sufficiently fine for capillaries to be filled with water; (4) the water table is sufficiently near to the soil surface for the existence of continuous capillary water between aquifer and surface.

2.14 Percolation

Percolation is the process of solute transport downwards in the soil profile. When precipitation exceeds evapotranspiration, taking account of the water storage capacity, solutes will move down the soil profile towards the aquifer.

2.15 Irrigation

Crops may be irrigated to ensure agricultural production.

2.16 Surface run-off

Precipitation which does not infiltrate the soil, but moves across the surface directly into a surface water body, e.g. a river, is called surface run-off. It may be an important cause of erosion.

2.17 Bioturbation

Fauna in the soil, e.g. earthworms, can redistribute material (and sorbed radionuclides) between different horizons and result in a homogenisation of the soil layers. This process can operate significantly faster than other mixing processes, e.g. diffusion.

2.18 Suspended sediment transport

Radionuclides may sorb on suspended sediments or colloids. This may influence overall radionuclide transport.

2.19 Earthworks (human actions, dredging, etc.)

Human actions may result in significant movement of solid material from one part of the biosphere to another. For example, earthworks, dam construction, dredging of sediments from lakes and rivers.

2.20 Ploughing

The top layer of agricultural soil is ploughed annually which results in a mixing of this layer.

2.21 Exfiltration to spring

Deep groundwater may exfiltrate to a spring.

3. RADIONUCLIDE MIGRATION PROCESSES (Biosphere)

3.01 Radionuclide accumulation in sediments

Radionuclides can accumulate in river sediments by the physico-chemical interaction of dissolved radionuclides with the sediments. Deposition of previously contaminated sediments may lead to further accumulation.

3.02 Radionuclide accumulation in soils

Radionuclide accumulation in soils may occur as a result of the physico-chemical interaction of dissolved radionuclides with the soil. Different sources of such radionuclides include contaminated groundwater, contaminated irrigation water and contaminated lateral inflow. Radionuclide accumulation in soils may also occur due to the deposition of contaminated particulates. Other possible sources are dredged sediments and atmospheric deposition.

3.03 Radionuclide transport as solute

Dissolved radionuclides will be transported with the water.

3.04 Radionuclide transport with solid material

Radionuclides may be transported in the form of suspended, contaminated sediment (with radionuclides sorbed onto the sedimentary particles) or sorbed onto suspended particles or colloids.

3.05 Radionuclide sorption

The physico-chemical interaction of dissolved radionuclides with soils and sediment is termed sorption. This interaction is affected by chemical and physical conditions.

3.06 Speciation and solubility

Radionuclides may be present in different dissolved forms (speciation), which will affect their sorption properties. Concentrations are too low for solubility to be considered.

3.07 Diffusion/dispersion

Diffusive transport is driven by concentration gradients; dispersion is caused by varying solute flow velocities.

3.08 Radionuclide volatilisation/aerosol/dust production

Radionuclides may be transported directly from the geosphere to the biosphere as gases and/or aerosols (if they are volatile). Radionuclide volatilisation and/or aerosol production may also occur within the biosphere.

3.09 Dilution of radionuclides in surface water (aquifer, river, lake etc.)

In general, radionuclides transported with groundwater from the geosphere become diluted in the larger water bodies of the biosphere that they enter.

3.11 Uptake by crops

Radionuclides may be incorporated in, or deposited on, crops as a result of root uptake, irrigation, and particulate deposition onto the vegetation surface. These crops may be used as fodder for livestock and/or consumed directly by humans.

3.12 Uptake by livestock

Livestock may accumulate radionuclides as a result of ingestion of water, fodder and soil/sediment and inhalation of aerosols and particulates. Depending on the livestock, they may be used for human consumption directly, or their produce, e.g. milk, eggs may be consumed.

3.13 Uptake in fish

Radionuclides can accumulate in fish via ingestion and gill epithelial filtration. Fish may be consumed by man.

3.15 Foodchain equilibrium

Instantaneous equilibrium with the radionuclide concentrations in the media from which the contamination is derived is assumed for the foodchains and the atmosphere.

3.16 Secular equilibrium of radionuclide chains

Doses arising from short-lived daughters are implicitly incorporated in the dose factors by assuming secular equilibrium of parent and short-lived daughters in water and foodstuffs etc.

3.17 Removal mechanisms

There are a variety of physical and biological processes which lead to the transport of radionuclides out of the local environmental media. Such processes include the harvesting of crops; slaughter of animals; removal of soil due to erosion (wind, water); movement of sediment and water downstream.

3.18 Food and water processing

Processing of raw materials, food and water may influence radionuclide concentrations (increase or decrease possible).

3.2 RADIONUCLIDE EXPOSURE PROCESSES (Biosphere)

3.21 Exposure pathways

Possible exposure pathways to man include ingestion of food and water, inhalation and external irradiation. The significance of exposure pathways depends on the radionuclide of concern, the time of release and the point of exfiltration to the biosphere.

3.22 Age groups

The variability in physiology and metabolism will lead to differences in diet, water intake, inhalation rates and dose coefficients.

3.23 Dosimetry

The radiation dose is calculated from exposure rates (external, inhalation and ingestion) and dose conversion factors. The latter are based upon radiation type, human metabolism, metabolism of the element of concern in the human body, and the duration of exposure.

3.24 Human lifestyle

Human lifestyle will influence the critical exposure pathways to man. Lifestyles and human food requirements are assumed to remain relatively constant which provides a basis for quantitative estimates of radionuclide uptake.

3.25 Contaminated products (non-food)

Various products can be derived from contaminated material, including clothing (e.g. hides, leather, linen, wool); furniture (e.g. wood, metal); building materials (e.g. stone, clay for bricks, wood, dung); fuel (e.g. peat).

3.26 Consumption of uncontaminated products

Consumption of uncontaminated agricultural produce imported from outside the region affected by the repository will result in lower doses of the population living in the area.

3.27 Radon pathways and doses

Rn-222 is the daughter of Ra-226 and is a noble gas with a half-life of about 4 days; it decays through a series of very short-lived radionuclides (half-life 27 minutes or less) to Pb-210 (half-life 21 years). In the biosphere, if Ra-226 is present in soil, then a fraction of the Rn-222 produced (a few to a few tens of %) would escape to the atmosphere and be rapidly dispersed. However, there is a potential for significant doses from Rn-222 and its short-lived daughters in conditions of limited air circulation. In buildings, Rn-222 emanating from Ra-226 in underlying soil and rocks, or in building materials, may accumulate.

4. SPECIAL ISSUES (Biosphere)

4.01 Future biosphere conditions

The actual conditions that will exist in the biosphere in the far future cannot be known. Climate change is predictable to a certain extent and in general terms, but the patterns of future human behaviour and local resource use that determine doses received by individuals or populations living in the future are largely unpredictable.

4.02 Non-radiological effects

E.g. chemotoxic compounds released from the waste repository. This is not considered any further.

4.03 Radiological effects on non-human biota

It is assumed that if man is protected, non-human biota will also be protected. This is not considered any further.

11. Geological processes & events

2. ENVIRONMENTAL PROCESSES (Geological P&E)

2.01 Regional vertical movements

The Alpine orogeny and the up-doming of the Black Forest region will lead to gradual uplift of the Zürcher Weinland. As a result of the up-doming of the Black Forest, erosion of the overburden will occur; the possibility also exists of a southward shift of the river Rhine, with consequent changes of the groundwater flowpath and hydraulic gradients.

2.02 Regional horizontal movements

Based on the anticipated tectonic evolution in northern Switzerland, it is expected that there will be some horizontal movements. A GPS survey has been set up in order to quantify these movements.

2.03 Compaction of Opalinus Clay

There are indications that the porewater in the Opalinus Clay is overpressured, even though the overlying sediments are currently being eroded. This possibly reflects an earlier period of rapid loading, during which concomitant drainage and compaction of the Opalinus Clay was only partially achieved. As a result of future glaciations, an episodic increase of the total load on the Opalinus Clay is expected. Overpressures can be dissipated either by porewater drainage and compaction of the clay or by reduction of the total load imposed (erosion of overburden).

2.04 Erosion

Erosion is a process which will cause significant changes in the topography and thus also in the local and regional hydrology and the biosphere. The extent of erosion depends on uplift, climate, human activities and lithology in the region of interest. Erosion may also lead to decompaction of Opalinus Clay, which eventually may affect Opalinus Clay properties.

2.05 Evolution of regional stress regime

In northern Switzerland, the maximal horizontal stress is oriented NW-SE in the western part and N-S in the eastern part. Generally, a compressive stress field is observed in the Zürcher Weinland, with the maximal horizontal stress being approximately 30 % larger than both the minimal horizontal stress and the vertical stress. During the next one million years, no significant changes in the regional stress field are expected.

2.06 Neo-tectonic activity

The main fault systems in the Zürcher Weinland are the Neuhausen fault and the Wildensbucher flexure. Based on the present knowledge, no significant neo-tectonic activity is expected in the Zürcher Weinland within the next one million years, but a minor reactivation of the Neuhausen fault cannot be ruled out completely.

2.07 Self-sealing of faults

For an overburden larger than 200 m, discontinuities in the Opalinus Clay are hydraulically not distinguishable from the undisturbed rock matrix. This is explained by the fact that self-sealing processes (swelling of clay minerals, creep) are very effective within the Opalinus Clay. Based on the present knowledge, it can be expected that naturally and artificially created fractures within the host rock will be effectively self-sealed.

2.08 Seismic activity

In the next one million years, only minor to moderate seismic activity is expected in the Zürcher Weinland. Once the repository is closed, no mechanical damage to the barrier system due to seismic activity is expected. In addition, future earthquakes to be expected in Switzerland will not have magnitudes that cause serious damage to a deep underground tunnel system during the operational phase. Significant earthquake-induced fluid migration can be excluded in the case of Opalinus Clay because of its low hydraulic conductivity and self-sealing capacity.

2.09 Magmatic activity (volcanism and plutonism)

If magmatic activity occurred at or near the repository site, it could have a major impact on the system performance. A direct intrusion or extrusion of magma is extremely unlikely in northern Switzerland during the next ten million years. Magmatic activity is not, therefore, considered further.

2.10 Hydrothermal activity

Indications of hydrothermal activity (in a broad sense) in northern Switzerland are the thermal springs (< 50 ˚C) to the north and south of the Permo-Carboniferous Trough (e.g. at Zurzach). The pattern of hydrothermal activity in the region is not expected to change significantly over the next million years. It is also expected that significant geothermal anomalies can be avoided by repository siting. Future extraction of deep groundwater in the vicinity of the repository, used for hydrothermal purposes or as mineral water for drinking, can not be ruled out.

12. Climatic processes & events

1. FEATURES AND CHARACTERISTICS (Climatic P&E)

1.01 Present-day climatic conditions

The present-day climate of northern Switzerland is described as cool temperate and is representative of interglacial conditions.

1.02 Future climatic conditions

Palaeo-evidence indicates that climatic conditions in northern Switzerland have varied greatly in the past. Over the last one million years the climate has cycled between Pleistocene glacials and interglacials with the last glaciation ending around 10 000 years ago. Climatic change is to be expected over the timescales relevant to repository performance as a result of natural processes and human activities e.g. greenhouse effect.

1.03 Glacial climate

A glacial climate marks the height of a glaciation and is characterised by the pressure of an ice mass on the landscape, e.g. ice sheet, valley glacier. Significant erosion may be associated with glacial action (abrasion, over deepening of valleys) and glacial meltwaters. Assuming the climate continues to cycle between glacial and interglacial periods, the next glacial climate is expected to begin in about 50 000 years from now.

1.04 Permafrost

As the climate cools, air temperatures will fall substantially below freezing point for much of the year. If these conditions are sustained, then permafrost (permanently frozen ground) may develop, with depths up to a few hundred metres in currently temperate regions. If summer temperatures remain above freezing point, then a zone of seasonally unfrozen ground will remain above the permafrost layer. Significant groundwater discharge zones and the courses of major rivers and lakes are liable to remain open ("taliks").

1.05 Tundra climate

A tundra climate is characterised by low mean annual temperatures which result in a short growing season. The soil is often waterlogged because of a layer of permafrost (permanently frozen ground) which melts to some extent depending on the summer temperatures. The vegetation is dominated by herbaceous plants, lichens and mosses and the cover may be incomplete. Such conditions occur around an ice sheet in those areas which are not glaciated. At present such a climate is typical of subarctic regions in the northern hemisphere.

1.06 Dry climate

A dry climate is characterised by high mean annual temperatures, low mean annual rainfall with episodic precipitation, very low effective moisture, through-flowing major rivers (e.g. Rhine) with reduced run-off. Tributaries have intermittent run-off and shift with a poorly defined tributary network. Vegetation cover is sparse.

1.07 Warm seasonal humid climate

A warm seasonal humid climate is significantly warmer than the present-day climate exhibiting a marked seasonal variation between warm, humid, rainy seasons and cool, dry seasons (monsoon-like). Evapotranspiration is moderate and there is moderate effective moisture. Streams are perennial with marked seasonal variations in run-off. Vegetation cover is moderate. Such a climate may occur if the greenhouse effect becomes dominant and glaciation cycling ends.

1.08 Warm equable humid climate

This climate state is characterised by high temperatures, precipitation and moderate evapotranspiration with minor seasonal variations. This results in high effective moisture, and a well defined network of perennial streams with high run-off. Vegetation cover is complete and continuous. Such a climate may occur if the greenhouse effect becomes dominant and glaciation cycling ends.

1.09 Seasonality of climate

The degree of seasonality of climate is one factor that distinguishes the warm, seasonal humid climate from the warm, equable humid climate. In the seasonal climate, marked seasonal variations in precipitation, run-off, erosion and groundwater recharge occur. In the equable climate more uniform conditions prevail. These alternative climate states have been identified as potential alternative biosphere scenarios if it is assumed that the present warm period is not just another interglacial episode but signals the end of the Quaternary ice ages (either due to greenhouse effects or natural causes). Significant for biosphere conditions.

2. ENVIRONMENTAL PROCESSES (Climatic P&E)

2.02 Fluvial erosion/sedimentation

Fluvial erosion/sedimentation is affected by climatic factors as well as geological factors – the impact on domains depends on the net amount of fluvial erosion/sedimentation caused by these two controlling sets of factors. The amount of fluvial erosion/sedimentation affects flowpath lengths and location, and characteristics of the biosphere.

2.03 Glacial erosion/sedimentation

Erosion and sedimentation caused by glacial ice results in overdeepening of valleys, scouring of upland areas, deposition of glacial moraines and modification of stream channel networks. The net effect is similar to that of fluvial erosion/sedimentation – potential shortening of flowpaths and modifications of the biosphere. During the course of the next million years, glacial erosion in northern Switzerland could lead to further deepening of existing valleys/channels.

2.04 Glacial-fluvial erosion/sedimentation

Erosion and deposition by glacial meltwaters occurs early in interglacial intervals. The process potentially results in downcutting of river channels, deposition of alluvium and glacial outwash and formation of stream terraces. The net effect is similar to other forms of erosion/sedimentation – potential shortening of flowpaths and modifications of the biosphere.

2.05 Ice sheet effects (loading, melt water recharge)

As the ice sheet advances then recharge may occur from the meltwater formed under pressure at the base of the ice sheet. In the case of a static or retreating ice sheet, this water may escape as sub-glacial rivers between the ice and ground. However, in the case of an advancing ice sheet a sealed front may be created by the ice sheet advancing over permafrost so that the meltwater is forced downward into the underlying rock. Glacial loading/unloading of Opalinus Clay may occur due to advancing/retreating ice sheets.

2.06 Effective moisture (recharge)

Effective moisture is the net flux of water available for groundwater recharge, taking into account precipitation, evaporation, transpiration and run-off, and incorporating such climatic factors as temperature, cloud cover and humidity. A climatic change that results in an increase in effective moisture also results in increased recharge and groundwater flux.

2.09 Greenhouse effect

Global changes in climate and sea levels caused by a warming of the atmosphere may occur due to the release of gases, principally carbon dioxide but also methane, through human activities (e.g. burning of fossil fuels, forest clearance, industrial processes). If this effect becomes dominant, markedly warmer climate states are predicted for northern Switzerland. The general consensus is that anthropogenically induced climate forcing may delay but not prevent a next ice age.

13. Future human actions

1. FUTURE HUMAN ACTIONS (Future human actions)

1.01 Exploratory drilling

Exploratory boreholes may be sunk in the repository region in search of natural resources, e.g. water, minerals, oil, gas, or to identify geothermal sources or geological formations suitable for disposal of liquid wastes by injection. Exploratory boreholes are considered more likely when the knowledge of the repository and of the presence or absence of resource materials is lost. Boreholes may intersect the repository or pass by closely, perturbing the groundwater flowpaths. Boreholes may affect repository gas. Indirect effects (e.g. deformation of repository structures and geological strata) are possible.

1.02 Resource exploitation through boreholes

Boreholes may be drilled to exploit, e.g., gas, oil, geothermal energy, or water.

1.03 Mining activities

Mining or excavation activities carried out in the vicinity of the repository (with or without knowledge of the repository). Mining activities are expected to be preceded by drilling of boreholes.

1.04 Geothermal exploitation

The potential exists for extraction of geothermal energy in northern Switzerland, although the potential siting area in the Zürcher Weinland is less suitable for this purpose than other areas for a number of reasons. See also 13./1.01.

1.05 Deep groundwater extraction

Deep groundwaters may be abstracted for human use (e.g. mineral water, household/drinking water, spas) and agricultural use (e.g. irrigation, animal watering). The deep groundwaters could be exploited as a water source for human consumption especially in the future if, for example, nearer surface groundwater and surface waters had become polluted. In this case the water would most probably be tested for various natural and artificial contaminants before use.

1.06 Liquid waste injection

Technologies exist for the disposal of liquid waste deep underground in suitable geologic formations by injection. The receiving formation should have adequate porosity and permeability for storage and movement of the waste, but should be confined by strata with low permeabilities to isolate it. Opalinus Clay would not be considered suitable for such disposal because of its very low permeability. However, rocks above or below the Opalinus Clay might be considered suitable. The boreholes for the injection might influence the repository, however, the effects of liquid injection are considered to be insignificant.

2.01 Human-induced climate change

Human activities could affect the change of climate either globally or in a region. These climate changes would have no direct effects on the repository, however, they might change recharge of aquifers and surface hydrology. The long-term impact of anthropogenic greenhouse gases on climate is unclear. However, the general consensus is that anthropogenically induced climate forcing may delay, but not prevent a next ice age.

2.02 Surface pollution (soils, rivers)

Human activity unrelated to the repository may result in pollution of the groundwaters, surface waters, soils and sediments. In the case of groundwater pollution, contaminants could change the geochemistry of the geosphere aquifers, and hence affect the speciation, solubility and sorption of radionuclides released from the repository and the host rock. This is not considered any further.

2.03 Groundwater pollution

Human activity unrelated to the repository may result in pollution of the groundwaters, surface waters, soils and sediments. In the case of groundwater pollution, contaminants could change the geochemistry of the geosphere aquifers, and hence affect the speciation, solubility and sorption of radionuclides released from the repository and the host rock. This is not considered any further.

2.04 Water management schemes

Water is a valuable resource and water management schemes provide increased control over its distribution and availability in the environment through construction of dams, barrages, canalisation, pumping stations and pipelines. These schemes may affect the groundwater infiltration, groundwater transport, groundwater exfiltration points, its dilution and its subsequent movement through the environment. It is assumed that such schemes would not significantly alter the critical exposure pathways.

3.01 Intentional intrusion

Deliberate interference with, or intrusion into, a repository after closure. This is not considered any further.

3.02 Inadvertent intrusion

If the knowledge of the existence, location and/or nature of the repository is lost, humans might drill or mine into the strata in which the repository is located.

3.03 Repository records, markers

Records of a repository location will be placed in local and national libraries and archives. Repository markers have been considered especially in the USA but are of uncertain efficacy. This is not considered any further.

3.04 Planning restrictions

It is expected that human intrusion into a repository would be prevented (or its likelihood reduced) by planning restrictions. However, HSK/KSA Protection Objective 3 requires that long-term repository safety must not rely on administrative measures. Therefore, such planning restrictions are not considered any further.

3.05 Abandonment of repository

The repository may be abandoned after the waste is emplaced but before final sealing occurs.

Appendix 3: Results of the audit of the OPA FEP List

A3.1 Introduction

As described in Section 3.3 of the main text, the OPA FEP List is audited against two international FEP Lists suitable for this purpose:

- The NEA International FEP List (NEA 2000a), which provides a comprehensive list of relatively generically described FEPs intended as either a starting point, or audit tool, for assessment of any solid radioactive waste disposal system;
- the NEA FEPCAT List related to natural clays (Mazurek et al. 2002), which is based on a compilation and review of observations and results from experimental studies on natural clay samples in the laboratory and in underground testing facilities.

A3.2 Audit against the NEA International FEP List

In the audit process each OPA FEP is "mapped", i.e. an electronic connection is made, to one or more FEPs of the NEA International FEP (IFEP) list of which it provided a project-specific example or is most closely related. Thus a set of binary connections between OPA FEPs and IFEPs are made.

Tab. A3.2.1 shows the compilation of connections between IFEPs and OPA FEPs arranged in the order of the IFEP List. This allows the distribution of the OPA FEPs against the IFEP List to be analysed.

The results of the audit are discussed in Section 3.3.

Tab. A3.2.1: The mapping of OPA FEPs to the NEA International FEP (IFEP) List

The IFEPs in the category "ASSESSMENT BASIS" (see Tab. A1.1.1) are not mapped because they are considered outside the FEP management process.

IFEP no.	IFEP name OPA FEP category no. & name		OPA FEP no. & name within category	
1.1.01	**Site investigation**			
	7	OPA host rock	4.01	Exploratory boreholes
1.1.02	**Excavation / construction**			
	1	Siting and design	3.08	Effect of construction and operation phase
	5.3	ILW backfill and liner	1.04	Effects of initial (operating) conditions
	5.3	ILW backfill and liner	4.02	Poor emplacement
	8	Tunnels & shafts	4.02	Influx of oxidising water
1.1.03	**Emplacement of wastes and backfilling**			
	4.1	Bentonite buffer	1.01	Bentonite emplacement and composition
	4.1	Bentonite buffer	1.01.2	Corrosion of structural elements in HCB blocks
	5.3	ILW backfill and liner	1.02	Backfill emplacement
	5.3	ILW backfill and liner	1.04	Effects of initial (operating) conditions
1.1.04	**Closure and repository sealing**			
	1	Siting and design	3.07	Closure and sealing
1.1.05	**Records and markers, repository**			
	13	Future human actions	3.03	Repository records, markers
1.1.06	**Waste allocation**			
	0	Assessment basis	1.01	Waste form and packaging
	1	Siting and design	2.04	ILW reference inventory
	2.3	ILW waste and packages	1.08	Organics
1.1.07	**Repository design**			
	1	Siting and design	1.01	Repository site
	1	Siting and design	3.01	Repository layout/constraints
	1	Siting and design	3.02	SF / HLW emplacement panels – reference design
	1	Siting and design	3.03	SF / HLW emplacement panels – alternative design
	1	Siting and design	3.04	ILW emplacement tunnels – reference design
	1	Siting and design	3.05	ILW emplacement tunnels – alternative design
	2.1	Vitrified HLW	1.05	Heat output (RN decay heat)
	2.2	Spent fuel	1.05	Heat output (RN decay heat)
	2.3	ILW waste and packages	4.01	Effects of co-disposal with SF / HLW
	3.1	Canister	1.01	Cast steel canister (vitrified waste)
	3.1	Canister	1.01.1	Cast steel canister (spent fuel)
	3.1	Canister	1.01.2	Cu / steel canister (spent fuel)
	3.1	Canister	1.02	Canister thickness / specification (vitrified waste canister)
	3.1	Canister	1.02.1	Canister thickness / specification (cast steel SF canister)
	3.1	Canister	1.02.2	Canister thickness / specification (Cu / steel canister)
	3.1	Canister	2.11.1	Canister breaching – reference (Cu / steel canister – SF)
	4.1	Bentonite buffer	1.01	Bentonite emplacement and composition
	4.1	Bentonite buffer	2.1	Interaction with cement components
	7	OPA host rock	1.09	Heterogeneity within OPA
	8	Tunnels & shafts	1.01	Access tunnels, ramp and shaft
1.1.08	**Quality control**			
	2.1	Vitrified HLW	4.01	Quality control
	2.1	Vitrified HLW	4.03	Fuel mixing at reprocessing – variant specification
	2.2	Spent fuel	4.01	Quality control of the inventory of fuel in a canister
	2.2	Spent fuel	4.05	Extreme temperature of cladding
	2.3	ILW waste and packages	4.00.1	Quality control
	3.1	Canister	4.01	Quality control
	4.1	Bentonite buffer	4.01	Quality Control
	5.3	ILW backfill and liner	4.01	Quality control

1.1.09	**Schedule and planning**			
	1	Siting and design	3.06	Operations / excavation / emplacement schedule
1.1.10	**Administrative control, repository site**			
	13	Future human actions	3.03	Repository records, markers
	13	Future human actions	3.04	Planning restrictions
1.1.11	**Monitoring of repository**			
	0	Assessment basis	1.6	Appropriate repository design and closure
	1	Siting and design	3.1	Monitoring (part of design basis)
1.1.12	**Accidents and unplanned events**			
	2.1	Vitrified HLW	4.02	Handling accidents
	2.2	Spent fuel	4.02	Handling accidents
	2.3	ILW waste and packages	4.00.2	Handling accidents
	8	Tunnels & shafts	4.01	Oil or organic fluid spill
	13	Future human actions	3.05	Abandonment of repository
1.1.13	**Retrievability**			
	1	Siting and design	3.09	Retrievability
1.2.01	**Tectonic movements and orogeny**			
	1	Siting and design	1.02	Host rock / geology – regional character
	9	OPA-SA	1.02	Geological formation / history
	9	OPA-SA	1.06	Faults, distribution and properties
	11	Geological P&E	2.01	Regional vertical movements
	11	Geological P&E	2.02	Regional horizontal movements
	11	Geological P&E	2.05	Evolution of regional stress regime
	11	Geological P&E	2.06	Neo-tectonic activity
1.2.02	**Deformation, elastic, plastic or brittle**			
	11	Geological P&E	2.03	Compaction of Opalinus Clay
1.2.03	**Seismicity**			
	5.3	ILW backfill and liner	4.04	Seismic effects
	11	Geological P&E	2.08	Seismic activity
1.2.04	**Volcanic and magmatic activity**			
	11	Geological P&E	2.09	Magmatic activity (volcanism and plutonism)
1.2.05	**Metamorphism**			
		No mapped OPA FEPs		
1.2.06	**Hydrothermal activity**			
	11	Geological P&E	2.1	Hydrothermal activity
1.2.07	**Erosion and sedimentation**			
	9	OPA-SA	1.02	Geological formation / history
	11	Geological P&E	2.03	Compaction of Opalinus Clay
	11	Geological P&E	2.04	Erosion
	12	Climatic P&E	1.03	Glacial climate
	12	Climatic P&E	2.02	Fluvial erosion / sedimentation
	12	Climatic P&E	2.03	Glacial erosion / sedimentation
	12	Climatic P&E	2.04	Glacial-fluvial erosion / sedimentation
1.2.08	**Diagenesis**			
		No mapped OPA FEPs		
1.2.09	**Salt diapirism and dissolution**			
		No mapped OPA FEPs		
1.2.10	**Hydrological / hydrogeological response to geological changes**			
	11	Geological P&E	2.01	Regional vertical movements
1.3.01	**Climate change, global**			
	12	Climatic P&E	2.09	Greenhouse effect
1.3.02	**Climate change, regional and local**			
	0	Assessment basis	1.04	Local and regional surface environment
	10	Biosphere	1.09	Climate
	10	Biosphere	2.07	Erosion / deposition
	10	Biosphere	4.01	Future biosphere conditions
	12	Climatic P&E	1.01	Present-day climatic conditions
	12	Climatic P&E	1.02	Future climatic conditions
	12	Climatic P&E	1.03	Glacial climate
1.3.03	**Sea level change**			
		No mapped OPA FEPs		

1.3.04	**Periglacial effects**			
	12	Climatic P&E	1.04	Permafrost
	12	Climatic P&E	1.05	Tundra climate
1.3.05	**Glacial and ice sheet effects, local**			
	6.1	Bentonite – HR interface	2.06	Compaction of EDZ
	6.3	Concrete – HR interface	2.06	Compaction of EDZ
	10	Biosphere	1.05	Surface water bodies
	11	Geological P&E	2.03	Compaction of Opalinus Clay
	12	Climatic P&E	1.03	Glacial climate
	12	Climatic P&E	2.03	Glacial erosion / sedimentation
	12	Climatic P&E	2.04	Glacial-fluvial erosion / sedimentation
	12	Climatic P&E	2.05	Ice sheet effects (loading, melt water recharge)
1.3.06	**Warm climate effects (tropical and desert)**			
	12	Climatic P&E	1.06	Dry climate
	12	Climatic P&E	1.07	Warm seasonal humid climate
	12	Climatic P&E	1.08	Warm equable humid climate
	12	Climatic P&E	1.09	Seasonality of climate
1.3.07	**Hydrological / hydrogeological response to climate changes**			
	10	Biosphere	2.05	Surface water flow
	12	Climatic P&E	1.04	Permafrost
	12	Climatic P&E	1.06	Dry climate
	12	Climatic P&E	1.07	Warm seasonal humid climate
	12	Climatic P&E	1.08	Warm equable humid climate
	12	Climatic P&E	2.05	Ice sheet effects (loading, melt water recharge)
	12	Climatic P&E	2.06	Effective moisture (recharge)
1.3.08	**Ecological response to climate changes**			
	12	Climatic P&E	1.05	Tundra climate
	12	Climatic P&E	1.07	Warm seasonal humid climate
	12	Climatic P&E	1.08	Warm equable humid climate
1.3.09	**Human response to climate changes**			
	10	Biosphere	1.13	Hunter/gathering lifestyle
1.4.01	**Human influences on climate**			
	12	Climatic P&E	1.08	Warm equable humid climate
	12	Climatic P&E	2.09	Greenhouse effect
	13	Future human actions	2.01	Human-induced climate change
1.4.02	**Motivation and knowledge issues (inadvertent / deliberate human actions)**			
	13	Future human actions	3.01	Intentional intrusion
	13	Future human actions	3.02	Inadvertent intrusion
1.4.03	**Un-intrusive site investigation**			
		No mapped OPA FEPs		
1.4.04	**Drilling activities (human intrusion)**			
	13	Future human actions	1.01	Exploratory drilling
	13	Future human actions	1.02	Resource exploitation through boreholes
	13	Future human actions	1.04	Geothermal exploitation
	13	Future human actions	1.05	Deep groundwater extraction
	13	Future human actions	1.06	Liquid waste injection
1.4.05	**Mining and other underground activities (human intrusion)**			
	13	Future human actions	1.03	Mining activities
1.4.06	**Surface environment, human activities**			
	10	Biosphere	1.12	Natural and semi-natural environments
	10	Biosphere	2.19	Earthworks (human actions, dredging, etc.)
	10	Biosphere	4.01	Future biosphere conditions
	13	Future human actions	2.02	Surface pollution (soils, rivers)
	13	Future human actions	2.03	Groundwater pollution
1.4.07	**Water management (wells, reservoirs, dams)**			
	10	Biosphere	1.02	Geosphere – biosphere interface
	10	Biosphere	2.03	Water resource exploitation
	10	Biosphere	2.04	Filtration
	10	Biosphere	2.19	Earthworks (human actions, dredging, etc.)
	11	Geological P&E	2.1	Hydrothermal activity
	13	Future human actions	1.05	Deep groundwater extraction
	13	Future human actions	2.04	Water management schemes

1.4.08 Social and institutional developments

No mapped OPA FEPs

1.4.09 Technological developments

No mapped OPA FEPs

1.4.10 Remedial actions

No mapped OPA FEPs

1.4.11 Explosions and crashes

No mapped OPA FEPs

1.5.01 Meteorite impact

No mapped OPA FEPs

1.5.02 Species evolution

No mapped OPA FEPs

1.5.03 Miscellaneous and FEPs of uncertain relevance

No mapped OPA FEPs

2.1.01 Inventory, radionuclide and other material

1	Siting and design	2.02	HLW reference inventory
1	Siting and design	2.03	SF reference inventory
1	Siting and design	2.04	ILW reference inventory
2.1	Vitrified HLW	4.03	Fuel mixing at reprocessing – variant specification
2.2	Spent fuel	1.01	Typical waste unit – spent fuel
2.2	Spent fuel	1.03	Zircaloy cladding and structural elements
2.2	Spent fuel	1.06	Distribution of radionuclides in spent fuel
2.2	Spent fuel	1.07	Chemically toxic contaminants
2.2	Spent fuel	4.01	Quality control of the inventory of fuel in a canister
2.3	ILW waste and packages	1.01	ILW waste types
2.3	ILW waste and packages	1.01.1	ILW waste groups
2.3	ILW waste and packages	1.03	Chemically toxic components

2.1.02 Waste form materials and characteristics

2.1	Vitrified HLW	1.01	Typical waste unit – vitrified HLW
2.1	Vitrified HLW	1.02	Waste form (glass)
2.1	Vitrified HLW	1.03	Stainless steel fabrication flask (incl.void space)
2.1	Vitrified HLW	1.04	Glass cracking and surface area
2.1	Vitrified HLW	2.01	Glass recrystallisation
2.1	Vitrified HLW	2.02	Phase separation
2.1	Vitrified HLW	2.03	Temperature evolution
2.1	Vitrified HLW	2.04	Radiation damage
2.1	Vitrified HLW	2.05	Glass alteration / dissolution
2.1	Vitrified HLW	2.06	Rate of glass dissolution
2.1	Vitrified HLW	2.07	Congruent dissolution
2.1	Vitrified HLW	2.08	Selective leaching
2.1	Vitrified HLW	2.1	Precipitation of silicates / silica gel and glass dissolution
2.1	Vitrified HLW	3.06	Solute transport resistance
2.1	Vitrified HLW	4.01	Quality control
2.1	Vitrified HLW	4.02	Handling accidents
2.2	Spent fuel	1.01	Typical waste unit – spent fuel
2.2	Spent fuel	1.02	UO2 fuel matrix
2.2	Spent fuel	1.03	Zircaloy cladding and structural elements
2.2	Spent fuel	1.06	Distribution of radionuclides in spent fuel
2.2	Spent fuel	1.08	Fuel cracking and surface area
2.2	Spent fuel	2.05	Cladding integrity
2.2	Spent fuel	4.03	Damaged fuel
2.2	Spent fuel	4.05	Extreme temperature of cladding
2.2	Spent fuel	4.06	Cracking of fuel pellets by He buildup
2.3	ILW waste and packages	1.04	Compacted waste (hulls / ends)
2.3	ILW waste and packages	1.05	Conditioning materials
2.3	ILW waste and packages	1.06	Waste packages
2.3	ILW waste and packages	1.06.2	Voids
5.3	ILW backfill and liner	1.05.5	Organics

2.1.03 Container materials and characteristics

2.1	Vitrified HLW	1.03	Stainless steel fabrication flask (incl.void space)
2.2	Spent fuel	1.04	Filling material and voids
2.2	Spent fuel	2.04	Zircaloy corrosion

	2.2	Spent fuel	4.03	Damaged fuel
	2.3	ILW waste and packages	1.02	Typical waste package / emplacement containers
	2.3	ILW waste and packages	1.04	Compacted waste (hulls / ends)
	2.3	ILW waste and packages	1.06	Waste packages
	3.1	Canister	1.01	Cast steel canister (vitrified waste)
	3.1	Canister	1.01.1	Cast steel canister (spent fuel)
	3.1	Canister	1.01.2	Cu/steel canister (spent fuel)
	3.1	Canister	1.02	Canister thickness / specification (vitrified waste canister)
	3.1	Canister	1.02.1	Canister thickness / specification (cast steel SF canister)
	3.1	Canister	1.02.2	Canister thickness / specification (Cu / steel canister)
	3.1	Canister	2.01.1	Canister temperature evolution (spent fuel)
	3.1	Canister	2.02	Corrosion on wetting (steel canister – vitrified waste or SF)
	3.1	Canister	2.02.1	Corrosion on wetting (Cu / steel canister)
	3.1	Canister	2.06	Localised corrosion (steel canister – vitrified waste/ SF)
	3.1	Canister	2.06.1	Localised corrosion (Cu / steel canister – spent fuel)
	3.1	Canister	2.07	Total extent of corrosion (steel canister – vitrified waste / SF)
	3.1	Canister	2.07.1	Total corrosion (steel canister – spent fuel)
	3.1	Canister	2.07.2	Total corrosion (Cu / steel canister – spent fuel)
	3.1	Canister	2.08	Stress corrosion cracking (steel canister – vitrified waste / SF)
	3.1	Canister	2.09	Other canister degradation processes (steel and Cu / steel)
	3.1	Canister	2.1	Radiation shielding
	3.1	Canister	2.11	Canister breaching – reference (steel canister)
	3.1	Canister	2.11.1	Canister breaching – reference (Cu / steel canister)
	3.1	Canister	2.16	Corrosion products – physical effects (steel canister)
	3.1	Canister	4.01	Quality control
	3.1	Canister	4.02	Mis-sealed canister
2.1.04	**Buffer / backfill materials and characteristics**			
	2.3	ILW waste and packages	1.06.1	Backfill
	4.1	Bentonite buffer	1.01	Bentonite emplacement and composition
	4.1	Bentonite buffer	1.01.1	Pellets
	4.1	Bentonite buffer	1.01.2	Corrosion of structural elements in HCB blocks
	4.1	Bentonite buffer	1.02	Bentonite swelling pressure
	4.1	Bentonite buffer	1.03	Bentonite plasticity
	4.1	Bentonite buffer	1.05	Bentonite porewater chemistry
	4.1	Bentonite buffer	1.07	Inhomogeneities (properties and evolution)
	4.1	Bentonite buffer	2.02	Bentonite saturation
	4.1	Bentonite buffer	2.03	Mineralogical alteration – short term
	4.1	Bentonite buffer	2.04	Mineralogical alteration – long term
	4.1	Bentonite buffer	2.09	Bentonite erosion
	4.1	Bentonite buffer	3.04	Colloid filtration
	4.1	Bentonite buffer	4.01	Quality Control
	4.1	Bentonite buffer	4.03	Organics / contamination of bentonite
	5.3	ILW backfill and liner	1.01	Backfill material
	5.3	ILW backfill and liner	1.03	Hydraulic and gas permeability
	5.3	ILW backfill and liner	1.05.4	Cement additives
	5.3	ILW backfill and liner	1.08	Voids in backfill / liner
	5.3	ILW backfill and liner	2.1	Pore-structure heterogeneity and evolution
	5.3	ILW backfill and liner	4.04	Seismic effects
	8	Tunnels & shafts	4.03	Intrusion of saline groundwater
	8	Tunnels & shafts	4.05	Alteration of backfill by liner of access tunnels
2.1.05	**Seals, cavern / tunnel / shaft**			
	1	Siting and design	3.07	Closure and sealing
	5.3	ILW backfill and liner	1.05.3	Seals
	6.1	Bentonite – HR interface	3.01	Radionuclide migration pathways
	6.3	Concrete – HR interface	3.01	Radionuclide migration pathways
	8	Tunnels & shafts	1.01	Access tunnels, ramp and shaft

	8	Tunnels & shafts	1.02	Tunnel, ramp and shaft seals
	8	Tunnels & shafts	2.01	Seal performance (during and after swelling)
	8	Tunnels & shafts	2.02	Tunnel backfill performance
	8	Tunnels & shafts	2.04	Preferential flow of water
	8	Tunnels & shafts	2.05	Colloid transport
	8	Tunnels & shafts	2.06	Gas transport
	8	Tunnels & shafts	2.07	Fluid fluxes by coupled processes (Onsager)
	8	Tunnels & shafts	2.08	Density-driven groundwater flow (thermal and saline)
2.1.06	**Other engineered features materials and characteristics**			
	5.3	ILW backfill and liner	1.05	Lining material
	5.3	ILW backfill and liner	1.05.1	Drainage system
	5.3	ILW backfill and liner	1.06	Rock bolts
	5.3	ILW backfill and liner	1.07	Joints and cracks in backfill / liner
	5.3	ILW backfill and liner	4.03	Interfaces, cracks and slabbing
	5.3	ILW backfill and liner	4.04	Seismic effects
	6.1	Bentonite – HR interface	1.01.1	Rock bolts and mesh
	6.1	Bentonite – HR interface	1.02	Open contact joints
	6.3	Concrete – HR interface	1.01.1	Rock bolts
2.1.07	**Mechanical processes and conditions (in wastes and EBS)**			
	2.2	Spent fuel	2.05	Cladding integrity
	2.2	Spent fuel	2.1	Fuel alteration product formation
	2.2	Spent fuel	2.11.1	Volume expansion
	2.3	ILW waste and packages	1.06.2	Voids
	2.3	ILW waste and packages	2.01.1	Host rock creep: effect on near field (tunnel convergence)
	2.3	ILW waste and packages	2.06.1	Volume expansion
	2.3	ILW waste and packages	2.07	Degradation / failure of disposal containers and emplacement packages
	3.1	Canister	1.02.1	Canister thickness / specification (cast steel SF canister)
	3.1	Canister	1.02.2	Canister thickness / specification (Cu / steel canister)
	3.1	Canister	2.16	Corrosion products – physical effects (steel canister)
	3.1	Canister	2.16.1	Corrosion products – physical effects (Cu / steel canister)
	3.1	Canister	3.01	Residual canister – crack / hole effects (vitrified waste)
	3.1	Canister	3.02	Residual canister – crack / hole effects (spent fuel)
	4.1	Bentonite buffer	1.02	Bentonite swelling pressure
	4.1	Bentonite buffer	1.03	Bentonite plasticity
	4.1	Bentonite buffer	2.05	Bentonite cementation
	4.1	Bentonite buffer	2.06	Bentonite – iron interactions (canister)
	4.1	Bentonite buffer	2.11	Gas fracturing
	5.3	ILW backfill and liner	2.03	Mechanical strength / stability
	5.3	ILW backfill and liner	2.04	Mechanical evolution and external forces
	5.3	ILW backfill and liner	2.04.1	Effect of liner on rock creep
	5.3	ILW backfill and liner	2.07	Degradation due to reaction with sulphate
	5.3	ILW backfill and liner	2.09	Volume expanding materials
	5.3	ILW backfill and liner	2.10.1	Compaction
	5.3	ILW backfill and liner	2.11	Formation of advective paths
	6.1	Bentonite – HR interface	2.03	Geomechanical processes
	6.1	Bentonite – HR interface	2.04	Effect of bentonite swelling on EDZ
	6.1	Bentonite – HR interface	2.05	Swelling of clay-minerals in EDZ
	8	Tunnels & shafts	2.01	Seal performance (during and after swelling)
	8	Tunnels & shafts	2.03	Drainage of water
2.1.08	**Hydraulic / hydrogeological processes and conditions (in wastes and EBS)**			
	2.1	Vitrified HLW	3.06	Solute transport resistance
	2.2	Spent fuel	2.02	Saturation / water content
	2.3	ILW waste and packages	2.01	Resaturation of repository
	2.3	ILW waste and packages	2.04.2	Degradation of backfill
	4.1	Bentonite buffer	1.02	Bentonite swelling pressure
	4.1	Bentonite buffer	1.04	Buffer permeability
	4.1	Bentonite buffer	2.02	Bentonite saturation
	4.1	Bentonite buffer	2.05	Bentonite cementation
	4.1	Bentonite buffer	2.06	Bentonite – iron interactions (canister)

	4.1	Bentonite buffer	2.09	Bentonite erosion
	5.3	ILW backfill and liner	1.03	Hydraulic and gas permeability
	5.3	ILW backfill and liner	1.07	Joints and cracks in backfill / liner
	5.3	ILW backfill and liner	2.05	Saturation / hydraulic evolution
	5.3	ILW backfill and liner	2.11	Formation of advective paths
	5.3	ILW backfill and liner	2.15	2-phase flow
	5.3	ILW backfill and liner	3.02	Flow and advective transport through backfill & liner
	5.3	ILW backfill and liner	4.03	Interfaces, cracks and slabbing
	6.1	Bentonite – HR interface	1.02	Open contact joints
	6.1	Bentonite – HR interface	1.03	Effective hydraulic properties
	6.1	Bentonite – HR interface	1.08	Hydraulic gradient
	6.1	Bentonite – HR interface	1.09	Water flow at bentonite – host rock interface
	6.1	Bentonite – HR interface	2.01	Desaturation / resaturation of EDZ
	6.1	Bentonite – HR interface	2.06	Compaction of EDZ
	6.1	Bentonite – HR interface	3.08	Convergence-induced transport
	6.3	Concrete – HR interface	3.08	Convergence-induced transport
	8	Tunnels & shafts	1.02	Tunnel, ramp and shaft seals
	8	Tunnels & shafts	1.03	Effective hydraulic properties
	8	Tunnels & shafts	1.04	Hydraulic gradient
	8	Tunnels & shafts	2.01	Seal performance (during and after swelling)
	8	Tunnels & shafts	2.03	Drainage of water
	8	Tunnels & shafts	2.04	Preferential flow of water
	8	Tunnels & shafts	2.08	Density-driven groundwater flow (thermal and saline)
	8	Tunnels & shafts	3.06	Dilution of radionuclides
2.1.09	**Chemical / geochemical processes and conditions (in wastes and EBS)**			
	2.1	Vitrified HLW	2.05	Glass alteration / dissolution
	2.1	Vitrified HLW	2.06	Rate of glass dissolution
	2.1	Vitrified HLW	2.09	Iron corrosion products / clay minerals and glass dissolution
	2.1	Vitrified HLW	2.1	Precipitation of silicates / silica gel and glass dissolution
	2.1	Vitrified HLW	3.02	Elemental (and RN) solubility limits
	2.1	Vitrified HLW	3.03	Co-precipitates / solid solutions (of RNs)
	2.1	Vitrified HLW	3.05	Colloids formation (RN bearing)
	2.2	Spent fuel	2.03.1	Fuel matrix dissolution
	2.2	Spent fuel	2.04	Zircaloy corrosion
	2.2	Spent fuel	2.06	Galvanic effects
	2.2	Spent fuel	2.07	Alpha-radiolysis – production of oxidants and hydrogen, and recombination
	2.2	Spent fuel	2.1	Fuel alteration product formation
	2.2	Spent fuel	2.11	Canister corrosion products
	2.2	Spent fuel	3.03	Radionuclide elemental solubilities and precipitation
	2.2	Spent fuel	3.05	Co-precipitation of radionuclides
	2.3	ILW waste and packages	1.08	Organics
	2.3	ILW waste and packages	2.03	Chemical evolution – pH
	2.3	ILW waste and packages	2.04	Chemical evolution – redox
	2.3	ILW waste and packages	2.04.1	Galvanic effects
	2.3	ILW waste and packages	2.04.2	Degradation of backfill
	2.3	ILW waste and packages	2.05	Radiolysis
	2.3	ILW waste and packages	2.09	Effect of temperature on chemical processes
	2.3	ILW waste and packages	2.1	Microbial activity and effects
	2.3	ILW waste and packages	4.01	Effects of co-disposal with SF / HLW
	3.1	Canister	2.02	Corrosion on wetting (steel canister)
	3.1	Canister	2.02.1	Corrosion on wetting (Cu / steel canister)
	3.1	Canister	2.03	Oxic uniform corrosion (steel canister)
	3.1	Canister	2.03.1	Oxic uniform corrosion (Cu / steel canister)
	3.1	Canister	2.04	Microbially-mediated corrosion (steel canister)
	3.1	Canister	2.04.1	Microbially-mediated corrosion (Cu / steel canister)
	3.1	Canister	2.05	Anoxic corrosion (steel canister)
	3.1	Canister	2.05.1	Anoxic corrosion (Cu / steel canister)
	3.1	Canister	2.06.1	Localised corrosion (Cu / steel)
	4.1	Bentonite buffer	1.05	Bentonite porewater chemistry
	4.1	Bentonite buffer	2.03	Mineralogical alteration – short term
	4.1	Bentonite buffer	2.04	Mineralogical alteration – long term

	4.1	Bentonite buffer	2.05	Bentonite cementation
	4.1	Bentonite buffer	2.06	Bentonite – iron interactions (canister)
	4.1	Bentonite buffer	2.06.1	Bentonite – Cu interactions
	4.1	Bentonite buffer	2.1	Interaction with cement components
	4.1	Bentonite buffer	3.03	Elemental solubility / precipitation
	5.3	ILW backfill and liner	2.01	Cement hydration
	5.3	ILW backfill and liner	2.06	Chemical degradation
	5.3	ILW backfill and liner	2.07	Degradation due to reaction with sulphate
	5.3	ILW backfill and liner	2.08	Degradation due to reaction with magnesium
	5.3	ILW backfill and liner	2.08.1	Degradation due to other reactions
	5.3	ILW backfill and liner	2.09	Volume expanding materials
	5.3	ILW backfill and liner	2.13	Colloid formation through backfill degradation
	6.1	Bentonite – HR interface	2.05	Swelling of clay-minerals in EDZ
	8	Tunnels & shafts	2.07	Fluid fluxes by coupled processes (Onsager)
	8	Tunnels & shafts	4.02	Influx of oxidising water
	8	Tunnels & shafts	4.03	Intrusion of saline groundwater
	8	Tunnels & shafts	4.04	Chemical plume from ILW
	8	Tunnels & shafts	4.05	Alteration of backfill by liner of access tunnels
2.1.10	**Biological / biochemical processes and conditions (in wastes and EBS)**			
	2.1	Vitrified HLW	2.13	Microbial activity and effects
	2.2	Spent fuel	2.12	Microbial activity and effects
	2.3	ILW waste and packages	1.09	Extraneous materials (including microbes / biological materials)
	2.3	ILW waste and packages	2.1	Microbial activity and effects
	3.1	Canister	2.04	Microbially-mediated corrosion (steel canister)
	3.1	Canister	2.04.1	Microbially-mediated corrosion (Cu / steel canister)
	4.1	Bentonite buffer	2.07	Microbial activity
	5.3	ILW backfill and liner	2.12	Biofilms
	6.1	Bentonite – HR interface	1.07	Microbial activity
2.1.11	**Thermal processes and conditions (in wastes and EBS)**			
	2.1	Vitrified HLW	1.04	Glass cracking and surface area
	2.1	Vitrified HLW	1.05	Heat output (RN decay heat)
	2.1	Vitrified HLW	2.03	Temperature evolution
	2.2	Spent fuel	1.05	Heat output (RN decay heat)
	2.2	Spent fuel	2.01	Temperature evolution
	2.3	ILW waste and packages	1.07	Heat output
	2.3	ILW waste and packages	2.02	Temperature evolution of near field
	2.3	ILW waste and packages	2.09	Effect of temperature on chemical processes
	3.1	Canister	2.01	Canister temperature evolution (vitrified waste / spent fuel)
	3.1	Canister	2.01.1	Canister temperature evolution (spent fuel)
	3.1	Canister	2.06	Localised corrosion (steel canister)
	3.1	Canister	2.09	Other canister degradation processes (steel and Cu / steel canisters)
	4.1	Bentonite buffer	2.01	Thermal evolution
	5.3	ILW backfill and liner	2.01	Cement hydration
	5.3	ILW backfill and liner	2.02	Temperature evolution
	5.3	ILW backfill and liner	2.14	Effects of temperature gradients
	6.1	Bentonite – HR interface	2.02	Thermal evolution
	6.3	Concrete – HR interface	2.02	Thermal evolution
	8	Tunnels & shafts	2.08	Density-driven groundwater flow (thermal and saline)
2.1.12	**Gas sources and effects (in wastes and EBS)**			
	2.2	Spent fuel	2.03	Gas generation in intact canister
	2.2	Spent fuel	2.07	Alpha-radiolysis – production of oxidants and hydrogen, and recombination
	2.2	Spent fuel	2.13	Zircaloy corrosion / hydrogen gas production
	2.3	ILW waste and packages	2.06	Corrosion of metallic components
	2.3	ILW waste and packages	2.08	Gas generation and transport
	3.1	Canister	2.05	Anoxic corrosion (steel canister)
	3.1	Canister	2.14	Hydrogen production (steel canister)
	3.1	Canister	2.14.1	Hydrogen production (Cu / steel canister)
	3.1	Canister	2.15	Effect of hydrogen on corrosion
	4.1	Bentonite buffer	1.06	Gas permeability

	4.1	Bentonite buffer	2.11	Gas fracturing
	5.3	ILW backfill and liner	1.03	Hydraulic and gas permeability
	5.3	ILW backfill and liner	1.06	Rock bolts
	5.3	ILW backfill and liner	2.15	2-phase flow
	6.1	Bentonite – HR interface	1.01.1	Rock bolts and mesh
	6.1	Bentonite – HR interface	2.01	Desaturation / resaturation of EDZ
	6.1	Bentonite – HR interface	2.09	Gas transport
	6.3	Concrete – HR interface	2.09	Gas transport
	8	Tunnels & shafts	2.01	Seal performance (during and after swelling)
2.1.13	**Radiation effects (in wastes and EBS)**			
	2.1	Vitrified HLW	2.04	Radiation damage
	2.1	Vitrified HLW	2.11	Radiolysis
	2.1	Vitrified HLW	2.12	He gas production
	2.2	Spent fuel	2.07	Alpha-radiolysis – production of oxidants and hydrogen, and recombination
	2.2	Spent fuel	2.08	Beta / gamma-radiolysis effects
	2.2	Spent fuel	2.09	Radiation damage
	2.2	Spent fuel	2.1	Fuel alteration product formation
	2.2	Spent fuel	4.06	Cracking of fuel pellets by He buildup
	2.3	ILW waste and packages	2.05	Radiolysis
	2.3	ILW waste and packages	2.05.1	Alpha-radiolysis
	2.3	ILW waste and packages	2.05.2	Beta / gamma-radiolysis
	3.1	Canister	2.09	Other canister degradation processes (steel and Cu / steel canisters)
	3.1	Canister	2.1	Radiation shielding
	4.1	Bentonite buffer	2.08	Radiolysis
	6.3	Concrete – HR interface	2.01	Desaturation / resaturation of EDZ
	8	Tunnels & shafts	2.07	Fluid fluxes by coupled processes (Onsager)
2.1.14	**Nuclear criticality**			
	2.1	Vitrified HLW	4.04	Nuclear criticality
	2.2	Spent fuel	1.04	Filling material and voids
	2.2	Spent fuel	4.04	Nuclear criticality
	2.3	ILW waste and packages	4.03	Nuclear criticality
2.2.01	**Excavation disturbed zone, host rock**			
	6.1	Bentonite – HR interface	1.01	Excavation-disturbed zone (EDZ)
	6.1	Bentonite – HR interface	1.03	Effective hydraulic properties
	6.1	Bentonite – HR interface	2.01	Desaturation / resaturation of EDZ
	6.1	Bentonite – HR interface	2.02	Thermal evolution
	6.1	Bentonite – HR interface	2.06	Compaction of EDZ
	6.1	Bentonite – HR interface	2.1	Colloid production and effects
	6.3	Concrete – HR interface	1.01	Excavation-disturbed zone (EDZ)
	6.3	Concrete – HR interface	1.03	Effective hydraulic properties
	6.3	Concrete – HR interface	1.04	Mineralogy
	6.3	Concrete – HR interface	1.05	Groundwater composition
	6.3	Concrete – HR interface	1.08	Hydraulic gradient
	6.3	Concrete – HR interface	1.09	Water flow at concrete – host rock interface
	6.3	Concrete – HR interface	2.01	Desaturation/resaturation of EDZ
	6.3	Concrete – HR interface	2.02	Thermal evolution
	6.3	Concrete – HR interface	2.03	Geomechanical processes
	6.3	Concrete – HR interface	2.05	Swelling of clay-minerals in EDZ
	6.3	Concrete – HR interface	2.06	Compaction of EDZ
	6.3	Concrete – HR interface	2.07	Geochemical alteration
	6.3	Concrete – HR interface	2.1	Colloid production and effects
	8	Tunnels & shafts	2.02	Tunnel backfill performance
2.2.02	**Host rock**			
	0	Assessment basis	1.03	Host geology
	1	Siting and design	1.03	Host rock / geology – at repository location
	7	OPA host rock	1.02	OPA matrix
	7	OPA host rock	1.03	Effective hydraulic properties
	7	OPA host rock	1.04	Mineralogy
	7	OPA host rock	1.05	Groundwater composition
	7	OPA host rock	1.07	Stress regime
	7	OPA host rock	1.08	Hydraulic gradient

	7	OPA host rock	1.09	Heterogeneity within OPA
	7	OPA host rock	1.1	Calcite veins
	7	OPA host rock	1.11	Overpressures
	7	OPA host rock	2.01	Thermal effects
	7	OPA host rock	2.03	Swelling of clay
	7	OPA host rock	2.04	Geochemical alteration
	7	OPA host rock	2.05	Microbial activity
	7	OPA host rock	2.06	Effects of gas on OPA
	7	OPA host rock	2.07	Groundwater flow
	7	OPA host rock	2.09	Colloid transport
	7	OPA host rock	2.1	Effect of colloids on OPA properties
	9	OPA-SA	1.02	Geological formation / history
	11	Geological P&E	2.07	Self-sealing of faults
2.2.03	**Geological units, other**			
	1	Siting and design	1.02	Host rock / geology – regional character
	1	Siting and design	1.03	Host rock / geology – at repository location
	7	OPA host rock	3.01	Radionuclide migration pathways
	9	OPA-SA	1.01	Lithostratigraphy
	9	OPA-SA	1.03.1	Sedimentology, mineralogy etc. – overlying formations
	9	OPA-SA	1.03.3	Sedimentology, mineralogy etc. – underlying formations
	9	OPA-SA	2.01	Hydrogeological units
	9	OPA-SA	2.04	Hydraulic gradient
2.2.04	**Discontinuities, large scale (in geosphere)**			
	7	OPA host rock	1.01	Discontinuities
	7	OPA host rock	1.09	Heterogeneity within OPA
	9	OPA-SA	1.06	Faults, distribution and properties
	11	Geological P&E	2.06	Neo-tectonic activity
2.2.05	**Contaminant transport path characteristics (in geosphere)**			
	7	OPA host rock	1.1	Calcite veins
	7	OPA host rock	3.01	Radionuclide migration pathways
	7	OPA host rock	3.03	Advective / dispersive / diffusive transport
	7	OPA host rock	3.04	Matrix diffusion
	7	OPA host rock	3.07	Colloid-facilitated transport
	7	OPA host rock	4.01	Exploratory boreholes
	8	Tunnels & shafts	3.01	Radionuclide migration pathways
	8	Tunnels & shafts	3.04	Matrix diffusion
	9	OPA-SA	3.01	Radionuclide migration pathways
	9	OPA-SA	3.02	Dilution of radionuclides
2.2.06	**Mechanical processes and conditions (in geosphere)**			
	4.1	Bentonite buffer	4.04	Canister sinking
	6.1	Bentonite – HR interface	2.06	Compaction of EDZ
	6.1	Bentonite – HR interface	3.08	Convergence-induced transport
	6.3	Concrete – HR interface	2.03	Geomechanical processes
	6.3	Concrete – HR interface	2.05	Swelling of clay-minerals in EDZ
	6.3	Concrete – HR interface	2.06	Compaction of EDZ
	6.3	Concrete – HR interface	3.08	Convergence-induced transport
	7	OPA host rock	1.07	Stress regime
	7	OPA host rock	2.03	Swelling of clay
	8	Tunnels & shafts	3.09	Convergence-induced transport
	9	OPA-SA	1.05	Regional stress regime
	11	Geological P&E	2.05	Evolution of regional stress regime
	11	Geological P&E	2.07	Self-sealing of faults
2.2.07	**Hydraulic / hydrogeological processes and conditions (in geosphere)**			
	1	Siting and design	3.08	Effect of construction and operation phase
	6.1	Bentonite – HR interface	2.08	Fluid and heat fluxes by coupled processes (Onsager)
	6.3	Concrete – HR interface	1.03	Effective hydraulic properties
	6.3	Concrete – HR interface	1.08	Hydraulic gradient
	6.3	Concrete – HR interface	1.09	Water flow at concrete – host rock interface
	6.3	Concrete – HR interface	2.01	Desaturation / resaturation of EDZ
	7	OPA host rock	1.08	Hydraulic gradient
	7	OPA host rock	1.1	Calcite veins
	7	OPA host rock	1.11	Overpressures

	7	OPA host rock	2.07	Groundwater flow
	7	OPA host rock	2.1	Effect of colloids on OPA properties
	7	OPA host rock	2.11	Density-driven groundwater flow (thermal and saline)
	7	OPA host rock	2.12	Fluid fluxes by coupled processes (Onsager)
	7	OPA host rock	3.01	Radionuclide migration pathways
	7	OPA host rock	3.03	Advective / dispersive / diffusive transport
	8	Tunnels & shafts	3.03	Advective / dispersive / diffusive transport
	9	OPA-SA	2.01	Hydrogeological units
	9	OPA-SA	2.02	Effective hydraulic properties
	9	OPA-SA	2.03	Recharge / discharge zones
	9	OPA-SA	2.04	Hydraulic gradient
	9	OPA-SA	2.05	Groundwater flowpaths
	9	OPA-SA	2.06	Density-driven groundwater flow (thermal and saline)
	9	OPA-SA	3.01	Radionuclide migration pathways
	9	OPA-SA	3.02	Dilution of radionuclides
	10	Biosphere	1.1	Present-day biosphere
2.2.08	**Chemical / geochemical processes and conditions (in geosphere)**			
	1	Siting and design	3.08	Effect of construction and operation phase
	3.1	Canister	2.13	Chemical buffering (canister corrosion products)
	6.1	Bentonite – HR interface	2.07	Geochemical alteration
	6.1	Bentonite – HR interface	3.09	Transport by coupled processes (Onsager)
	6.3	Concrete – HR interface	1.04	Mineralogy
	6.3	Concrete – HR interface	1.05	Groundwater composition
	6.3	Concrete – HR interface	2.07	Geochemical alteration
	6.3	Concrete – HR interface	2.08	Fluid and heat fluxes by coupled processes (Onsager)
	6.3	Concrete – HR interface	3.09	Transport by coupled processes (Onsager)
	7	OPA host rock	1.05	Groundwater composition
	7	OPA host rock	1.06	Natural organics
	7	OPA host rock	2.04	Geochemical alteration
	7	OPA host rock	2.12	Fluid fluxes by coupled processes (Onsager)
	7	OPA host rock	3.02	Elemental solubility
	7	OPA host rock	3.1	Transport by coupled processes (Onsager)
	7	OPA host rock	4.03	Influx of oxidising water
	7	OPA host rock	4.04	Intrusion of saline groundwater
	7	OPA host rock	4.05	Chemical plume from ILW
	8	Tunnels & shafts	3.1	Transport by coupled processes (Onsager)
	8	Tunnels & shafts	4.02	Influx of oxidising water
	8	Tunnels & shafts	4.03	Intrusion of saline groundwater
	8	Tunnels & shafts	4.04	Chemical plume from ILW
2.2.09	**Biological / biochemical processes and conditions (in geosphere)**			
	6.3	Concrete – HR interface	1.07	Microbial activity
	7	OPA host rock	2.05	Microbial activity
2.2.10	**Thermal processes and conditions (in geosphere)**			
	6.1	Bentonite – HR interface	2.08	Fluid and heat fluxes by coupled processes (Onsager)
	6.1	Bentonite – HR interface	3.09	Transport by coupled processes (Onsager)
	6.3	Concrete – HR interface	2.08	Fluid and heat fluxes by coupled processes (Onsager)
	6.3	Concrete – HR interface	3.09	Transport by coupled processes (Onsager)
	7	OPA host rock	2.01	Thermal effects
	7	OPA host rock	2.12	Fluid fluxes by coupled processes (Onsager)
	7	OPA host rock	3.1	Transport by coupled processes (Onsager)
	8	Tunnels & shafts	3.1	Transport by coupled processes (Onsager)
2.2.11	**Gas sources and effects (in geosphere)**			
	6.1	Bentonite – HR interface	2.09	Gas transport
	7	OPA host rock	2.06	Effects of gas on OPA
	7	OPA host rock	2.08	Gas transport
	7	OPA host rock	3.08	Gas-induced transport
	8	Tunnels & shafts	3.08	Gas-induced transport (of RNs)
2.2.12	**Undetected features (in geosphere)**			
		No mapped OPA FEPs		

2.2.13	**Geological resources**			
	9	Geology & hydrology	1.08	Natural resources
	9	OPA-SA	2.01	Hydrogeological units
	13	Future human actions	1.01	Exploratory drilling
	13	Future human actions	1.02	Resource exploitation through boreholes
	13	Future human actions	1.03	Mining activities
2.3.01	**Topography and morphology**			
	0	Assessment basis	1.04	Local and regional surface environment
	1	Siting and design	1.04	Surface environment
	10	Biosphere	1.01	Topography and geomorphology
	12	Climatic P&E	2.03	Glacial erosion / sedimentation
2.3.02	**Soil and sediment**			
	10	Biosphere	1.03	Soils
	10	Biosphere	2.09	Soil formation
	10	Biosphere	2.13	Capillary rise
	10	Biosphere	2.14	Percolation
	10	Biosphere	2.17	Bioturbation
	10	Biosphere	2.2	Ploughing
2.3.03	**Aquifers and water-bearing features, near surface**			
	9	OPA-SA	2.03	Recharge / discharge zones
	10	Biosphere	1.02	Geosphere – biosphere interface
	10	Biosphere	1.04	Aquifers
	10	Biosphere	2.01	Exfiltration to a biosphere aquifer
	10	Biosphere	2.06	Groundwater flow
2.3.04	**Lakes, rivers, streams and springs**			
	1	Siting and design	1.04	Surface environment
	9	OPA-SA	2.03	Recharge / discharge zones
	10	Biosphere	1.02	Geosphere – biosphere interface
	10	Biosphere	1.04	Aquifers
	10	Biosphere	1.05	Surface water bodies
	10	Biosphere	2.02	Exfiltration to surface waters
	10	Biosphere	2.05	Surface water flow
	10	Biosphere	2.06	Groundwater flow
	10	Biosphere	2.08	Sedimentation
	10	Features and characteristics	2.21	Exfiltration to spring
2.3.05	**Coastal features**			
		No mapped OPA FEPs		
2.3.06	**Marine features**			
		No mapped OPA FEPs		
2.3.07	**Atmosphere**			
	10	Biosphere	1.06	Atmosphere
2.3.08	**Vegetation**			
	10	Biosphere	1.08	Vegetation
2.3.09	**Animal populations**			
	10	Biosphere	1.07	Animals
2.3.10	**Meteorology**			
	10	Biosphere	1.09	Climate
	10	Biosphere	2.11	Precipitation
	12	Climatic P&E	1.09	Seasonality of climate
2.3.11	**Hydrological regime and water balance (near-surface)**			
	10	Biosphere	2.01	Exfiltration to a biosphere aquifer
	10	Biosphere	2.02	Exfiltration to surface waters
	10	Biosphere	2.03	Water resource exploitation
	10	Biosphere	2.06	Groundwater flow
	10	Biosphere	2.11	Precipitation
	10	Biosphere	2.12	Evapotranspiration
	10	Biosphere	2.13	Capillary rise
	10	Biosphere	2.14	Percolation
	10	Biosphere	2.15	Irrigation
	10	Biosphere	2.16	Surface run-off

2.3.12	**Erosion and deposition**			
	10	Biosphere	2.07	Erosion / deposition
	10	Biosphere	2.08	Sedimentation
	10	Biosphere	2.09	Soil formation
	10	Biosphere	2.16	Surface run-off
2.3.13	**Ecological / biological / microbial systems**			
	10	Biosphere	2.17	Bioturbation
2.4.01	**Human characteristics (physiology, metabolism)**			
	10	Biosphere	3.22	Age groups
2.4.02	**Adults, children, infants and other variations**			
	10	Biosphere	3.22	Age groups
2.4.03	**Diet and fluid intake**			
	10	Biosphere	3.11	Uptake by crops
	10	Biosphere	3.12	Uptake by livestock
	10	Biosphere	3.13	Uptake in fish
	10	Biosphere	3.22	Age groups
	10	Biosphere	3.24	Human lifestyle
2.4.04	**Habits (non-diet-related behaviour)**			
	10	Biosphere	3.24	Human lifestyle
2.4.05	**Community characteristics**			
	10	Biosphere	1.13	Hunter / gathering lifestyle
2.4.06	**Food and water processing and preparation**			
	10	Biosphere	2.04	Filtration
	10	Biosphere	3.18	Food and water processing
	10	Biosphere	3.26	Consumption of uncontaminated products
2.4.07	**Dwellings**			
	10	Biosphere	3.25	Contaminated products (non-food)
	10	Biosphere	3.27	Radon pathways and doses
2.4.08	**Wild and natural land and water use**			
	10	Biosphere	1.12	Natural and semi-natural environments
2.4.09	**Rural and agricultural land and water use (incl. fisheries)**			
	10	Biosphere	1.03	Soils
	10	Biosphere	1.07	Animals
	10	Biosphere	1.08	Vegetation
	10	Biosphere	1.11	Agricultural practices
	10	Biosphere	2.12	Evapotranspiration
	10	Biosphere	2.15	Irrigation
	10	Biosphere	2.2	Ploughing
	10	Biosphere	3.02	Radionuclide accumulation in soils
	10	Biosphere	3.26	Consumption of uncontaminated products
2.4.10	**Urban and industrial land and water use**			
		No mapped OPA FEPs		
2.4.11	**Leisure and other uses of environment**			
		No mapped OPA FEPs		
3.1.01	**Radioactive decay and in-growth**			
	0.5	Common FEPs	1.01	Radioactive decay
	10	Biosphere	3.16	Secular equilibrium of radionuclide chains
3.1.02	**Chemical / organic toxin stability**			
	2.2	Spent fuel	1.07	Chemically toxic contaminants
3.1.03	**Inorganic solids / solutes**			
		No mapped OPA FEPs		
3.1.04	**Volatiles and potential for volatility**			
	0.5	Common FEPs	1.03	Gaseous and volatile isotopes
	2.2	Spent fuel	3.09	Gaseous radionuclide release
3.1.05	**Organics and potential for organic forms**			
	0.5	Common FEPs	1.03	Gaseous and volatile isotopes
	2.2	Spent fuel	3.09	Gaseous radionuclide release
	2.3	ILW waste and packages	1.08	Organics
	2.3	ILW waste and packages	1.09	Extraneous materials (including microbes / biological materials)
	2.3	ILW waste and packages	2.1	Microbial activity and effects
	2.3	ILW waste and packages	3.05.1	Complexation

	5.3	ILW backfill and liner	1.05.5	Organics
	5.3	ILW backfill and liner	3.07	Complexation
	6.1	Bentonite – HR interface	1.06	Natural organics
	6.3	Concrete – HR interface	1.06	Natural organics
	7	OPA host rock	1.06	Natural organics
	7	OPA host rock	4.05	Chemical plume from ILW
3.1.06	**Noble gases**			
	0.5	Common FEPs	1.03	Gaseous and volatile isotopes
	2.1	Vitrified HLW	2.12	He gas production
3.2.01	**Dissolution, precipitation and crystallisation, contaminant**			
	2.1	Vitrified HLW	2.07	Congruent dissolution
	2.1	Vitrified HLW	2.08	Selective leaching
	2.1	Vitrified HLW	3.01	Radionuclide release from glass
	2.1	Vitrified HLW	3.03	Co-precipitates / solid solutions (of RNs)
	2.2	Spent fuel	1.08	Fuel cracking and surface area
	2.2	Spent fuel	2.03.1	Fuel matrix dissolution
	2.2	Spent fuel	3.01	Radionuclide release from fuel
	2.2	Spent fuel	3.02	RN release from cladding and structural materials
	2.2	Spent fuel	3.05	Co-precipitation of radionuclides
	2.3	ILW waste and packages	3.01	Radionuclide release through waste form degradation
	2.3	ILW waste and packages	3.02	Instant release fraction
	2.3	ILW waste and packages	3.04	Sorption on and co-precipitation with corrosion products
	2.3	ILW waste and packages	3.05	Co-precipitation with calcite
	3.1	Canister	3.03	Radionuclide sorption on and co-precipitation with canister corrosion products
	5.3	ILW backfill and liner	3.06	Co-precipitation (of RNs)
3.2.02	**Speciation and solubility, contaminant**			
	0.5	Common FEPs	1.02	Speciation
	2.1	Vitrified HLW	2.13	Microbial activity and effects
	2.1	Vitrified HLW	3.02	Elemental (and RN) solubility limits
	2.2	Spent fuel	3.03	Radionuclide elemental solubilities and precipitation
	2.3	ILW waste and packages	3.03.1	Gas dissolution in porewater
	4.1	Bentonite buffer	2.08	Radiolysis
	4.1	Bentonite buffer	3.03	Elemental solubility / precipitation
	5.3	ILW backfill and liner	3.05	Solubility
	6.1	Bentonite – HR interface	2.07	Geochemical alteration
	6.1	Bentonite – HR interface	3.03	Elemental solubility
	7	OPA host rock	1.06	Natural organics
	7	OPA host rock	3.02	Elemental solubility
	7	OPA host rock	4.03	Influx of oxidising water
	8	Tunnels & shafts	3.02	Elemental solubility
	8	Tunnels & shafts	4.04	Chemical plume from ILW
	10	Biosphere	3.06	Speciation and solubility
	13	Future human actions	2.03	Groundwater pollution
3.2.03	**Sorption / desorption processes, contaminant**			
	2.2	Spent fuel	3.06	Sorption of radionuclides inside canister
	2.3	ILW waste and packages	3.03.2	Sorption on cement materials
	3.1	Canister	3.03	Radionuclide sorption on and co-precipitation with canister corrosion products
	4.1	Bentonite buffer	2.08	Radiolysis
	4.1	Bentonite buffer	3.01	Radionuclide transport through buffer
	4.1	Bentonite buffer	3.02	Radionuclide retardation
	5.3	ILW backfill and liner	3.03	Radionuclide sorption in backfill and liner
	6.1	Bentonite – HR interface	1.04	Mineralogy
	6.1	Bentonite – HR interface	1.05	Groundwater composition
	6.1	Bentonite – HR interface	2.07	Geochemical alteration
	6.1	Bentonite – HR interface	3.02	Radionuclide sorption
	6.3	Concrete – HR interface	2.07	Geochemical alteration
	6.3	Concrete – HR interface	3.02	Radionuclide sorption
	6.3	Concrete – HR interface	3.03	Elemental solubility
	7	OPA host rock	1.04	Mineralogy
	7	OPA host rock	1.05	Groundwater composition

	7	OPA host rock	3.05	Radionuclide sorption
	7	OPA host rock	4.03	Influx of oxidising water
	7	OPA host rock	4.04	Intrusion of saline groundwater
	8	Tunnels & shafts	3.05	Radionuclide sorption
	8	Tunnels & shafts	4.04	Chemical plume from ILW
	9	Geology & hydrology	1.07	Groundwater composition
	9	Geology & hydrology	3.03	Sorption / retardation
	10	Biosphere	3.01	Radionuclide accumulation in sediments
	10	Biosphere	3.02	Radionuclide accumulation in soils
	10	Biosphere	3.05	Radionuclide sorption
	13	Future human actions	2.03	Groundwater pollution
3.2.04	**Colloids, contaminant interactions and transport with**			
	2.1	Vitrified HLW	3.05	Colloids formation (RN bearing)
	2.2	Spent fuel	3.08	Formation of radionuclide-bearing colloids
	2.3	ILW waste and packages	3.06	Colloid generation
	4.1	Bentonite buffer	3.04	Colloid filtration
	5.3	ILW backfill and liner	2.13	Colloid formation through backfill degradation
	5.3	ILW backfill and liner	3.04	Sorption / incorporation of radionuclides on colloids and microbes
	6.1	Bentonite – HR interface	2.1	Colloid production and effects
	6.1	Bentonite – HR interface	3.07	Colloid-facilitated transport
	6.3	Concrete – HR interface	2.1	Colloid production and effects
	6.3	Concrete – HR interface	3.07	Colloid-facilitated transport
	7	OPA host rock	2.09	Colloid transport
	7	OPA host rock	3.07	Colloid-facilitated transport
	8	Tunnels & shafts	2.05	Colloid transport
	8	Tunnels & shafts	3.07	Colloid-facilitated transport
	10	Biosphere	3.04	Radionuclide transport with solid material
3.2.05	**Chemical / complexing agents, effects on contaminant speciation / transport**			
	2.2	Spent fuel	3.07	Complexation of radionuclides
	2.3	ILW waste and packages	1.08	Organics
	2.3	ILW waste and packages	3.05.1	Complexation
	4.1	Bentonite buffer	4.03	Organics / contamination of bentonite
	5.3	ILW backfill and liner	1.05.4	Cement additives
	5.3	ILW backfill and liner	1.05.5	Organics
	5.3	ILW backfill and liner	2.12	Biofilms
	5.3	ILW backfill and liner	3.07	Complexation
	6.1	Bentonite – HR interface	1.06	Natural organics
	6.3	Concrete – HR interface	1.06	Natural organics
	6.3	Concrete – HR interface	1.07	Microbial activity
	8	Tunnels & shafts	4.01	Oil or organic fluid spill
3.2.06	**Microbial / biological / plant-mediated processes, contaminant**			
	2.1	Vitrified HLW	2.13	Microbial activity and effects
	2.2	Spent fuel	2.12	Microbial activity and effects
	2.2	Spent fuel	2.12	Microbial activity and effects
	2.3	ILW waste and packages	2.1	Microbial activity and effects
	5.3	ILW backfill and liner	3.04	Sorption / incorporation of radionuclides on colloids and microbes
	6.1	Bentonite – HR interface	1.07	Microbial activity
	6.3	Concrete – HR interface	1.07	Microbial activity
	7	OPA host rock	2.05	Microbial activity
3.2.07	**Water-mediated transport of contaminants**			
	2.3	ILW waste and packages	3	RN Transport
	2.3	ILW waste and packages	3.00.1	Diffusive transport
	2.3	ILW waste and packages	3.00.2	Flow and advective transport
	3.1	Canister	3.01	Residual canister – crack / hole effects (vitrified waste)
	3.1	Canister	3.02	Residual canister – crack / hole effects (spent fuel)
	4.1	Bentonite buffer	3.01	Radionuclide transport through buffer
	4.1	Bentonite buffer	3.05	Interaction and diffusion between canisters
	5.3	ILW backfill and liner	3.01	Diffusive transport through backfill and liner
	5.3	ILW backfill and liner	3.02	Flow and advective transport through backfill & liner
	6.1	Bentonite – HR interface	3.01	Radionuclide migration pathways
	6.1	Bentonite – HR interface	3.04	Advective / dispersive / diffusive transport

	6.1	Bentonite – HR interface	3.05	Matrix diffusion
	6.3	Concrete – HR interface	3.01	Radionuclide migration pathways
	6.3	Concrete – HR interface	3.04	Advective / dispersive / diffusive transport
	6.3	Concrete – HR interface	3.05	Matrix diffusion
	7	OPA host rock	3.01	Radionuclide migration pathways
	7	OPA host rock	3.03	Advective / dispersive / diffusive transport
	7	OPA host rock	3.04	Matrix diffusion
	7	OPA host rock	3.06	Dilution of radionuclides
	7	OPA host rock	3.1	Transport by coupled processes (Onsager)
	7	OPA host rock	4.01	Exploratory boreholes
	8	Tunnels & shafts	2.02	Tunnel backfill performance
	8	Tunnels & shafts	3.03	Advective / dispersive / diffusive transport
	8	Tunnels & shafts	3.04	Matrix diffusion
	8	Tunnels & shafts	3.06	Dilution of radionuclides
	8	Tunnels & shafts	3.09	Convergence-induced transport
	8	Tunnels & shafts	3.1	Transport by coupled processes (Onsager)
	9	Geology & hydrology	3.03	Sorption / retardation
	10	Biosphere	2.1	Interface effects
	10	Biosphere	3.03	Radionuclide transport as solute
	10	Biosphere	3.07	Diffusion / dispersion
	10	Biosphere	3.09	Dilution of radionuclides in surface water (aquifer, river, lake, etc.)
	10	Biosphere	3.17	Removal mechanisms
3.2.08	**Solid-mediated transport of contaminants**			
	10	Biosphere	2.07	Erosion / deposition
	10	Biosphere	2.08	Sedimentation
	10	Biosphere	2.18	Suspended sediment transport
	10	Biosphere	2.19	Earthworks (human actions, dredging, etc.)
	10	Biosphere	3.04	Radionuclide transport with solid material
	10	Biosphere	3.17	Removal mechanisms
3.2.09	**Gas-mediated transport of contaminants**			
	2.3	ILW waste and packages	3	RN transport
	2.3	ILW waste and packages	3.00.2	Flow and advective transport
	2.3	ILW waste and packages	3.03	Release of volatile radionuclides over gas pathway
	2.3	ILW waste and packages	3.03.1	Gas dissolution in porewater
	3.1	Canister	2.14	Hydrogen production (steel canister)
	6.1	Bentonite – HR interface	3.06	Gas-induced transport
	6.3	Concrete – HR interface	2.09	Gas transport
	6.3	Concrete – HR interface	3.06	Gas-induced transport
	7	OPA host rock	3.08	Gas-induced transport
	7	OPA host rock	4.01	Exploratory boreholes
	8	Tunnels & shafts	2.02	Tunnel backfill performance
	8	Tunnels & shafts	2.06	Gas transport
	10	Biosphere	1.06	Atmosphere
	10	Biosphere	3.08	Radionuclide volatilisation / aerosol / dust production
3.2.10	**Atmospheric transport of contaminants**			
	10	Biosphere	1.06	Atmosphere
	10	Biosphere	3.02	Radionuclide accumulation in soils
	10	Biosphere	3.08	Radionuclide volatilisation / aerosol / dust production
	10	Biosphere	3.15	Foodchain equilibrium
	10	Biosphere	3.27	Radon pathways and doses
3.2.11	**Animal, plant and microbe mediated transport of contaminants**			
	10	Biosphere	3.17	Removal mechanisms
3.2.12	**Human-action-mediated transport of contaminants**			
	13	Future human actions	1.01	Exploratory drilling
	13	Future human actions	1.02	Resource exploitation through boreholes
	13	Future human actions	1.03	Mining activities
	13	Future human actions	1.04	Geothermal exploitation
	13	Future human actions	1.05	Deep groundwater extraction
	13	Future human actions	1.06	Liquid waste injection
	13	Future human actions	3.01	Intentional intrusion

	13	Future human actions	3.02	Inadvertent intrusion
	13	Future human actions	3.05	Abandonment of repository
3.2.13	**Foodchains, uptake of contaminants in**			
	10	Biosphere	3.11	Uptake by crops
	10	Biosphere	3.12	Uptake by livestock
	10	Biosphere	3.13	Uptake in fish
	10	Biosphere	3.15	Foodchain equilibrium
	10	Biosphere	3.18	Food and water processing
3.3.01	**Drinking water, foodstuffs and drugs, contaminant concentrations in**			
	10	Biosphere	3.21	Exposure pathways
3.3.02	**Environmental media, contaminant concentrations in**			
	10	Biosphere	3.01	Radionuclide accumulation in sediments
	10	Biosphere	3.02	Radionuclide accumulation in soils
	10	Biosphere	3.03	Radionuclide transport as solute
	10	Biosphere	3.08	Radionuclide volatilisation / aerosol / dust production
	10	Biosphere	3.09	Dilution of radionuclides in surface water (aquifer, river, lake, etc.)
	10	Biosphere	3.15	Foodchain equilibrium
	10	Biosphere	3.16	Secular equilibrium of radionuclide chains
3.3.03	**Non-food products, contaminant concentrations in**			
	10	Biosphere	3.25	Contaminated products (non-food)
3.3.04	**Exposure modes**			
	10	Biosphere	1.06	Atmosphere
	10	Biosphere	3.21	Exposure pathways
	10	Biosphere	3.23	Dosimetry
3.3.05	**Dosimetry**			
	10	Biosphere	3.16	Secular equilibrium of radionuclide chains
	10	Biosphere	3.22	Age groups
	10	Biosphere	3.23	Dosimetry
3.3.06	**Radiological toxicity / effects**			
	10	Biosphere	4.03	Radiological effects on non-human biota
3.3.07	**Non-radiological toxicity / effects**			
	10	Biosphere	4.02	Non-radiological effects
3.3.08	**Radon and radon daughter exposure**			
	10	Biosphere	3.27	Radon pathways and doses

A3.3 Audit against the NEA FEPCAT List

In the audit process each OPA FEP is "mapped" to one or more FEPs of the FEPCAT List. Tab. A3.3.1 shows the mapping between OPA FEPs and FEPCAT FEPs arranged in the order of the FEPCAT List.

In the case of 19 FEPCAT FEPs, no direct map to the OPA FEP List exists, although they have been considered in the geosynthesis report (Nagra 2002c), which is a key part of the scientific basis for the Safety Report (Nagra 2002a). These 19 FEPs are marked as follows:

GDS: FEPCAT FEP that is considered in the derivation of the geodataset, which is used in the safety assessment calculations (16 FEPs).

IEV: FEPCAT FEP that is used as an independent evidence, supporting the arguments for the low hydraulic permeability and long-term stability of the Opalinus Clay (3 FEPs).

Tab. A3.3.1: The mapping of OPA FEPs to the NEA FEPCAT List

GDS: FEPCAT FEP that is considered in the derivation of the geodataset, which is used in the safety assessment calculations. IEV: FEPCAT FEP that is used as an independent evidence, supporting the arguments for the low hydraulic permeability and long-term stability of the Opalinus Clay. FEPCAT FEPs denoted by GDS or IEV are not mapped to the OPA FEP List.

NEA FEPCAT List			Map to OPA FEP List		
FEP		**Structured FEP classification**	**FEP**		**Comment**
No.	**Hierarchy**		**No.**	**Name**	
	A	UNDISTURBED SYSTEM			
	A1	**Transport mechanisms**			
1	A1.1	Advection/dispersion	7./3.03	Advective/dispersive /diffusive transport	
2	*A1.1.1*	*Size and geometry of the host rock and of surrounding units, migration pathlength*	0./1.03	Host geology	
			1./1.02	Host rock / geology – regional character	
			1./1.03	Host rock / geology – at repository location	
			7./1.09	Heterogeneity within Opalinus Clay	
			9./1.03.1	Sedimentology, mineralogy etc. – overlying formations	Upper confining units (incl. Wedelsandstein), Malm aquifer
			9./1.03.3	Sedimentology, mineralogy etc. – underlying formations	Lower confining units (incl. Sandsteinkeuper), Muschelkalk aquifer
3	*A1.1.2*	*Migration pathways, including heterogeneity and anatomy*	7./3.01	Radionuclide migration pathway	Vertical migration within Opalinus Clay (40 m), followed by direct release to biosphere
			9./3.01	Radionuclide migration pathway	Direct release from Opalinus Clay to biosphere or vertical transport through upper/lower confining units or horizontal transport along Wedelsandstein and Sandsteinkeuper
			7./1.09	Heterogeneity within Opalinus Clay	Observed layering and discontinuities within Opalinus Clay are covered by adequate choice of transport parameters
4	*A1.1.3*	*Undetected geological features*	7./1.01	Discontinuities	Transmissive discontinuities not observed, but postulated in "what if?" case
			7./1.09	Heterogeneity within Opalinus Clay	Observed layering and discontinuities within Opalinus Clay are covered by adequate choice of transport parameters

Tab. A.3.3.1: (Cont.)

NEA FEPCAT List			Map to OPA FEP List		
FEP		Structured FEP classification	FEP		Comment
No.	Hierarchy		No.	Name	
5	*A1.1.4*	*Hydraulic potentials and gradients in the host rock, including boundary conditions*	7./1.08	Hydraulic gradient	Mean hydraulic gradient of 1 $m\,m^{-1}$ within Opalinus Clay (directed upwards)
			7./1.11	Overpressures	Anomalous pore pressures above hydrostatic
			9./2.04	Hydraulic gradient	Under- / overlying units
6	*A1.1.5*	*Hydraulic properties of the host rock*	7./1.03	Effective hydraulic properties	Flow porosity and hydraulic conductivity of Opalinus Clay
			7./2.07	Groundwater flow	Very minor groundwater flow in the Opalinus Clay (Darcy velocity 2×10^{-14} $m\,s^{-1}$)
			9./2.02	Effective hydraulic properties	Flow porosity and hydraulic conductivity of under- / overlying units
7	*A1.1.6*	*Units over- and underlying the host formation: local and regional hydrogeologic framework*	9./2.01	Hydrogeological units	
			9./2.03	Recharge / discharge zones	Discharge zones as locations of potential radionuclide release
			9./2.05	Groundwater flowpaths	Considered in definition of radionuclide migration pathways
	A1.2	Diffusion			
8	*A1.2.1*	*Diffusivity*	7./3.03	Advective/dispersive /diffusive transport	Diffusion predominantly perpendicular to bedding planes
9	*A1.2.2*	*Connected matrix porosity*	GDS		Separate diffusion accessible porosities for anions and non-anions considered
10	*A1.2.3*	*Ion exclusion*	GDS		Taken into account in derivation of sorption constants
11	*A1.2.4*	*Surface diffusion*	GDS		Pessimistic diffusion constants for cationic species (parameter variation)

Tab. A.3.3.1: (Cont.)

NEA FEPCAT List			Map to OPA FEP List		
FEP No.	**FEP Hierarchy**	**Structured FEP classification**	**FEP No.**	**FEP Name**	**Comment**
12	A1.3	Colloid formation, transport and filtration	6.1/2.10	Colloid production and effects (SF/HLW EDZ)	Colloids assumed to be filtered in Opalinus Clay
			6.3/2.10	Colloid production and effects (ILW EDZ)	
			7./2.09	Colloid transport	
			7./2.10	Effect of colloids on Opalinus Clay properties	E.g. clogging of pores by filtration
			7./3.07	Colloid-facilitated transport	Colloid-facilitated radio-nuclide transport in Opalinus Clay considered negligible
			6.1/3.07	Colloid-facilitated transport (SF / HLW EDZ)	
			6.3/3.07	Colloid-facilitated transport (ILW EDZ)	
	A2	**Retardation mechanisms**			
	A2.1	Matrix diffusion			
8	*A2.1.1*	*Diffusivity*	7./3.04	Matrix diffusion	Diffusion parallel to bedding planes (enhanced diffusion)
9	*A2.1.2*	*Connected matrix porosity*	GDS		Separate diffusion accessible porosity for anions and non-anions considered
13	*A2.1.3*	*Flow-wetted surface and accessibility of matrix*	GDS		Included in effective parameters for matrix diffusion from transmissive discontinuities ("what if?" case)
10	*A2.1.4*	*Ion exclusion*	GDS		For anions, only free water is diffusion accessible
11	*A2.1.5*	*Surface diffusion*	GDS		Pessimistic diffusion constants for cationic species (parameter variation)

Tab. A.3.3.1: (Cont.)

NEA FEPCAT List			Map to OPA FEP List		
FEP		**Structured FEP classification**	**FEP**		**Comment**
No.	**Hierarchy**		**No.**	**Name**	
	A2.2	Sorption (broad definition)	7./3.05	Radionuclide sorption	
14	*A2.2.1*	*Lithology, mineralogy of rocks and fracture infills*	7./1.04	Mineralogy	
			7./1.09	Heterogeneity within Opalinus Clay	
15	*A2.2.2*	*Natural organics, complexation*	7./1.06	Natural organics	
16	*A2.2.3*	*Mineral-surface area*	GDS		Taken into account in derivation of sorption constants
17	*A2.2.4*	*Pore- and fracture water composition*	7./1.05	Groundwater composition	
18	*A2.2.5*	*Dissolution / precipitation of solid phases*	GDS		Solubility limitation for radionuclides in geosphere is considered a reserve FEP
19	*A2.2.6*	*Solid solutions / co-precipitation*	7./3.02	Elemental solubility	Reserve FEP
20	*A2.2.7*	*Ion exchange*	GDS		Taken into account in derivation of sorption constants
21	*A2.2.8*	*Surface complexation*	GDS		
22	*A2.2.9*	*Thermodynamic and kinetic modelling data*	GDS		
	A3	**System understanding and independent methods / tools to build confidence in predictive models**			
23	A3.1	Palaeo-hydrogeology of the host formation and of embedding units	IEV		Independent evidence for low hydraulic permeability and long-term stability of Opalinus Clay (A3.1 – A3.3)
24	A3.2	Evolution of pore-fluid (water and gas) chemistry and minera-logy in the host formation and in embedding units	IEV		
25	A3.3	Water residence times in the host formation	IEV		

Tab. A.3.3.1: (Cont.)

NEA FEPCAT List			Map to OPA FEP List		
FEP		Structured FEP classification	FEP		Comment
No.	Hierarchy		No.	Name	
	B	REPOSITORY-INDUCED PERTURBATIONS			
	B1	**Chemical perturbations**			
26	B1.1	Oxidation of the host rock	6.1/2.07	Geochemical alteration (SF / HLW EDZ)	Partially negligible / beneficial effect on radionuclide sorption constants
			6.3/2.07	Geochemical alteration (ILW EDZ)	
27	*B1.1.1*	*Redox buffering capacity of the host rock*	GDS		
28	B1.2	Effects of repository components on pore-water chemistry in the host rock	6.1/2.07 6.3/2.07	Geochemical alteration (SF / HLW / ILW EDZ)	See FEP No. 26
29	*B1.2.1*	*Interactions of hyperalkaline fluids and host rock*	7./4.05	Chemical plume from ILW	Limited high-pH plume penetration expected
30	*B1.2.2*	*Organics from waste and their effect on transport properties of the host rock*	7./4.05	Chemical plume from ILW	Organic content of the ILW waste considered to be too small to lead to an organic plume
	B2	**Thermal perturbations**			
31	B2.1	Thermal effects on mineral stability and pore-water composition	6.1/2.02	Thermal evolution (SF / HLW EDZ)	Temperatures within Opalinus Clay remain below maximal temperatures in the past (approx. 90 °C)
			6.3/2.02	Thermal evolution (ILW EDZ)	Negligible impact expected
			7./2.01	Thermal effects	No significant thermal effects on Opalinus Clay expected
32	B2.2	Thermal rock properties	1./3.01	Repository layout / constraints	Thermal rock properties are considered in calculations of thermal evolution (repository design / layout)
33	B2.3	Thermally induced consolidation of the host rock	GDS		Taken into account in argumentation on self-sealing of EDZ
	B3	**Geomechanical perturbations**			
34	B3.1	Geomechanical stability	6.1/2.03	Geomechanical processes (SF / HLW EDZ)	
			6.3/2.03	Geomechanical processes (ILW EDZ)	
35	B3.2	Size and structure of the EDZ	6.1/1.01	Excavation-disturbed zone (SF/HLW EDZ)	Reduced stability (rock bolts and mesh)
			6.3/1.01	Excavation-disturbed zone (ILW EDZ)	Reduced stability (rock bolts and concrete liner)

Tab. A.3.3.1: (Cont.)

NEA FEPCAT List			Map to OPA FEP List		
FEP		**Structured FEP classification**	**FEP**		**Comment**
No.	**Hierarchy**		**No.**	**Name**	
36	B3.3	Effects of bentonite swelling on the host rock	4.1/1.02	Bentonite swelling pressure	Tunnel convergence until bentonite swelling pressure balances external stress field
			4.1/1.03	Bentonite plasticity	Ensures closure of voids within and around bentonite
			6.1/2.06	Compaction of SF / HLW EDZ	
			6.3/2.06	Compaction of ILW EDZ	
37	B3.4	Geomechanical rock properties	1./3.01	Repository layout/constraints	Rock properties are considered in geomechanical calculations (repository design / layout)
	B4	**Hydraulic perturbations**			
38	B4.1	Hydraulic properties of the EDZ	6.1/1.03	Effective hydraulic properties (SF / HLW EDZ)	Increased flow porosity and hydraulic conductivity
			6.3/1.03	Effective hydraulic properties (ILW EDZ)	Increased flow porosity and hydraulic conductivity
			6.1/1.09	Water flow at bentonite – host rock interface	Limited by bentonite swelling
			6.3/1.09	Water flow at concrete – host rock interface	Relevant in the vicinity of sealing zones and concrete plugs
			7./2.11	Density-driven groundwater flow (thermal and saline)	Insignificant effect
39	B4.2	State of saturation of the EDZ and desiccation cracking	6.1/2.01	Desaturation / resaturation of SF / HLW EDZ	Desaturation stiffens clay; resaturation and bentonite swelling results in self-sealing of EDZ; saturation time one to several hundred years
			6.3/2.01	Desaturation / resaturation of ILW EDZ	Saturation time approx. 500 years

Tab. A.3.3.1: (Cont.)

NEA FEPCAT List			Map to OPA FEP List		
FEP		Structured FEP classification	FEP		Comment
No.	Hierarchy		No.	Name	
	B5	**Perturbations from coupled processes**			
40	B5.1	Coupled thermo-hydro-mechanic processes	GDS		See FEP No. 33
41	B5.2	Swelling	7./2.03	Swelling of clay	1 – 7 % swelling capacity of Opalinus Clay results in self-sealing of EDZ
			6.1/2.05	Swelling of clay-minerals in SF / HLW EDZ	
			6.3/2.05	Swelling of clay-minerals in ILW EDZ	
42	B5.3	Self-sealing	7./2.03	Swelling of clay	See FEP No. 41
			11./2.07	Self-sealing of faults	See FEP No. 41
43	B5.4	Off-diagonal Onsager processes except chemical osmosis	6.1/2.08	Fluid and heat fluxes by coupled processes (Onsager, SF / HLW EDZ)	Insignificant fluxes
			6.1/3.09	Transport by coupled processes (Onsager, SF / HLW EDZ)	Insignificant radionuclide transport
			6.3/2.08	Fluid and heat fluxes by coupled processes (Onsager, ILW EDZ)	Insignificant fluxes
			6.3/3.09	Transport by coupled processes (Onsager, ILW EDZ)	Insignificant radionuclide transport
			7./2.12	Fluid fluxes by coupled processes (Onsager)	See above
			7./3.10	Transport by coupled processes (Onsager)	See above
44	B5.5	Chemical osmosis			See FEP No. 43
	B6	**Perturbations from waste-derived gas**			
45	B6.1	Gas dissolution and chemical interactions between gas and pore water	7./2.06	Effects of gas on Opalinus Clay	Pressure buildup, gas dissolution, degassing of geogas, pathway dilation
46	B6.2	Gas migration through the primary porosity (matrix, natural fractures)	7./2.08	Gas transport	Transport of free and dissolved gas; two-phase flow in Opalinus Clay

Tab. A.3.3.1: (Cont.)

NEA FEPCAT List			Map to OPA FEP List		
FEP		**Structured FEP classification**	**FEP**		**Comment**
No.	**Hierarchy**		**No.**	**Name**	
47	B6.3	Gas migration through stress-induced porosity (gas fracs, pathway dilation)	7./2.08	Gas transport	Transport of free and dissolved gas; flow through dilated pathways in Opalinus Clay, bentonite / concrete interface
			6.1/2.09	Gas transport (SF / HLW EDZ)	
			6.3/2.09	Gas transport (ILW EDZ)	
48	B6.4	Gas-induced transport in water	6.1/3.06	Gas-induced transport (SF / HLW EDZ)	Gas-induced transport of dissolved radionuclides by porewater displacement
			6.3/3.06	Gas-induced transport (ILW EDZ)	
			7./3.08	Gas-induced transport (OPA)	
49	**B7**	**Microbiological perturbations**	7./2.05	Microbial activity (OPA)	Insignificant effect
			6.1/1.07	Microbial activity (SF / HLW EDZ)	Impact decreases with self-sealing
			6.3/1.07	Microbial activity (ILW EDZ)	Impact decreases with self-sealing
	C	LONG-TERM EVOLUTION			
		Diagenesis			
	C1.1	Past basin evolution			
23	*C1.1.1*	*Palaeo-hydrogeology of the host formation and of the embedding units*			See FEP No. 23
24	*C1.1.2*	*Evolution of pore-fluid (water and gas) chemistry and mineralogy in the host formation and in embedding units*			See FEP No. 24
50	*C1.1.3*	*Past burial history*	9./1.02	Geological formation/history	
			7./2.01	Thermal effects	Maximal temperature in Opalinus Clay did not exceed approx. 90 °C, thus thermal degradation assumed to be negligible
			11./2.01	Regional vertical movements	Taken into account in derivation of long-term uplift rates

Tab. A.3.3.1: (Cont.)

NEA FEPCAT List			Map to OPA FEP List		
FEP		Structured FEP classification	FEP		Comment
No.	Hierarchy		No.	Name	
	C1.2	Ongoing and future processes			
51	*C1.2.1*	*Present and future geothermal regime and related processes*	11./2.10	Hydrothermal activity	Significant geothermal anomalies can be avoided by repository siting
			13./1.04	Geothermal exploitation	Case with inadvertant borehole penetration of repository
52	*C1.2.2*	*Future changes in hydrochemistry of the host rock and of surrounding formations (e.g. due to out-diffusion, water-rock interactions, uplift)*	GDS		Taken into account in derivation of long-term geochemical data
	C2	**Deformation events**			
53	C2.1	Past deformation events	9./1.06	Faults, distribution and properties	Taken into account in derivation of geodataset (faulting, age of porewater, etc.)
54	C2.2	Future fault (re)activation, changes in migration pathways; changes of hydraulic parameters; flow events	11./2.06	Neo-tectonic activity	Transmissive discontinuities not observed, but postulated in "what if?" case
			11./2.08	Seismic activity	Minor seismic activity in Zürcher Weinland expected, negligible impact on closed repository
41	C2.3	Swelling	11./2.07	Self-sealing of faults	
42	C2.4	Self-sealing	11./2.07	Self-sealing of faults	
55	C2.5	Present-day stress regime	7./1.07	Stress regime	Taken into account in repository design / layout
			9./1.05	Regional stress regime	
56	C2.6	Future stress regime	11./2.05	Evolution of regional stress regime	Formation of significant new fractures considered to be very unlikely
			11./2.01	Regional vertical movements	
			11./2.02	Regional horizontal movements	

Tab. A.3.3.1: (Cont.)

NEA FEPCAT List			Map to OPA FEP List		
FEP		Structured FEP classification	FEP		Comment
No.	Hierarchy		No.	Name	
	C3	**Erosion and burial**			
57	C3.1	Geomechanical effects of erosion / unloading	11./2.04	Erosion	No changes expected in hydraulic properties of Opalinus Clay for next one million years
58	C3.2	Consolidation due to burial	11./2.03	Compaction of Opalinus Clay	Very low porewater drainage rates expected
			12./2.05	Ice sheet effects (loading, melt water recharge)	Case with repeated glacial loading / unloading investigated
59	C3.3	Future evolution of hydraulic potentials and gradients (e.g. due to erosion or burial)	11./2.04	Erosion	See FEP No. 57
			11./2.03	Compaction of Opalinus Clay	See FEP No. 58
			7./1.08	Hydraulic gradient	
			7./1.11	Overpressures	

Appendix 4: Key safety-relevant phenomena and the map to Super-FEPs

A4.1 Introduction

Key safety-relevant phenomena are identified based on the integrated scientific understanding of disposal system evolution, as described in Section 4.1. The key safety-relevant phenomena and their related uncertainties represent the integrated scientific understanding of the disposal system and its performance. They provide a more convenient basis for discussion and evaluation in the safety assessment than the more numerous individual OPA FEPs. The complete list of key safety-relevant features and phenomena and uncertainties associated with the disposal system evolution is given in Tab. A4.1.1. This table is identical to Tab. 5.7-1 in the Safety Report (Nagra 2002a), but with the addition of numbers to assist traceability to other tables. Note that in Tab. A4.1.1, three categories of phenomena / evolutions are defined:

- safety-relevant features, phenomena and evolutions related to the reference disposal system;
- safety-relevant phenomena / evolutions related to system design alternatives;
- speculative phenomena / evolutions involving future human behaviour or the evolution of the surface environment (the biosphere).

There is a close correspondence between the key safety-relevant phenomena, which are selected based on scientific understanding, and the Super-FEPs, which are key groupings of FEPs derived for the purpose of quantitative assessment (see Chapter 6 in the Safety Report). Tab. A4.1.2 presents the map between key safety-relevant phenomena (listed in Tab. A4.1.1) and the Super-FEPs (listed in Tab. A5.2.1 in Appendix 5).

Tab. A4.1.1: Key safety-relevant features and phenomena and uncertainties associated with the disposal system evolution

SAFETY-RELEVANT FEATURES, PHENOMENA & EVOLUTIONS			
System Component	**Key Phenomena**	**Expected Evolution**	**Uncertainties and Possible Deviations**
Repository	**A.1.0** Repository layout, total waste inventory and design	Reference design parameters, waste inventory for 60 years power plant operation (current power plants only)	Alternative layout for larger waste inventory (300 GWa(e) power production)
	A.1.0.1 EBS for SF / HLW / ILW – design parameters	Reference design parameters	See design alternatives
Spent Fuel	**A.1.1** Radioactive inventories and decay processes (heat and radiation)	Inventories of radionuclides, half-lives and decay heat well defined; three canister inventories defined (BWR UO_2, PWR UO_2 and PWR MOX/UO_2) – average burnup 48 GWd/t_{IHM}	Different canister types incorporate IRF variability and variability in burnups, possible increase in burnup up to 75 GWd/t_{IHM}
	A.1.2 Cladding failure and corrosion	Possible short-term failure (cracking), partially failed cladding slows release; slow corrosion-rate controlled release of activation products from Zircaloy, preferential release of some organic ^{14}C from oxide film of cladding	
	A.1.3 Leaching of IRF	IRF dissolves upon canister breaching	Limited information on the IRF of MOX and high burnup UO_2 fuel
	A.1.4 Dissolution of SF matrix	Extremely slow dissolution rate (solubility-controlled) because of reducing capacity of H_2	Oxidising conditions at fuel surface from α-radiolysis (dissolution rate decreases proportionally with α-activity); preferential release of organic ^{14}C from fuel matrix; "what if?" case assuming high oxidant yield
	A.1.5 Criticality	Avoided by design basis (geometry, burnup credit)	

Tab. A4.1.1: (Cont.)

SAFETY-RELEVANT FEATURES, PHENOMENA & EVOLUTIONS			
System Component	**Key Phenomena**	**Expected Evolution**	**Uncertainties and Possible Deviations**
HLW Glass	**A.2.1** Radioactive inventories and decay processes (heat and radiation)	Inventories of radionuclides, half-lives and decay heat well defined; two HLW glass types defined (BNFL and COGEMA)	
	A.2.2 Dissolution of glass	Different rates for each glass type based on laboratory experiments	Long-term extrapolation uncertain – rates 100 × higher or 20 × lower
Steel SF / HLW canisters	**A.3.1** Failure mechanisms	Brief oxic corrosion phase, limited pitting and microbial corrosion, slow anaerobic corrosion, no SCC – 10 000 a lifetime	Unlikely shorter-term failure (e.g. uncertainties regarding SCC) leading to loss of containment in 1000 a; residual transport resistance not considered
	A.3.2 Gas generation	Anaerobic corrosion producing H_2 gas continuously at a low rate	Uncertainty in anaerobic corrosion rate, possible gas-induced porewater displacement (from void space in SF canisters)
	A.3.3 Corrosion products – sorption and redox effects	Sorption of radionuclides onto corrosion products (difficult to quantify); corrosion contributes to reducing conditions	
	A.3.4 Corrosion products – volume expansion effects	Small effect on canister load prior to 10 000 a canister lifetime	
SF / HLW	**A.4.1** Precipitation of radionuclides	Solubility limits in the near field (canister / bentonite porewater) for many radio-nuclides, reducing conditions, co-precipitation of Ra with Ba and Sr	Uncertainties in solubilities; solubilities also defined for "what if?" case of oxidising conditions in near field
Bentonite	**A.5.0** Resaturation	Slow resaturation, delaying start of corrosion and radionuclide release	Time to resaturation is uncertain (~ 100 to 100s of years)
	A.5.1 Radionuclide transport	Diffusion only; good sorption; chemical stability (large amount of material, low water flow rate at outer boundary, mineralogical similarity to Opalinus Clay); colloid filtration	Uncertainty in diffusivity and sorption on bentonite

Tab. A4.1.1: (Cont.)

SAFETY-RELEVANT FEATURES, PHENOMENA & EVOLUTIONS			
System Component	**Key Phenomena**	**Expected Evolution**	**Uncertainties and Possible Deviations**
Bentonite	**A.5.2** Thermal alteration	Degradation mitigated by mixing of UO_2 / MOX fuel assemblies to keep tempera-tures down; little impact on swelling or plasticity	Some cementation and increased diffusivity near canister
	A.5.3 Additional transport processes (Onsager)	Impact likely small; driving forces small beyond 1000 a	
	A.5.4 Redox-front penetration (radiolytic oxidation)	Oxidants scavenged by H_2 and Fe	Evidence appears to eliminate redox front penetration, "what if?" case only
	A.5.5 Gas transport	Release to rock by pathway dilation; negligible water expulsion	
	A.5.6 Microbial effects	Lack of viability of microbes in dense bentonite, no significant effects	
Bentonite / EDZ	**A.6.1** Enhanced hydraulic flow along EDZ	Approximately 10 times higher long-term hydraulic conductivity, lack of connectivity of fractures; connected EDZ limited by bentonite seals at emplace-ment tunnel ends	Hypothetical EDZ hydraulic conductivity of 10^{-10} m s^{-1}
	A.6.2 Gas transport	Pathway dilation along EDZ and into host rock, capillary leakage into rock; alteration of groundwater transport properties of bentonite, EDZ not expected	
	A.6.3 Tunnel convergence and compaction of bentonite	Compaction most likely completed before canister breaching (concurrent with saturation), will be limited due to bentonite swelling	Long-term very slow further compaction

Tab. A4.1.1: (Cont.)

SAFETY-RELEVANT FEATURES, PHENOMENA & EVOLUTIONS			
System Component	**Key Phenomena**	**Expected Evolution**	**Uncertainties and Possible Deviations**
ILW	**A.7.1** Radioactive inventories and decay processes (heat and radiation)	Inventories of radionuclides, half-lives and decay heat well defined (cemented waste option)	Inventory option (high force compacted waste)
	A.7.2 Breaching of waste containers; dissolution / leaching of radionuclides	Potential breaching and radionuclide release begins after > 100 years, as a result of slow resaturation; release rates from cemented waste and bitumen uncertain; very slow release from Zircaloy because of low corrosion rate, with some rapid release from oxide film	Longer-term containment by some steel canisters
	A.7.3 Precipitation of radionuclides	Solubility limits in the near field (cementitious waste / mortar porewater) for many radionuclides, reducing conditions	Uncertainties in solubilities
	A.7.4 Reduced sorption, increased solubility of radionuclides due to complexants in ILW	Separate wastes with high complexant contents into separate emplacement tunnel (ILW-2)	
	A.7.5 Radionuclide transport in ILW tunnels	Low water flow rate (diffusion-dominated transport), good sorption	Uncertainties in sorption; "what if?" case for redox front formation from compacted hulls radiolysis
	A.7.6 Gas generation	Corrosion of metals and biodegradation of cellulose and other organics	Uncertainties in rates of gas generation
	A.7.6a Displacement of water by gas	Some porewater displaced from containers and mortar into rock	Water displaced along tunnels / EDZ if seals less effective
	A.7.7 Tunnel convergence and compaction of waste / mortar with water displacement	Effect mitigated by choice of materials (mortar), concurrent with saturation	Porewater displacement due to compaction of void space in waste packages after full resaturation
	A.7.8 Resaturation time	Long resaturation time (hundreds of years)	

Tab. A4.1.1: (Cont.)

SAFETY-RELEVANT FEATURES, PHENOMENA & EVOLUTIONS			
System Component	**Key Phenomena**	**Expected Evolution**	**Uncertainties and Possible Deviations**
Mortar / EDZ interface	**A.8.1** High pH plume migration into host rock	Porosity reduction in rock, self-sealing (conservatively neglected), depth of reaction front very limited	4 m maximum disturbance of Opalinus Clay based on mass balance
Tunnels / ramp / shaft seals	**A.8.2** Radionuclide transport by advection in tunnel backfill / EDZ	Effective sealing, no preferential transport because of limited EDZ conductivity, effective seals, relatively low gradient	Less effective seals, preferential transport in operations tunnel backfill, EDZ of tunnels, ramp and shaft (EDZ hydraulic conductivity of up to 10^{-10} m s^{-1})
	A.8.3 Transport of gas containing volatile ^{14}C along tunnels, ramp and shaft	Volatile ^{14}C not expected; if it forms it may move through pathways in host rock and EDZ, seals effective	Possibility that gas containing volatile ^{14}C is transported along tunnels, ramp and shaft – seals less effective
Tunnel plug / operations tunnel backfill	**A.9.1** Gas buildup and transport in ILW emplacement tunnels	Gas storage potential in operations tunnel backfill not considered	Effects of gas buildup and transport in ILW emplacement tunnels mitigated by axial pathway dilation through EDZ and past tunnel plug
Host rock	**A.10.1** Length of vertical transport path in Opalinus Clay above and below emplacement tunnels	Typical path length of ~ 50 m, minimum path length of 40 m	"What if ?" case of reduced path length
	A.10.2a Advective flow in Opalinus Clay	Flow rate of ~ 10^{-14} m s^{-1}, thus diffusion-dominated solute transport occurs	± 10 fold uncertainty; gas pressure buildup, tunnel convergence, transient increase of overpressure by glacial load, all may influence flow; "what if?" case for higher flows
	A.10.2b Geochemical retardation of radionuclide transport	Retardation of most radionuclides by sorption processes; effective colloid filtration	Uncertainties in sorption coefficients; "what if?" case for $K_d = 0$ for ^{129}I

Tab. A4.1.1: (Cont.)

SAFETY-RELEVANT FEATURES, PHENOMENA & EVOLUTIONS			
System Component	**Key Phenomena**	**Expected Evolution**	**Uncertainties and Possible Deviations**
Host rock	**A.10.3** Gas migration	Diffusion of dissolved gas, 2-phase flow and gas pathway dilation; low production rates and stress conditions favour slow horizontal propagation of 2-phase flow (homogeneous gas flow) and dilatant gas pathways, self-sealing of pathways, slow concurrent transport of volatile ^{14}C	Rapid volatile ^{14}C transport along a continuous gas pathway – "what if?" case
	A.10.4 Heterogeneous flow	Host rock has little hetero-geneity (layering and no hydraulically active disconti-nuities); self-sealing is effective	Undetected discontinuities (although impact negligible because of self-sealing); evidence appears to eliminate heterogeneous flow, but "what if?" case is considered for pathways with increased transmissivities
Geosphere	**A.11.1** Neo-tectonic activity	Choice of site with low neo-tectonic activity (low uplift / erosion rates, low seismic activity, no magmatic activity); no reactivation of discontinuities	
	A.11.2 Retardation in local and regional aquifers	Not well characterised, therefore conservatively neglected	Retardation in confining units (vertical path) and local aquifers (horizontal path)
	A.11.3 Natural resources	Choice of site with no viable natural resources	
Spent Fuel	**A.12.1** Definition of inventory for disposal	Current power plants operating for 60 years	Increased inventory of SF (300 GWa(e) scenario)
SF / HLW Canisters	**A.13.1** Potential canister breaching processes	Steel canisters for SF / HLW – 10 000 a design lifetime	Cu canister > 10^5 a lifetime; 1 in 1000 canisters fails immediately (quality assurance), residual transport resistance (pinhole)
	A.13.2 H_2 gas generation	Steel canisters for SF / HLW – continuous H_2 gas production	Selection of Cu, Ni alloy or Ti as external shell canister material, significant gas generation occurs only for failed canisters; use of alternative insert with negligible gas production

Tab. A4.1.1: (Cont.)

SAFETY-RELEVANT FEATURES, PHENOMENA & EVOLUTIONS			
System Component	**Key Phenomena**	**Expected Evolution**	**Uncertainties and Possible Deviations**
Bentonite / EDZ	**A.14.1** Alteration by concrete tunnel liner	Avoided by design basis (no concrete liner required in SF / HLW emplacement tunnels)	SF / HLW tunnels may require thin concrete or polymer liner; small effects expected
ILW	**A.15.1** Inventory definition	Cemented waste option	High force compacted waste option (radionuclide inventory similar to cemented waste option) → possibility for localised radiolysis
Surface environment	**A.16.2** Geomorphological evolution	Eroding river valley section, such as present-day Rhine valley below Rhine Falls, and exfiltration in Quaternary gravel at valley bottom assumed (Reference Biosphere)	River valley section with net sedimentation; wetlands; deep groundwater exfiltration to spring at valley sides
	A.16.1 Climatic evolution	"Icehouse" climate regime; present-day climate assumed in the Reference Biosphere	Alternative climates (wet climate, dry climate, periglacial climate)
	A.16.3 Future human behaviour	Unknown, therefore present-day diet and local production of food stuff is assumed (Reference Biosphere)	Alternative human behaviour during periglacial climate; deep well in Malm aquifer
Host rock	**A.17.1** Inadvertant borehole penetration of repository	Assuming current drilling technology: borehole sealed or collapses and self-seals, canisters not vulnerable (even if partly corroded)	Supported borehole is unsealed, penetrates repository to aquifer below, leakage of near-field porewater into borehole
Tunnels / ramp / shaft seals	**A.18.1** Repository abandoned without backfilling of ramp	Impacts minimised by design basis; seals, including sealed operations tunnels, isolate emplacement tunnels containing waste	

Tab. A4.1.2: Map between key safety-relevant features and phenomena (Tab. A4.1.1) and their uncertainties and the Super-FEPs and their alternative realisations (Tab. A5.2.1)

Reserve FEPs are indicated in italics.

Category: Safety-relevant features, phenomena & evolutions **System Component**: Repository			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.1.0 Repository layout, total waste inventory and design	Reference design parameters, waste inventory for 60 years power plant operation (current power plants only)	Alternative layout for larger waste inventory (300 GWa(e) power production)	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.1.1 Quantities and burnup of fuel and associated radionuclide inventories, including the instant release fraction (IRF) ***B.1.1.1*** *The possibility for increased nuclear power production*	Waste inventory based on 192 GWa(e) scenario, corresponding to 60 a lifetime	Larger amounts of waste possible	Waste inventory based on 300 Wa(e) scenario (5.1a)
B.2.1 Quantities of glass and associated radionuclide inventories *Low – compositions specified by the two reprocessors*	Inventory based on specified compositions (likely / expected)	Low – unless deviation from specified compositions is large	No alternative cases defined
B.3.1 Quantities of waste and associated radionuclide inventories *Uncertainty in inventories low, but two different waste specifications considered*	Inventory based on cemented waste option	Low – unless deviation from specified compositions is large	Inventory based on high force compaction option (5.2a)
Comment: Map is self-explanatory.			

Category: Safety-relevant features, phenomena & evolutions **System Component**: Repository			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.1.0.1 *EBS for SF / HLW / ILW – design parameters*	Reference design parameters	See design alternatives	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
Comment: Implicitly considered in a number of Super-FEPs. For example, the selected canister material and geometry affects the gas generation rates (B.3.6) and the canister breaching time (B.3.5).			

Tab. A4.1.2: (Cont.)

<table>
<tr><td colspan="4">Category: Safety-relevant features, phenomena & evolutions
System Component: Spent Fuel</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td colspan="2">Uncertainties and possible deviations</td></tr>
<tr><td>A.1.1
Radioactive inventories and decay processes (heat and radiation)</td><td>Inventories of radionuclides, half-lives and decay heat well defined; three canister inventories defined (BWR UO_2, PWR UO_2 and PWR MOX / UO_2) – average burnup 48 GWd/t_{IHM}</td><td colspan="2">Different canister types incorporate IRF variability and variability in burnups, possible increase in burnup up to 75 GWd/t_{IHM}</td></tr>
<tr><td>Super-FEP
Associated uncertainties and design / system options</td><td>Reference Case (1.1a)</td><td>Significance of uncertainties</td><td>Alternative cases (case numbers in parentheses)</td></tr>
<tr><td>B.1.1
Quantities and burnup of fuel and associated radionuclide inventories, including the instant release fraction (IRF)</td><td></td><td></td><td></td></tr>
<tr><td>B.1.1.1
The possibility for increased nuclear power production</td><td>Waste inventory based on 192 GWa(e) scenario, corresponding to 60 a lifetime</td><td>Larger amounts of waste possible</td><td>Waste inventory based on 300 GWa(e) scenario (5.1a)</td></tr>
<tr><td>B.1.1.2
The current trend to higher burnups</td><td>Burnup of 48 GWd/t_{IHM} assumed (likely / expected)</td><td>A higher average burnup results in a higher IRF – analyses of Reference Case indicate that radionuclides released in the IRF dominate the calculated dose maximum</td><td>Parameter variation with respect to Reference Case – increased burnups up to 75 GWd/t_{IHM} (1.1b)</td></tr>
<tr><td>B.1.1.2a
Chemical state of ^{14}C released from SF</td><td>^{14}C released in inorganic form</td><td>If ^{14}C released is organic, reduced geochemical retardation occurs</td><td>^{14}C released in organic form (1.1k)</td></tr>
<tr><td>B.1.1.3
The limited information available on the IRF of high burnup UO_2 fuel and MOX fuel</td><td>Burnup of 48 GWd/t_{IHM} assumed (likely / expected)</td><td>A higher average burnup results in a higher IRF – analyses of Reference Case indicate that radionuclides released in the IRF dominate the calculated dose maximum</td><td>Parameter variation with respect to Reference Case – increased burnups up to 75 GWd/t_{IHM} (1.1b)
(PDF for IRF)</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

Tab. A4.1.2: (Cont.)

<table>
<tr><td colspan="4">Category: Safety-relevant features, phenomena & evolutions
System Component: Spent Fuel</td></tr>
<tr><th>Key phenomenon</th><th>Expected evolution</th><th colspan="2">Uncertainties and possible deviations</th></tr>
<tr><td>A.1.2
Cladding failure and corrosion</td><td>Possible short-term failure (cracking), partially failed cladding slows release; slow corrosion-rate controlled release of activation products from Zircaloy, preferential release of some organic ^{14}C from oxide film of cladding</td><td colspan="2"></td></tr>
<tr><th>Super-FEP
Associated uncertainties and design / system options</th><th>Reference Case (1.1a)</th><th>Significance of uncertainties</th><th>Alternative cases (case numbers in parentheses)</th></tr>
<tr><td>B.1.2
Corrosion of cladding
(see also "The creation of gas pathways", B.7.1.1)
Whether preferential release of organic ^{14}C from the cladding occurs; corrosion rate of cladding</td><td>Constant rate of corrosion assumed, but with some organic ^{14}C assigned to the IRF (pessimistic)</td><td>Affects instant release fraction (IRF), time-dependent release rate and degree of geochemical retardation</td><td>"What if?" case with 10 × higher corrosion rate (4.9a)
(PDF for cladding corrosion rate)</td></tr>
<tr><td>B.1.3
Breaching of cladding
The possibility of early fracturing of the cladding, preventing an extended period of complete containment following canister breaching</td><td>Possibility of extended period of complete containment following canister breaching not included (pessimistic)</td><td>Sensitivity analyses indicate that the period of complete containment for canisters has small effects on overall system performance, within the range investigated; this is expected to apply to cladding as well</td><td>No alternative cases defined</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

Tab. A4.1.2: (Cont.)

Category: Safety-relevant features, phenomena & evolutions **System Component**: Spent Fuel			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.1.3 Leaching of IRF	IRF dissolves upon canister breaching	Limited information on the IRF of MOX and high burnup UO_2 fuel	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.1.1 Quantities and burnup of fuel and associated radionuclide inventories, including the instant release fraction (IRF)			
B.1.1.2 *The current trend to higher burnups*	Burnup of 48 GWd/t_{IHM} assumed (likely / expected)	A higher average burnup results in a higher IRF – analyses of Reference Case indicate that radionuclides released in the IRF dominate the calculated dose maximum	Parameter variation with respect to Reference Case – increased burnups up to 75 GWd / t_{IHM} (1.1b)
B.1.1.3 *The limited information available on the IRF of high burnup UO_2 fuel and MOX fuel*	Burnup of 48 GWd/t_{IHM} assumed (likely / expected)	A higher average burnup results in a higher IRF – analyses of Reference Case indicate that radionuclides released in the IRF dominate the calculated dose maximum	Parameter variation with respect to Reference Case – increased burnups up to 75 GWd/t_{IHM} (1.1b) (PDF for IRF)
B.7.1 The migration of repository induced gas ***B.7.1.6*** *Extent of preferential release of organic ^{14}C from SF cladding*	Gas pathways unimportant (likely / expected)	Could affect release of radionuclides with the potential to form volatile species along gas pathways	Some ^{14}C assigned to the IRF (all affected cases)
Comment: Map is self-explanatory.			

Tab. A4.1.2: (Cont.)

<table>
<tr><td colspan="4">Category: Safety-relevant features, phenomena & evolutions
System Component: Spent Fuel</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td colspan="2">Uncertainties and possible deviations</td></tr>
<tr><td>A.1.4
Dissolution of SF matrix</td><td>Extremely slow dissolution rate (solubility-controlled) because of reducing capacity of H_2</td><td colspan="2">Oxidising conditions at fuel surface from α-radiolysis (dissolution rate decreases proportionally with α-activity); preferential release of organic ^{14}C from fuel matrix; "what if?" case assuming high oxidant yield</td></tr>
<tr><td>Super-FEP
Associated uncertainties and design / system options</td><td>Reference Case (1.1a)</td><td>Significance of uncertainties</td><td>Alternative cases (case numbers in parentheses)</td></tr>
<tr><td>B.1.4
Dissolution of fuel matrix
B.1.4.1
Whether the rate of dissolution is controlled by the rate of production of radiolytic oxidants or (if reducing conditions prevail at the fuel surface) by the solubility of U(IV)</td><td>Rate of dissolution is controlled by the rate of production of radiolytic oxidants (conservative, given the pessimistically chosen parameters for this model – see below)</td><td>If, as expected, reducing conditions prevail at the fuel surface, then the fuel dissolution rate, and radionuclide release rates from the fuel matrix, will be very low, but the IRF will be unaffected</td><td>Alternative conceptualisation within the Reference Scenario – rate of dissolution controlled by diffusion and the solubility of U(IV) (1.2a)</td></tr>
<tr><td>B.1.4.2
If the rate of dissolution is controlled by the rate of production of radiolytic oxidants, the proportion of the oxidants that is available for reaction at the fuel surface (not recombined, e.g. with radiolytic reductants)</td><td>Proportionality is assumed between the production rate of oxidants and the dissolution rate of the fuel, with a proportionality constant pessimistically chosen on the basis of wide ranging experimental data and observations from nature</td><td>Affects the rate of release of radionuclides from the fuel matrix, but the IRF will be unaffected</td><td>"What if?" case of fuel dissolution rate increased 10 (4.3a) and 100 fold (4.3b) with respect to Reference Case
(PDF for fuel matrix dissolution rate)</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

<table>
<tr><td colspan="4">Category: Safety-relevant features, phenomena & evolutions
System Component: Spent Fuel</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td colspan="2">Uncertainties and possible deviations</td></tr>
<tr><td>A.1.5
Criticality</td><td>Avoided by design basis (geometry, burnup credit)</td><td colspan="2"></td></tr>
<tr><td>Super-FEP
Associated uncertainties and design / system options</td><td>Reference Case (1.1a)</td><td>Significance of uncertainties</td><td>Alternative cases (case numbers in parentheses)</td></tr>
<tr><td>B.1.5
Criticality
Whether or not it can be completely ruled out</td><td>Not considered further (analysis shows low burnups of SF can preclude criticality)</td><td>Ruled out by design and supporting calculations</td><td>Not considered</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

Tab. A4.1.2: (Cont.)

Category: Safety-relevant features, phenomena & evolutions **System Component**: HLW glass			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.2.1 Radioactive inventories and decay processes (heat and radiation)	Inventories of radionuclides, half-lives and decay heat well defined; two HLW glass types defined (BNFL and COGEMA)		
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.2.1 Quantities of glass and associated radionuclide inventories *Low – compositions specified by the two reprocessors*	Inventory based on specified compositions (likely / expected)	Low – unless deviation from specified compositions is large	No alternative cases defined
Comment: Map is self-explanatory.			

Category: Safety-relevant features, phenomena & evolutions **System Component**: HLW glass			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.2.2 Dissolution of glass	Different rates for each glass type based on laboratory experiments	Long-term extrapolation uncertain – rates 100 × higher or 20 × lower	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.2.2 Dissolution rate of glass *Long-term rates based on extrapolation of much shorter-term experiments; creation of additional surfaces for dissolution by fracturing of glass*	Long-term rates taken directly from experiments (likely / expected); fracturing represented in terms of equivalent spheres	Although sensitivity of dose to dissolution rate is expected to be small, a specific assessment case with an increased dissolution rate is analysed because the glass matrix is an important barrier	Pessimistic case with glass dissolution rate increased ~ 100 fold (1.1e) (PDF for glass dissolution rate)
Comment: Map is self-explanatory.			

Tab. A4.1.2: (Cont.)

Category: Safety-relevant features, phenomena & evolutions **System Component**: Steel SF / HLW canisters			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.3.1 Failure mechanisms	Brief oxic corrosion phase, limited pitting and microbial corrosion, slow anaerobic corrosion, no SCC – 10 000 a lifetime	Unlikely shorter-term failure (e.g. uncertainties regarding SCC) leading to loss of containment in 1000 a; residual transport resistance not considered	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.3.5 Breaching of steel canisters			
B.3.5.1 *The conditions under which mechanical failure of corroded canisters will occur; possibility of localised corrosion processes*	Canisters breached at 10 000 a (pessimistic assumption)	Sensitivity analyses indicate small effects on overall performance, although performance of canisters (a pillar of safety) is affected	Parameter variation with respect to Reference Case – further reduced canister lifetime of 1000 a (1.1c)
B.3.5.2 *The remote possibility of breaching prior to 1000 a, and the possibility of initially defective steel canisters*	Canisters breached at 10 000 a (pessimistic assumption)	Early failure has low probability (1 in 1000 canisters), thus early releases would be small	No alternative cases defined (see, however, "canister material", B.3.7)
B.3.5.3 *Distribution of canister breaching times*	All canisters breached simultaneously (conservative) *The spreading of radionuclide releases in time due to the fact that SF / HLW canisters would not be breached simultaneously is omitted (reserve FEP)*	Gives rise to attenuation of releases due to spreading in time	No alternative cases defined
Comment: Map is self-explanatory.			

Tab. A4.1.2: (Cont.)

Category: Safety-relevant features, phenomena & evolutions **System Component**: Steel SF / HLW canisters			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.3.2 Gas generation	Anaerobic corrosion producing H_2 gas continuously at a low rate	Uncertainty in anaerobic corrosion rate, possible gas induced porewater displacement (from void space in SF canisters)	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.3.6 Gas generation by steel canister corrosion	See "The creation of gas pathways", *B.7.1.1*		
B.3.7 Canister material *Design option of a copper canister with steel insert for SF (or alternative material to mitigate / avoid gas production)*	Steel canisters	Expected to give an extended period of complete containment and to largely eliminate gas generation in the case of SF	Copper / steel canisters, which are breached simultaneously at 100 000 a (5.3a), or a case in which one canister has an initial pinhole defect, with full breaching at 100 000 a (5.3b/c)
B.7.1 The migration of repository induced gas ***B.7.1.3*** *The rate of gas generation by corrosion of the SF / HLW canisters*	Gas pathways unimportant (likely / expected)	Affects rate of transport along gas pathways	No alternative cases defined
Comment: Map is self-explanatory.			

Tab. A4.1.2: (Cont.)

Category: Safety-relevant features, phenomena & evolutions **System Component**: Steel SF / HLW canisters			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.3.3 Corrosion products – sorption and redox effects	Sorption of radionuclides onto corrosion products (difficult to quantify); corrosion contributes to reducing conditions		
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.4.2 Geochemical immobilisation and retardation in the near field ***B.4.2.3*** *The extent of sorption of radionuclides on canister corrosion products*	*Sorption of radio-nuclides on canister corrosion products conservatively omitted (reserve FEP)*	Could significantly enhance retention and decay in the near field, but the neces-sary data for model-ling is unavailable	No alternative cases defined
Comment: Map is self-explanatory.			

Category: Safety-relevant features, phenomena & evolutions **System Component**: Steel SF / HLW canisters			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.3.4 Corrosion products – volume expansion effects	Small effect on canister load prior to 10 000 a canister lifetime		
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.3.5 Breaching of steel canisters ***B.3.5.1*** *The conditions under which mechanical failure of corroded canisters will occur; possibility of localised corrosion processes*	Canisters breached at 10 000 a (pessimistic assumption)	Sensitivity analyses indicate small effects on overall perfor-mance, although performance of canisters (a pillar of safety) is affected	Parameter variation with respect to Refe-rence Case – further reduced canister lifetime of 1000 a (1.1c)
Comment: Map is self-explanatory.			

Tab. A4.1.2: (Cont.)

Category: Safety-relevant features, phenomena & evolutions **System Component**: SF / HLW			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.4.1 Precipitation of radionuclides	Solubility limits in the near field (canister / bentonite porewater) for many radionuclides, reducing conditions, co-precipitation of Ra with Ba and Sr	Uncertainties in solubilities; solubilities also defined for "what if?" case of oxidising conditions in near field	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.4.2 Geochemical immobilisation and retardation in the near field			
B.4.2.1 *Thermodynamic data and water chemistry*	Solubility limits and sorption coefficients in the near field based on realistic near field geochemical dataset	Relevant to the evaluation of solubility limits and sorption coefficients, and thus to retention and decay in the near field	Parameter variations for solubilities and sorption coefficients in the near field based on pessimistic geochemical dataset (1.1d) and for pessimistic sorption coefficients in the geosphere (1.1i) (PDF for solubilities and K_d values)
B.4.2.2 *The extent of co-precipitation of radionuclides with secondary minerals derived from SF and glass dissolution and canister corrosion*	Co-precipitation of radium is taken into account *Co-precipitation of other radionuclides is conservatively omitted (reserve FEP)*	Co-precipitation could significantly enhance retention and decay in the near field, but the necessary data for modelling is unavailable for most radionuclides	No alternative cases defined
B.4.2.4 *The natural concentrations of isotopes in bentonite porewater*	*Natural concentrations of isotopes conservatively neglected when evaluating whether solubility limits are exceeded and precipitation occurs (reserve FEP)*	Could reduce the effective solubilities of some radionuclides	No alternative cases defined
Comment: Map is self-explanatory.			

Tab. A4.1.2: (Cont.)

Category: Safety-relevant features, phenomena & evolutions **System Component**: Bentonite			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.5.0 Resaturation	Slow resaturation, delaying start of corrosion and radionuclide release	Time to resaturation is uncertain (~ 100 to 100s of years)	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.4.1 The long resaturation time of the repository and its surroundings *The rate of the resaturation process*	*SF / HLW parts of repository are conservatively assumed to be resaturated at time of repository closure (reserve FEP)*	Delays commencement of corrosion and dissolution processes – likely to be of low importance for SF / HLW except in the case of earlier than expected canister breaching	No alternative cases defined
Comment: Map is self-explanatory.			

Category: Safety-relevant features, phenomena & evolutions **System Component**: Bentonite			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.5.1 Radionuclide transport	Diffusion only; good sorption; chemical stability (large amount of material, low water flow rate at outer boundary, mineralogical similarity to Opalinus Clay); colloid filtration	Uncertainty in diffusivity and sorption on bentonite	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.4.2 Geochemical immobilisation and retardation in the near field ***B.4.2.1a*** *Colloid filtration by bentonite*	No colloid transport because of small pore size and tortuosity of bentonite	Small pore size eliminates colloid transport	No alternative cases defined
B.4.5 Transport resistances provided by internal spaces (fractures) within the waste forms, by the breached SF / HLW canisters and by corrosion products *The magnitude and time-dependence of these resistances*	*Transport resistances conservatively omitted except for Cu canister cases (reserve FEP) (5.3b/c)*	Increases radionuclide transport times, but likely to be a small effect compared to the overall transport resistance of the clay barrier (bentonite buffer and Opalinus Clay)	No alternative cases defined
Comment: Map is self-explanatory.			

Tab. A4.1.2: (Cont.)

<table>
<tr><td colspan="4">Category: Safety-relevant features, phenomena & evolutions
System Component: Bentonite</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td colspan="2">Uncertainties and possible deviations</td></tr>
<tr><td>A.5.2
Thermal alteration</td><td>Degradation mitigated by mixing of UO_2 / MOX fuel assemblies to keep temperatures down; little impact on swelling or plasticity</td><td colspan="2">Some cementation and increased diffusivity near canister</td></tr>
<tr><td>Super-FEP
Associated uncertainties and design / system options</td><td>Reference Case (1.1a)</td><td>Significance of uncertainties</td><td>Alternative cases (case numbers in parentheses)</td></tr>
<tr><td>B.4.4
Thermal alteration of the bentonite buffer adjacent to the SF / HLW canisters
Existence / extent of any thermally altered region</td><td>No significant alteration occurs (likely / expected)</td><td>Some detrimental effects on transport-relevant properties within affected region cannot be excluded; sensitivity analyses indicate that degradation of properties of a small part of the bentonite is insignificant with respect to overall performance</td><td>Alternative conceptualisation within the Reference Scenario – inner half of bentonite thermally altered, with pore diffusion coefficient (D_p) set equal to that of free water; no effects on sorption (1.3a)</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

<table>
<tr><td colspan="3">Category: Safety-relevant features, phenomena & evolutions
System Component: Bentonite</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td>Uncertainties and possible deviations</td></tr>
<tr><td>A.5.3
Additional transport processes (Onsager)</td><td>Impact likely small; driving forces small beyond 1000 a</td><td></td></tr>
<tr><td colspan="3">Comment: Based on scientific evidence, off-diagonal Onsager processes can be shown to have a insignificant effect on radionuclide transport through the bentonite. For this reason, no specific Super-FEP and assessment case were considered for these processes.</td></tr>
</table>

Tab. A4.1.2: (Cont.)

Category: Safety-relevant features, phenomena & evolutions **System Component**: Bentonite			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.5.4 Redox-front penetration (radiolytic oxidation)	Oxidants scavenged by H_2 and Fe	Evidence appears to eliminate redox front penetration, "what if?" case only	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.4.3 Migration of radiolytic oxidants generated at SF surfaces into bentonite buffer *Degree to which these oxidants are scavenged by reductants in the system*	Oxidants consumed by steel – no migration into the bentonite (likely / expected)	Scoping calculations indicate that only a small proportion of the bentonite would be affected and sensitivity analyses indicate that degradation of properties of a small part of the bentonite is insignificant with respect to overall performance	"What if?" case (4.4a) of radiolytic oxidants affecting the bentonite, bounded by a redox front
Comment: Map is self-explanatory.			

Category: Safety-relevant features, phenomena & evolutions **System Component**: Bentonite			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.5.5 Gas transport	Release to rock by pathway dilation; negligible water expulsion		
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.4.7.1 Gas transport characteristics of bentonite *Uncertainties in corrosion rate*		Water transport unaffected by gas buildup and transport, except in the case of gas induced porewater displacement from void space in canisters	Alternative conceptualisation within the Reference Scenario (cases 1.8a)
Comment: Map is self-explanatory.			

Category: Safety-relevant features, phenomena & evolutions **System Component**: Bentonite		
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**
A.5.6 Microbial effects	Lack of viability of microbes in dense bentonite, no significant effects	
Comment: Based on scientific evidence, microbial effects can be shown to only insignificantly affect radionuclide transport through the bentonite. For this reason, no specific Super-FEP and assessment case were considered for these processes.		

Tab. A4.1.2: (Cont.)

Category: Safety-relevant features, phenomena & evolutions **System Component**: Bentonite / EDZ			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.6.1 Enhanced hydraulic flow along EDZ	Approximately 10 times higher long-term hydraulic conductivity, lack of connectivity of fractures; connected EDZ limited by bentonite seals at emplacement tunnel ends	Hypothetical EDZ hydraulic conductivity of 10^{-10} m s^{-1}	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.5.1 Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)			
B.5.1.1 *The hydraulic conductivity of the EDZs with respect to that of the surrounding undisturbed rock*	The self-sealing capacity of the host rock means that any EDZ with enhanced hydraulic conductivity is a transient feature, and can be neglected (likely / expected)	Relatively high hydraulic conductivity of the EDZ could allow dissolved radionuclides to migrate along the tunnels / ramp / shaft, driven by the natural hydraulic gradient	Alternative conceptualisation within the Reference Scenario – release of radionuclides affected by the ramp / shaft and their surrounding EDZs (1.6a/b)
B.5.1.3 *The driving force for flow along the EDZs provided by near field gas, as well as the rate of near field gas production (see also "The migration of repository induced gas",* B.7.1*)*	The self-sealing capacity of the host rock means that any EDZ with enhanced hydraulic conductivity is a transient feature, and can be neglected (likely / expected)	As B.5.1.1 (Relatively high hydraulic conductivity of the EDZ could allow dissolved radionuclides to migrate along the tunnels / ramp / shaft, driven by the natural hydraulic gradient), but with near field gas pressure providing the driving force for migration along the tunnels / ramp / shaft	Alternative conceptualisation within the Reference Scenario – gas induced release of dissolved radionuclides affected by the ramp / shaft and their surrounding EDZs, two different waste forms (SF and ILW) and for each waste form, two rates of water flow (1.8a/b)
Comment: Map is self-explanatory.			

Tab. A4.1.2: (Cont.)

<table>
<tr><td colspan="4">Category: Safety-relevant features, phenomena & evolutions
System Component: Bentonite / EDZ</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td colspan="2">Uncertainties and possible deviations</td></tr>
<tr><td>A.6.2
Gas transport</td><td>Pathway dilation along EDZ and into host rock, capillary leakage into rock; alteration of groundwater transport properties of bentonite, EDZ not expected</td><td colspan="2"></td></tr>
<tr><td>Super-FEP
Associated uncertainties and design / system options</td><td>Reference Case (1.1a)</td><td>Significance of uncertainties</td><td>Alternative cases (case numbers in parentheses)</td></tr>
<tr><td>B.4.7.1
Gas transport characteristics of bentonite
Uncertainties in corrosion rate</td><td></td><td>Water transport unaffected by gas build-up and transport, except in the case of gas induced pore-water displacement from void space in canisters</td><td></td></tr>
<tr><td>B.5.1
Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)
B.5.1.3
The driving force for flow along the EDZs provided by near field gas, as well as the rate of near field gas production (see also "The migration of repository induced gas", B.7.1)</td><td>The self-sealing capacity of the host rock means that any EDZ with enhanced hydraulic conductivity is a transient feature, and can be neglected (likely / expected)</td><td>As B.5.1.1 (Relatively high hydraulic conductivity of the EDZ could allow dissolved radionuclides to migrate along the tunnels / ramp / shaft, driven by the natural hydraulic gradient), but with near field gas pressure providing the driving force for migration along the tunnels / ramp / shaft</td><td>Alternative conceptualisation within the Reference Scenario – gas induced release of dissolved radionuclides affected by the ramp / shaft and their surrounding EDZs, two different waste forms (SF and ILW) and for each waste form, two rates of water flow (1.8a/b)</td></tr>
<tr><td>B.7.1
The migration of repository induced gas
B.7.1.2
The possibility that the EDZs would allow the tunnels / ramp / shaft to provide gas pathways and the uncertainties in gas permeability</td><td>Gas pathways unimportant (likely / expected)</td><td>Affects properties of pathways</td><td>Alternative conceptualisation within scenario addressing transport of radionuclides as volatile species – "leaky seals" (2.2a/b/c)</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

Tab. A4.1.2: (Cont.)

<table>
<tr><td colspan="4">Category: Safety-relevant features, phenomena & evolutions
System Component: Bentonite / EDZ</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td colspan="2">Uncertainties and possible deviations</td></tr>
<tr><td>A.6.3
Tunnel convergence and compaction of bentonite</td><td>Compaction most likely completed before canister breaching (concurrent with saturation), will be limited due to bentonite swelling</td><td colspan="2">Long-term very slow further compaction</td></tr>
<tr><td>Super-FEP
Associated uncertainties and design / system options</td><td>Reference Case (1.1a)</td><td>Significance of uncertainties</td><td>Alternative cases (case numbers in parentheses)</td></tr>
<tr><td>B.4.7
Hydraulic transport characteristics of bentonite
Compaction of bentonite by tunnel convergence</td><td>Decreased bentonite thickness due to tunnel convergence</td><td>Not significant, as convergence expected to be concurrent with resaturation</td><td>No alternative cases defined
(PDF for D_e)</td></tr>
<tr><td>B.5.1
Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)
B.5.1.2
The driving force for flow along the EDZs provided by tunnel convergence</td><td>The self-sealing capacity of the host rock means that any EDZ with enhanced hydraulic conductivity is a transient feature, and can be neglected (likely / expected)</td><td>As B.5.1.1 (Relatively high hydraulic conductivity of the EDZ could allow dissolved radionuclides to migrate along the tunnels / ramp / shaft, driven by the natural hydraulic gradient), but with tunnel convergence providing the driving force for migration along the tunnels / ramp / shaft</td><td>Alternative conceptualisation within the Reference Scenario – convergence induced release of radionuclides affected by the ramp / shaft and their surrounding EDZs, two different modelling approaches (1.7a/b)</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

Tab. A4.1.2: (Cont.)

<table>
<tr><td colspan="4">Category: Safety-relevant features, phenomena & evolutions
System Component: ILW</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td colspan="2">Uncertainties and possible deviations</td></tr>
<tr><td>A.7.1
Radioactive inventories and decay processes (heat and radiation)</td><td>Inventories of radio-nuclides, half-lives and decay heat well defined (cemented waste option)</td><td colspan="2">Inventory option (high force compacted waste)</td></tr>
<tr><td>Super-FEP
Associated uncertainties and design / system options</td><td>Reference Case (1.1a)</td><td>Significance of uncertainties</td><td>Alternative cases (case numbers in parentheses)</td></tr>
<tr><td>B.3.1
Quantities of waste and associated radionuclide inventories
Uncertainty in inventories low, but two different waste specifications considered</td><td>Inventory based on cemented waste option</td><td>Low – unless deviation from specified compositions is large</td><td>Inventory based on high force compaction option (5.2a)</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

Tab. A4.1.2: (Cont.)

Category: Safety-relevant features, phenomena & evolutions **System Component**: ILW			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.7.2 Breaching of waste containers; dissolution / leaching of radionuclides	Potential breaching and radionuclide release begins after > 100 a, as a result of slow resaturation; release rates from cemented waste and bitumen uncertain; very slow release from Zircaloy because of low corrosion rate, with some rapid release from oxide film	Longer-term containment by some steel canisters	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.3.2 Breaching of ILW steel drums and emplacement containers *The timing of drum / container breaching*	*Complete containment by drums / containers omitted (reserve FEP) –* Release from ILW delayed until 100 a after emplacement due to slow resaturation of near field	Affects period of total containment	No alternative cases defined
B.3.3 Corrosion / dissolution of ILW *Rate of corrosion / dissolution of waste matrix and rate of release of radionuclides*	Immediate release of all radionuclides in ILW into near-field porewater 100 a after emplacement of wastes *The delayed release of radionuclides due to the slow corrosion rate of ILW metallic materials (e.g. hulls and ends) is conservatively neglected (reserve FEP)*	The delayed release of radionuclides due to the slow corrosion rate of ILW metallic materials (e.g. hulls and ends) potentially significant	No alternative cases defined
Comment: Map is self-explanatory.			

Tab. A4.1.2: (Cont.)

<table>
<tr><td colspan="4">Category: Safety-relevant features, phenomena & evolutions
System Component: ILW</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td colspan="2">Uncertainties and possible deviations</td></tr>
<tr><td>A.7.3
Precipitation of radionuclides</td><td>Solubility limits in the near field (cementitious waste / mortar porewater) for many radionuclides, reducing conditions</td><td colspan="2">Uncertainties in solubilities</td></tr>
<tr><td>Super-FEP
Associated uncertainties and design / system options</td><td>Reference Case (1.1a)</td><td>Significance of uncertainties</td><td>Alternative cases (case numbers in parentheses)</td></tr>
<tr><td>B.3.3.2
Immobilisation and retardation in the ILW near field
Thermodynamic data and water chemistry</td><td>Solubility limits and sorption coefficients in the ILW near field based on realistic dataset
Sorption of nuclides on canister corrosion products conservatively neglected (reserve FEP)</td><td>Relevant to the evaluation of solubility limits and sorption coefficients, and thus to retention and decay in the near field</td><td>Parameter variations with respect to Reference Case – solubility limits and sorption coefficients in the near field based on pessimistic geochemical dataset (1.1d, 1.1i)
(PDF for solubilities in near field and K_d values in near and far field)
"What if?" case for redox front from compacted hulls (4.4a)</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

Tab. A4.1.2: (Cont.)

Category: Safety-relevant features, phenomena & evolutions **System Component**: ILW			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.7.4 Reduced sorption, increased solubility of radionuclides due to complexants in ILW	Separate wastes with high complexant contents into separate emplacement tunnel (ILW-2)		
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.3.3.2 Immobilisation and retardation in the ILW near field *Thermodynamic data and water chemistry*	Solubility limits and sorption coefficients in the ILW near field based on realistic dataset *Sorption of nuclides on canister corrosion products conservatively neglected (reserve FEP)*	Relevant to the evaluation of solubility limits and sorption coefficients, and thus to retention and decay in the near field	Parameter variations with respect to Reference Case – solubility limits and sorption coefficients in the near field based on pessimistic geochemical dataset (1.1d, 1.1i) (PDF for solubilities in near field and K_d values in near and far field) "What if?" case for redox front from compacted hulls (4.4a)
Comment: Map is self-explanatory.			

Category: Safety-relevant features, phenomena & evolutions **System Component**: ILW			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.7.5 Radionuclide transport in ILW tunnels	Low water flow rate (diffusion-dominated transport), good sorption	Uncertainties in sorption; "what if?" case for redox front formation from compacted hulls radiolysis	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.4.8 Hydraulic and gas transport characteristics of the ILW near field *Inflow rate of water; displacement of water by gas into rock and along tunnels*		Influences rate of gas pressure buildup and timing of gas pathway formation in Opalinus Clay	Alternative conceptualisation within the Reference Scenario (1.8b)
Comment: Map is self-explanatory.			

Tab. A4.1.2: (Cont.)

Category: Safety-relevant features, phenomena & evolutions **System Component**: ILW			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.7.6 Gas generation	Corrosion of metals and biodegradation of cellulose and other organics	Uncertainties in rates of gas generation	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.3.4 Gas generation	See "The creation of gas pathways", *B.7.1.1*		
B.4.8 Hydraulic and gas transport characteristics of the ILW near field *Inflow rate of water; displacement of water by gas into rock and along tunnels*		Influences rate of gas pressure buildup and timing of gas pathway formation in Opalinus Clay	Alternative conceptualisation within the Reference Scenario (1.8b)
B.7.1 The migration of repository induced gas ***B.7.1.5*** *The rate of generation of gas by ILW*	Gas pathways unimportant (likely / expected)	Affects rate of transport along gas pathways	No alternative cases defined
Comment: Map is self-explanatory.			

Category: Safety-relevant features, phenomena & evolutions **System Component**: ILW			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.7.6a Displacement of water by gas	Some porewater displaced from containers and mortar into rock	Water displaced along tunnels / EDZ if seals less effective	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.4.8 Hydraulic and gas transport characteristics of the ILW near field *Inflow rate of water; displacement of water by gas into rock and along tunnels*		Influences rate of gas pressure buildup and timing of gas pathway formation in Opalinus Clay	Alternative conceptualisation within the Reference Scenario (1.8b)
Comment: Map is self-explanatory.			

Tab. A4.1.2: (Cont.)

Category: Safety-relevant features, phenomena & evolutions **System Component**: ILW			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.7.7 Tunnel convergence and compaction of waste / mortar with water displacement	Effect mitigated by choice of materials (mortar with sufficient strength, relatively low porosity), process occurs concurrent with saturation	Porewater displacement due to compaction of void space in waste packages after full resaturation	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.3.3.1 Compaction of waste / mortar (see B.4.7) *Timing of convergence arising from void reduction of breached, corroded containers*			Alternative conceptualisation dealing with rapid and very slow convergence (1.7a/b)
B.5.1 Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs) ***B.5.1.2*** *The driving force for flow along the EDZs provided by tunnel convergence*	The self-sealing capacity of the host rock means that any EDZ with enhanced hydraulic conductivity is a transient feature, and can be neglected (likely / expected)	As B.5.1.1 (Relatively high hydraulic conductivity of the EDZ could allow dissolved radionuclides to migrate along the tunnels / ramp / shaft, driven by the natural hydraulic gradient), but with tunnel convergence providing the driving force for migration along the tunnels / ramp / shaft	Alternative conceptualisation within the Reference Scenario – convergence induced release of radionuclides affected by the ramp / shaft and their surrounding EDZs, two different modelling approaches (1.7a/b)
Comment: Map is self-explanatory.			

Tab. A4.1.2: (Cont.)

Category: Safety-relevant features, phenomena & evolutions **System Component**: ILW			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.7.8 Resaturation time	Long resaturation time (hundreds of years)		
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.3.3.3 The long resaturation time of the ILW tunnels *The rate of the resaturation process*	Release from ILW commences at 100 a after emplacement *The long resaturation time of the repository and its surroundings, which delays the commencement of corrosion and dissolution processes is conservatively neglected (reserve FEP)*	Delays commencement of corrosion and dissolution processes	No alternative cases defined
Comment: Map is self-explanatory.			

Category: Safety-relevant features, phenomena & evolutions **System Component**: Mortar / EDZ interface			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.8.1 High pH plume migration into host rock	Porosity reduction in rock, self-sealing (conservatively neglected), depth of reaction front very limited	4 m maximum disturbance of Opalinus Clay based on mass balance	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.6.4 Migration of high pH plume from ILW backfill into Opalinus Clay *The depth of migration, and associated physical and chemical changes in the clay*	Not considered further, because the maximum possible depth of migration, based on mass balance, is about 4 m	The maximum possible depth of migration, based on mass balance, is about 4 m; even if it is hypothetically assumed that this results in a complete loss of geochemical retardation over this distance, the sensitivity analyses show that the impact on the performance of the Opalinus Clay as a transport barrier is small	Not considered
Comment: Map is self-explanatory.			

Tab. A4.1.2: (Cont.)

Category: Safety-relevant features, phenomena & evolutions **System Component**: Tunnels / ramp / shaft seals			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.8.2 Radionuclide transport by advection in tunnel backfill / EDZ	Effective sealing, no preferential transport because of limited EDZ conductivity, effective seals, relatively low gradient	Less effective seals, preferential transport in operations tunnel backfill, EDZ of tunnels, ramp and shaft (EDZ hydraulic conductivity of up to 10^{-10} m s^{-1})	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.5.1 Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs) ***B.5.1.1*** *The hydraulic conductivity of the EDZs with respect to that of the surrounding undisturbed rock*	The self-sealing capacity of the host rock means that any EDZ with enhanced hydraulic conductivity is a transient feature, and can be neglected (likely / expected)	Relatively high hydraulic conductivity of the EDZ could allow dissolved radionuclides to migrate along the tunnels / ramp / shaft, driven by the natural hydraulic gradient	Alternative conceptualisation within the Reference Scenario – release of radionuclides affected by the ramp / shaft and their surrounding EDZs (1.6a/b)
Comment: Map is self-explanatory.			

Category: Safety-relevant features, phenomena & evolutions **System Component**: Tunnels / ramp / shaft seals			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.8.3 Transport of gas containing volatile ^{14}C along tunnels, ramp and shaft	Volatile ^{14}C not expected; if it forms it may move through pathways in host rock and EDZ, seals effective	Possibility that gas containing volatile ^{14}C is transported along tunnels, ramp and shaft – seals less effective	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.7.1 The migration of repository induced gas ***B.7.1.2*** *The possibility that the EDZs would allow the tunnels / ramp / shaft to provide gas pathways and the uncertainties in gas permeability*	Gas pathways unimportant (likely / expected)	Affects properties of pathways	Alternative conceptualisation within scenario addressing transport of radionuclides as volatile species – "leaky seals" (2.2a/b/c)
Comment: Map is self-explanatory.			

Tab. A4.1.2: (Cont.)

<table>
<tr><td colspan="4">Category: Safety-relevant features, phenomena & evolutions
System Component: Tunnel plug / operations tunnel backfill</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td colspan="2">Uncertainties and possible deviations</td></tr>
<tr><td>A.9.1
Gas buildup and transport in ILW emplacement tunnels</td><td>Gas storage potential in operations tunnel back-fill not considered</td><td colspan="2">Effects of gas buildup and transport in ILW emplacement tunnels mitigated by axial pathway dilation through EDZ and past tunnel plug</td></tr>
<tr><td>Super-FEP
Associated uncertainties and design / system options</td><td>Reference Case (1.1a)</td><td>Significance of uncertainties</td><td>Alternative cases (case numbers in parentheses)</td></tr>
<tr><td>B.5.2
The seals and the surrounding rock (see also "The creation of gas pathways", B.7.1.1)
The possibility of sealed zones being bypassed by relatively permeable EDZs</td><td>Seals remain effective (likely / expected)</td><td>The bypassing of seals could allow dissolved radio-nuclides to migrate preferentially along the tunnels / ramp / shaft, driven by near field gas pressure</td><td>"What if?" cases (4.5a/b) of gas induced release of dissolved radio-nuclides from ILW along ramp only, two different rates of water flow</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

<table>
<tr><td colspan="4">Category: Safety-relevant features, phenomena & evolutions
System Component: Host rock</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td colspan="2">Uncertainties and possible deviations</td></tr>
<tr><td>A.10.1
Length of vertical transport path in Opalinus Clay above and below emplacement tunnels</td><td>Typical path length of ~ 50 m, minimum path length of 40 m</td><td colspan="2">"What if ?" case of reduced path length</td></tr>
<tr><td>Super-FEP
Associated uncertainties and design / system options</td><td>Reference Case (1.1a)</td><td>Significance of uncertainties</td><td>Alternative cases (case numbers in parentheses)</td></tr>
<tr><td>B.6.1a
Length of vertical transport path from emplacement tunnels to overlying and underlying formations
Variability in path length</td><td>40 m path length (minimum value)</td><td>Relevant to transport time through Opalinus Clay and to degree of dispersion</td><td>"What if?" case based on 30 m path length (4.11a)
(PDF for transport path length)</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

Tab. A4.1.2: (Cont.)

Category: Safety-relevant features, phenomena & evolutions **System Component**: Host rock			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.10.2a Advective flow in Opalinus Clay	Flow rate of ~ 10^{-14} m s^{-1}, thus diffusion-dominated solute transport occurs	± 10 fold uncertainty; gas pressure buildup, tunnel convergence, transient increase of overpressure by glacial load, all may influence flow; "what if?" case for higher flows	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.6.1 Low groundwater flow rate through undisturbed Opalinus Clay (see also "Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones", B.5.1)			
B.6.1.1 *The groundwater flow rate through the Opalinus Clay, which is affected by uncertainties of about an order of magnitude*	Groundwater flow rate of 2×10^{-14} m s^{-1} (likely / expected)	Sensitivity analyses indicate that releases from Opalinus Clay of ^{129}I and ^{79}Se are affected by uncertainties in groundwater flow rate	Parameter variations with respect to Reference Case – groundwater flow rate in Opalinus Clay increased 10-fold (1.1f) and decreased 10-fold due to threshold hydraulic gradient (1.1g) (PDF for groundwater flow rate) "What if?"case (4.1a) – 100-fold increase with respect to Reference Case (RC) "What if?" case for no advection in rock (4.8a) "What if?"case (4.7a/b/c) – RC flow rate, 10-fold increase, 100-fold increase combined with pessimistic near field / geosphere geochemical dataset
B.6.1.2 *The effects of gas pressure buildup in the near field, tunnel convergence and ice loads on the hydraulic gradient*	The effects of gas pressure buildup in the near field, tunnel convergence and ice loads are insignificant (likely / expected)	Sensitivity analyses indicate that releases from Opalinus Clay of ^{129}I and ^{79}Se are affected by uncertainties in groundwater flow rate	Alternative conceptualisation within the Reference Scenario – glacially induced flow in the Opalinus Clay (1.4a)
B.6.1.3 *The eventual increase of hydraulic conductivity caused by erosion of the overburden*	Not considered because depth of overburden will be at least 450 m after 1 million years, thus hydraulic conductivity will be unaffected	Ruled out within the one million year period of primary interest in the safety assessment	Not considered
Comment: Map is self-explanatory.			

Tab. A4.1.2: (Cont.)

Category: Safety-relevant features, phenomena & evolutions **System Component**: Host rock			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.10.2b Geochemical retardation of radionuclide transport	Retardation of most radionuclides by sorption processes; effective colloid filtration	Uncertainties in sorption coefficients; "what if?" case for $K_d = 0$ for ^{129}I	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.6.2 Geochemical immobilisation and retardation in the Opalinus Clay and confining units			
B.6.2.1 *Sorption mechanisms and groundwater composition, diffusivity*	Sorption coefficients and diffusivities in the Opalinus Clay based on realistic geochemical dataset	Relevant to the evaluation of diffusion rates and sorption coefficients, and thus to retention and decay in the Opalinus Clay and confining units	Sorption coefficients in the Opalinus Clay based on pessimistic geochemical dataset (1.1h), pessimistic solubility limits and sorption coefficients in the near field (1.1i) and pessimistic geosphere diffusion constants (1.1j) (PDF for K_d values and diffusion constants in Opalinus Clay) "What if?" case for $K_d = 0$ for ^{129}I in bentonite and Opalinus Clay (4.10a)
B.6.2.2 *The effectiveness of long-term immobilisation processes (precipitation / co-precipitation) in the geosphere*	*Long-term immobilisation processes omitted (reserve FEP – conservative, except if a change in geochemical conditions leads to remobilisation of previously immobilised radionuclides)*	Could increase time available for decay during transport to the surface environment	No alternative cases defined
Comment: Map is self-explanatory.			

Tab. A4.1.2: (Cont.)

<table>
<tr><td colspan="4">Category: Safety-relevant features, phenomena & evolutions
System Component: Host rock</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td colspan="2">Uncertainties and possible deviations</td></tr>
<tr><td>A.10.3
Gas migration</td><td>Diffusion of dissolved gas, 2-phase flow and gas pathway dilation; low production rates and stress conditions favour slow horizontal propagation of 2-phase flow (homogeneous gas flow) and dilatant gas pathways, self-sealing of pathways; slow concurrent transport of volatile ^{14}C</td><td colspan="2">Rapid volatile ^{14}C transport along a continuous gas pathway – "what if?" case</td></tr>
<tr><td>Super-FEP
Associated uncertainties and design / system options</td><td>Reference Case (1.1a)</td><td>Significance of uncertainties</td><td>Alternative cases (case numbers in parentheses)</td></tr>
<tr><td>B.7.1
The migration of repository induced gas</td><td></td><td></td><td></td></tr>
<tr><td>B.7.1.1
The possibility that gas pathways are created through host rock and the uncertainty in gas permeability that might allow the transport of ^{14}C in a volatile form with flowing gas</td><td>Gas pathways unimportant (likely / expected)</td><td>Affects rate of transport of ^{14}C released by SF and ILW which has the potential to form volatile species</td><td>Alternative conceptualisation within scenario addressing transport of radionuclides as volatile species – "tight seals" (2.1a/b/c)</td></tr>
<tr><td>B.7.1.4
Rapid transport of radionuclides as volatile species through continuous gas path</td><td>Gas pathways unimportant (likely / expected)</td><td>Affects rate of transport along gas pathways</td><td>"What if?" case (4.6a-c) in which ^{14}C is transported unretarded through the host rock</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

Tab. A4.1.2: (Cont.)

Category: Safety-relevant features, phenomena & evolutions **System Component**: Host rock			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.10.4 Heterogeneous flow	Host rock has little heterogeneity (layering and no hydraulically active discontinuities); self-sealing is effective	Undetected discontinuities (although impact negligible because of self-sealing); evidence appears to eliminate heterogeneous flow, but "what if?" case is considered for pathways with increased transmissivities	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.6.3 Homogeneity			
B.6.3.1 *The possibility of low transmissivity (i.e. 10^{-10} $m^2\,s^{-1}$ or less) undetected discontinuities in the Opalinus Clay*	No discontinuities with significant transmissivities are present in the Opalinus Clay (likely / expected)	Although not totally excluded on the basis of current scientific understanding, these are shown by the sensitivity analyses to have negligible impact on the performance of the Opalinus Clay as a transport barrier, except possibly in the case of organic ^{14}C	"What if?" cases (4.2a/b/c) of a discontinuity of transmissivity 10^{-10} $m^2\,s^{-1}$ intersecting the repository, variants according to whether ILW or SF / HLW parts of the repository affected and, for SF / HLW, the number of canisters affected
B.6.3.2 *The possibility of higher-transmissivity discontinuities, faults and repository induced fractures*	Not considered; transmissivities of discontinuities $> 10^{-9}$ $m^2\,s^{-1}$ excluded because these are not observed even in folded, disturbed Opalinus Clay (rail and road tunnels) and because of self-sealing	Ruled out because of the self-sealing capacity of the clay	"What if?" cases for discontinuity with transmissivity 10^{-9} $m^2\,s^{-1}$ intersecting SF / HLW near field (4.2d/e) and ILW near field (4.2f)
Comment: Map is self-explanatory.			

Tab. A4.1.2: (Cont.)

Category: Safety-relevant features, phenomena & evolutions **System Component**: Geosphere		
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**
A.11.1 Neo-tectonic activity	Choice of site with low neo-tectonic activity (low uplift / erosion rates, low seismic activity, no magmatic activity); no reactivation of discontinuities	
Comment: Based on current scientific understanding, the existence of preferential pathways due to small fracture zones affected by neo-tectonic events can be excluded. No Super-FEP has therefore been considered for neo-tectonic activity. However, small fracture zones with an enhanced transmissivity are included in the safety analysis as a "what if?" case (4.2a-f), to test the effect of such enhanced transmissivities on system performance.		

Category: Safety-relevant features, phenomena & evolutions **System Component**: Geosphere			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.11.2 Retardation in local and regional aquifers	Not well characterised, therefore conservatively neglected	Retardation in confining units (vertical path) and local aquifers (horizontal path)	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.6.5 Radionuclide transport through the confining units and regional aquifers *Transport-relevant properties of the confining units and regional aquifers*	Decay during transport through the confining units / aquifers omitted (conservative)	Slow transport could increase time available for decay during transport to the surface environment	Alternative conceptualisation within the Reference Scenario – decay during vertical transport through the confining units (1.5a) or horizontal transport in local aquifers (1.5b) taken into account
Comment: Map is self-explanatory.			

Category: Safety-relevant features, phenomena & evolutions **System Component**: Geosphere		
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**
A.11.3 Natural resources	Choice of site with no viable natural resources	
Comment: The lack of resource conflicts in the siting area reduces the likelihood of intrusion. For this reason, no specific Super-FEP was considered for issues related to natural resources. However, a borehole penetration of the repository is investigated in the safety analysis (3.1a-g), to test the effect of such a borehole on the system performance.		

Tab. A4.1.2: (Cont.)

<table>
<tr><td colspan="4">Category: Safety-relevant phenomena / evolutions related to design basis and alternatives
System Component: Spent Fuel</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td colspan="2">Uncertainties and possible deviations</td></tr>
<tr><td>A.12.1
Definition of inventory for disposal</td><td>Current power plants operating for 60 years</td><td colspan="2">Increased inventory of SF (300 GWa(e) scenario)</td></tr>
<tr><td>Super-FEP
Associated uncertainties and design / system options</td><td>Reference Case (1.1a)</td><td>Significance of uncertainties</td><td>Alternative cases (case numbers in parentheses)</td></tr>
<tr><td>B.1.1
Quantities and burnup of fuel and associated radionuclide inventories, including the instant release fraction (IRF)
B.1.1.1
The possibility for increased nuclear power production</td><td>Waste inventory based on 192 GWa(e) scenario, corresponding to 60 a lifetime</td><td>Larger amounts of waste possible</td><td>Waste inventory based on 300 GWa(e) scenario (5.1a)</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

<table>
<tr><td colspan="4">Category: Safety-relevant phenomena / evolutions related to design basis and alternatives
System Component: SF / HLW canisters</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td colspan="2">Uncertainties and possible deviations</td></tr>
<tr><td>A.13.1
Potential canister breaching processes</td><td>Steel canisters for SF / HLW – 10 000 year design lifetime</td><td colspan="2">Cu canister > 10^5 a lifetime; 1 in 1000 canisters fails immediately (quality assurance), residual transport resistance (pinhole)</td></tr>
<tr><td>Super-FEP
Associated uncertainties and design / system options</td><td>Reference Case (1.1a)</td><td>Significance of uncertainties</td><td>Alternative cases (case numbers in parentheses)</td></tr>
<tr><td>B.3.7
Canister material
Design option of a copper canister with steel insert for SF (or alternative material to mitigate / avoid gas production)</td><td>Steel canisters</td><td>Expected to give an extended period of complete containment and to largely eliminate gas generation in the case of SF</td><td>Copper / steel canisters, which are breached simultaneously at 100 000 a (5.3a), or a case in which one canister has an initial pinhole defect, with full breaching at 100 000 a (5.3b/c)</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

Tab. A4.1.2: (Cont.)

Category: Safety-relevant phenomena / evolutions related to design basis and alternatives **System Component**: SF / HLW canisters			
Key phenomenon	**Expected evolution**	**Uncertainties and possible deviations**	
A.13.2 H_2 gas generation	Steel canisters for SF / HLW – continuous H_2 gas production	Selection of Cu, Ni alloy or Ti as external shell canister material, significant gas generation occurs only for failed canisters; use of alternative insert with negligible gas production	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.3.7 Canister material *Design option of a copper canister with steel insert for SF (or alternative material to mitigate / avoid gas production)*	Steel canisters	Expected to give an extended period of complete containment and to largely eliminate gas generation in the case of SF	Copper / steel canisters, which are breached simultaneously at 100 000 a (5.3a), or a case in which one canister has an initial pinhole defect, with full breaching at 100 000 a (5.3b/c)
Comment: Map is self-explanatory.			

Category: Safety-relevant phenomena / evolutions related to design basis and alternatives **System Component**: Bentonite / EDZ			
A.14.1 Alteration by concrete tunnel liner	Avoided by design basis (no concrete liner required in SF / HLW emplacement tunnels)	SF / HLW tunnels may require thin concrete or polymer liner; small effects expected	
Super-FEP ***Associated uncertainties and design / system options***	**Reference Case (1.1a)**	**Significance of uncertainties**	**Alternative cases (case numbers in parentheses)**
B.4.6 Tunnel liner *Design option of concrete or polymer liners for emplacement tunnels in case increased tunnel support required*	No liner required (likely / expected)	Effects on bentonite expected to be small	No alternative cases defined
Comment: Map is self-explanatory.			

Tab. A4.1.2: (Cont.)

<table>
<tr><td colspan="4">Category: Safety-relevant phenomena / evolutions related to design basis and alternatives
System Component: ILW</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td colspan="2">Uncertainties and possible deviations</td></tr>
<tr><td>A.15.1
Inventory definition</td><td>Cemented waste option</td><td colspan="2">High force compacted waste option (radio-nuclide inventory similar to cemented waste option) → possibility for localised radiolysis</td></tr>
<tr><td>Super-FEP
Associated uncertainties and design / system options</td><td>Reference Case (1.1a)</td><td>Significance of uncertainties</td><td>Alternative cases (case numbers in parentheses)</td></tr>
<tr><td>B.3.1
Quantities of waste and associated radionuclide inventories
Uncertainty in inventories low, but two different waste specifications considered</td><td>Inventory based on cemented waste option</td><td>Low – unless deviation from specified compositions is large</td><td>Inventory based on high force compaction option (5.2a)</td></tr>
<tr><td>B.3.3.2
Immobilisation and retardation in the ILW near field
Thermodynamic data and water chemistry</td><td>Solubility limits and sorption coefficients in the ILW near field based on realistic dataset
Sorption of nuclides on canister corrosion products conservatively neglected (reserve FEP)</td><td>Relevant to the evaluation of solubility limits and sorption coefficients, and thus to retention and decay in the near field</td><td>Parameter variations with respect to Reference Case – solubility limits and sorption coefficients in the near field based on pessimistic geochemical dataset (1.1d, 1.1i)
(PDF for solubilities in near field and K_d values in near and far field)
"What if?" case for redox front from compacted hulls (4.4a)</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

Tab. A4.1.2: (Cont.)

<table>
<tr><td colspan="4">Category: Speculative phenomena / evolutions
System Component: Surface environment</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td colspan="2">Uncertainties and possible deviations</td></tr>
<tr><td>A.16.1
Climatic evolution</td><td>"Icehouse" climate regime; present-day climate assumed in the Reference Biosphere</td><td colspan="2">Alternative climates (wet climate, dry climate, periglacial climate)</td></tr>
<tr><td>Super-FEP
Associated uncertainties and design / system options</td><td>Reference Case (1.1a)</td><td>Significance of uncertainties</td><td>Alternative cases (case numbers in parentheses)</td></tr>
<tr><td>B.8
Climatic evolution
The nature and timing of climate change</td><td>Present-day climatic conditions are assumed to persist for all calculated times (stylised conceptualisation) – also referred to as (6.2a)</td><td>Affects dilution in the surface environment and the exposure pathways that are relevant. It also affects geomorphological evolution (see B.9)</td><td>Alternative stylised conceptualisations in which a dry warm climate (6.2b), humid warm climate (6.2c) and periglacial climate (6.2d) are assumed to persist for all calculated times</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

<table>
<tr><td colspan="4">Category: Speculative phenomena / evolutions
System Component: Surface environment</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td colspan="2">Uncertainties and possible deviations</td></tr>
<tr><td>A.16.2
Geomorphological evolution</td><td>Eroding river valley section, such as present-day Rhine valley below Rhine Falls, and exfiltration in Quaternary gravel at valley bottom assumed (Reference Biosphere)</td><td colspan="2">River valley section with net sedimentation; wetlands; deep groundwater exfiltration to spring at valley sides</td></tr>
<tr><td>Super-FEP
Associated uncertainties and design / system options</td><td>Reference Case (1.1a)</td><td>Significance of uncertainties</td><td>Alternative cases (case numbers in parentheses)</td></tr>
<tr><td>B.9
Geomorphological evolution
Properties of the discharge area for groundwater conveying radionuclides</td><td>Discharge to section of the Rhine valley where the groundwater table is at some distance from the soil (likely / expected)</td><td>Affects radionuclide transport / uptake in the surface environment</td><td>Discharge where the groundwater table is close to the soil – either to a sedimentation area (6.1b) or to wetland (6.1c); discharge to a spring at the side of a valley (6.1d)</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

Tab. A4.1.2: (Cont.)

<table>
<tr><td colspan="4">Category: Speculative phenomena / evolutions
System Component: Surface environment</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td colspan="2">Uncertainties and possible deviations</td></tr>
<tr><td>A.16.3
Future human behaviour</td><td>Unknown, therefore present-day diet and local production of food stuff is assumed (Reference Biosphere)</td><td colspan="2">Alternative human behaviour during periglacial climate; deep well in Malm aquifer</td></tr>
<tr><td>Super-FEP
Associated uncertainties and design / system options</td><td>Reference Case (1.1a)</td><td>Significance of uncertainties</td><td>Alternative cases (case numbers in parentheses)</td></tr>
<tr><td>B.7.2
Future human actions</td><td></td><td></td><td></td></tr>
<tr><td>B.7.2.1
Possibility of future drilling of a borehole inadvertently affecting the barrier system</td><td>No borehole is drilled in the future that affects the barrier system</td><td>It is likely that any borehole would either be sealed, or collapse and self seal, and so would not provide a radionuclide transport path; most significant if unsealed and supported borehole penetrates the repository</td><td>Borehole penetration of the repository is considered as one conceptualisation of the scenario addressing future human actions, with and without an SF canister being directly hit (3.1a-g)</td></tr>
<tr><td>B.7.2.2
Possibility of future extraction of drinking water from a deep well drilled into the Malm aquifer and the production rate of such a well should it be created</td><td>No deep well for drinking water is created in the Malm aquifer</td><td>Could lead to ingestion of radionuclides with less dilution than if they had reached the surface environment</td><td>Drinking water extraction from the Malm aquifer, with different capture efficiencies of the well (3.2a/b)</td></tr>
<tr><td>B.7.2.3
Possibility of the repository being abandoned before it is backfilled and sealed</td><td>The repository is successfully backfilled and sealed as planned</td><td>Could lead to preferential transport of radionuclides through collapsed access tunnels</td><td>Preferential transport of radionuclides from repository occurs through collapsed tunnels (3.3a)</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

Tab. A4.1.2: (Cont.)

<table>
<tr><td colspan="4">Category: Speculative phenomena / evolutions
System Component: Host rock</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td colspan="2">Uncertainties and possible deviations</td></tr>
<tr><td>A.17.1
Inadvertant borehole penetration of repository</td><td>Assuming current drilling technology: borehole sealed or collapses and self-seals, canisters not vulnerable (even if partly corroded)</td><td colspan="2">Supported borehole is unsealed, penetrates repository to aquifer below, leakage of near field porewater into borehole</td></tr>
<tr><td>Super-FEP
Associated uncertainties and design / system options</td><td>Reference Case (1.1a)</td><td>Significance of uncertainties</td><td>Alternative cases (case numbers in parentheses)</td></tr>
<tr><td>B.7.2
Future human actions
B.7.2.1
Possibility of future drilling of a borehole inadvertently affecting the barrier system</td><td>No borehole is drilled in the future that affects the barrier system</td><td>It is likely that any borehole would either be sealed, or collapse and self seal, and so would not provide a radionuclide transport path; most significant if unsealed and supported borehole penetrates the repository</td><td>Borehole penetration of the repository is considered as one conceptualisation of the scenario addressing future human actions, with and without an SF canister being directly hit (3.1a-g)</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

<table>
<tr><td colspan="4">Category: Speculative phenomena / evolutions
System Component: Tunnels / ramp / shaft seals</td></tr>
<tr><td>Key phenomenon</td><td>Expected evolution</td><td colspan="2">Uncertainties and possible deviations</td></tr>
<tr><td>A.18.1
Repository abandoned without backfilling of ramp</td><td>Impacts minimised by design basis; seals, including sealed operations tunnels, isolate emplacement tunnels containing waste</td><td colspan="2"></td></tr>
<tr><td>Super-FEP
Associated uncertainties and design / system options</td><td>Reference Case (1.1a)</td><td>Significance of uncertainties</td><td>Alternative cases (case numbers in parentheses)</td></tr>
<tr><td>B.7.2
Future human actions
B.7.2.3
Possibility of the repository being abandoned before it is backfilled and sealed</td><td>The repository is successfully backfilled and sealed as planned</td><td>Could lead to preferential transport of radionuclides through collapsed access tunnels</td><td>Preferential transport of radionuclides from repository occurs through collapsed tunnels (3.3a)</td></tr>
<tr><td colspan="4">Comment: Map is self-explanatory.</td></tr>
</table>

Appendix 5: Super-FEPs and Assessment cases, interactions between Super-FEPs, and reserve FEPs

A5.1 Introduction

The purpose of this appendix is to show how the Super-FEPs are represented in the various assessment cases, to show the interactions between Super-FEPs / their associated uncertainties, to list the reserve FEPs and to address the topic of outstanding issues with the potential to compromise safety.

The appendix consists of four parts:

- an evaluation of the significance and treatment in assessment cases of uncertainties and design / system options associated with specific Super-FEPs;
- a list of scenarios, "what if?" cases, design system options and illustrations of the effects of biosphere uncertainty with associated conceptualisation and parameter variations;
- an interaction matrix showing the interactions between Super-FEPs / their associated uncertainties and how they were treated in safety assessment;
- a table listing the reserve FEPs.

A5.2 Significance and treatment in assessment cases of uncertainties and design / system options associated with specific Super-FEPs

Tab. A5.2.1 summarises the significance and treatment in assessment cases of uncertainties and design / system options associated with specific Super-FEPs. The table is based on Tab. 6.8-1 in Nagra (2002a), but with an additional column listing the safety-relevant aspects of each Super-FEP that are considered when evaluating the Super-FEPs using quantitative models and computer codes. These safety-relevant aspects are taken from Tab. A1.2-2 of Nagra (2002b). A numbering scheme is used for the Super-FEPs, for uncertainties and design / system options and for the safety-relevant aspects to assist traceability to other tables.

A5.3 Scenarios, "what if?" cases, design system options and illustrations of the effects of biopshere uncertainty with associated conceptualisation and parameter variations

Tab. A5.3.1 indicates how the various uncertainties are treated in both the Reference Case and in any alternative cases that address their consequences. The table is identical to Tab. 6.8-2 in Nagra (2002a). In this table, the assessment cases identified in Tab. A5.2.1 are re-arranged into a number of groups according to the issues or types of uncertainty (or their range of influence, see Tab. 4.2-1) that they address. The top-level groups (first column in Tab. A5.3.1) correspond to alternative scenarios and explore scenario uncertainty. Each of these groups is further divided according to alternative conceptualisations, which explore conceptual uncertainty (second column in Tab. A5.3.1). Finally, a specific conceptualisation may be evaluated using different parameter sets, thereby exploring parameter uncertainty (third column in Tab. A5.3.1).

A5.4 Interactions between Super-FEPs

Tab. A5.4.1 lists the interactions between Super-FEPs / their associated uncertainties (see Tab. A5.2.1). In Tab. A5.2.1, there are a total of n = 50 Super-FEPs / associated uncertainties; thus the interaction matrix is a 50 × 50 matrix. However, a large number of the matrix cells are empty since there is no interaction between the corresponding Super-FEPs / their associated uncertainties (e.g. between Super-FEP B.1.1 "Quantities and burnup of fuel" and Super-FEP B.9 "Geomorphological evolution"); thus the interaction matrix is a sparse matrix. Tab. A5.4.1 represents this sparse 50 × 50 interaction matrix in the following manner. In the two left-most columns, all the 50 Super-FEPs and their associated uncertainties are listed; this corresponds to the left-most column of the full interaction matrix. In the third and fourth columns, only those Super-FEPs and associated uncertainties corresponding to the top row of the full interaction matrix appear for which the corresponding matrix cell is not empty. Finally, in the last column in Tab. A5.4.1, the treatment of the interaction in safety assessment is briefly described. The original 50 × 50 interaction matrix is in the form of an electronic (EXCEL) file.

It should be pointed out that the filling in of the original 50 × 50 matrix involves a large degree of expert judgement; thus it cannot be expected that the result is unique. Nevertheless, it is felt that the fact that no interaction was identified that would strongly suggest to introduce an additional assessment case gives further confidence that the range of assessment cases analysed is broad enough.

Finally, we note that a rather large number of interactions are qualified as "NA"; i.e. "interaction possible, but not analysed". This is to be expected, however, since the structure of the interaction matrix gives rise to a large number of interactions, many of which are similar in nature and can be bounded by a single assessment case; such interactions are thus judged not to warrant the introduction of a special assessment case.

A5.5 Reserve FEPs and outstanding issues with the potential to compromise safety

Identification of reserve FEPs

Some FEPs that are considered likely to occur and are beneficial to safety are deliberately (and conservatively) excluded from quantitative analysis because suitable models, codes or databases are unavailable. Such FEPs are termed *reserve FEPs*, since they may be mobilised at a later stage of the waste disposal programme when the necessary models, codes and databases will have been developed. Important reserve FEPs identified in the course of the present safety assessment, and other FEPs that are treated conservatively, are compiled in Tab. A5.5.1.

The reserve FEPs have the potential, in the future, to provide additional quantitative contributions to the evaluated performance of the disposal system. Even in the current assessment, the presence of these reserve FEPs constitutes, in effect, an additional qualitative argument for safety, since it indicates that the actual performance of the disposal system will, in reality, be more favourable than that evaluated in the analysis of assessment cases.

Absence of outstanding issues with the potential to compromise safety

The current safety assessment, despite an analysis of a wide range of assessment cases that were derived in a careful and methodical way, has not identified any outstanding issues with the potential to compromise safety.

Tab. A5.2.1: The significance and treatment in assessment cases of uncertainties and design / system options associated with specific Super-FEPs

Reserve FEPs and other FEPs that are conservatively omitted in analysing the assessment cases are indicated in italics. The cases are assigned numbers and are presented in sequence in Tab. A5.3.1. The term PDF indicates that a probability density function is defined for probabilistic assessment calculations.

Super-FEP	**Associated uncertainties and design / system options**	**Significance of uncertainties**	**Safety-relevant aspects that are affected by uncertainties and design / system options**	**Treatment of uncertainties in assessment cases / realisations of safety-relevant aspects** (case numbers in parentheses; PDF refers to probability distribution functions that have been defined for some parameters)	
				Reference Case (1.1a)	**Alternative cases**
SF					
B.1.1 Quantities and burnup of fuel and associated radionuclide inventories, including the instant release fraction (IRF)	**B.1.1.1** The possibility for increased nuclear power production	Larger amounts of waste possible	**SF1** Waste inventory in a single package and number of packages	Waste inventory based on 192 GWa(e) scenario, corresponding to 60 a lifetime	Waste inventory based on 300 GWa(e) scenario (5.1a)
	B.1.1.2 The current trend to higher burnups	A higher average burnup results in a higher IRF – analyses of Reference Case indicate that radionuclides released in the IRF dominate the calculated dose maximum	**SF1** Waste inventory in a single package and number of packages	Burnup of 48 GWd/t_{IHM} assumed (likely / expected)	Parameter variation with respect to Reference Case – increased burnups up to 75 GWd/t_{IHM} (1.1b)
			SF2 Partitioning between fuel matrix, cladding and IRF		
	B.1.1.2a Chemical state of ^{14}C released from SF	If ^{14}C released is organic, reduced geochemical retardation occurs	**SF3** ^{14}C in organic and inorganic form upon release	^{14}C released in inorganic form	^{14}C released in organic form (1.1k)
	B.1.1.3 The limited information available on the IRF of high burnup UO_2 fuel and MOX fuel	See above	**SF2** Partitioning between fuel matrix, cladding and IRF	See above	See above (1.1b) (PDF for IRF)
B.1.2 Corrosion of cladding (see also "The creation of gas pathways", B.7.1.1)	Whether preferential release of organic ^{14}C from the cladding occurs; corrosion rate of cladding	Affects instant release fraction (IRF), time-dependent release rate and degree of geochemical retardation	**SF5** Corrosion rate	Constant rate of corrosion assumed, but with some organic ^{14}C assigned to the IRF (pessimistic)	"What if?" case with 10 × higher corrosion rate (4.9a) (PDF for cladding corrosion rate)

Tab. A5.2.1: (Cont.)

Super-FEP	**Associated uncertainties and design / system options**	**Significance of uncertainties**	**Safety-relevant aspects that are affected by uncertainties and design / system options**	**Treatment of uncertainties in assessment cases / realisations of safety-relevant aspects** (case numbers in parentheses; PDF refers to probability distribution functions that have been defined for some parameters)	
				Reference Case (1.1a)	**Alternative cases**
			SF		
B.1.3 Breaching of cladding	The possibility of early fracturing of the cladding, preventing an extended period of complete containment following canister breaching	Sensitivity analyses indicate that the period of complete containment for canisters has small effects on overall system performance, within the range investigated; this is expected to apply to cladding as well	**SF6** Timing	Possibility of extended period of complete containment following canister breaching not included (pessimistic)	No alternative cases defined
B.1.4 Dissolution of fuel matrix	**B.1.4.1** Whether the rate of dissolution is controlled by the rate of production of radiolytic oxidants or (if reducing conditions prevail at the fuel surface) by the solubility of U(IV)	If, as expected, reducing conditions prevail at the fuel surface, then the fuel dissolution rate, and radionuclide release rates from the fuel matrix, will be very low but the IRF will be unaffected	**SF7** Dissolution rate	Rate of dissolution is controlled by the rate of production of radiolytic oxidants (conservative, given the pessimistically chosen parameters for this model – see below)	Alternative conceptualisation within the Reference Scenario – rate of dissolution controlled by diffusion and the solubility of U(IV) (1.2a)
	B.1.4.2 If the rate of dissolution is controlled by the rate of production of radiolytic oxidants, the proportion of the oxidants that is available for reaction at the fuel surface (not recombined, e.g. with radiolytic reductants)	Affects the rate of release of radionuclides from the fuel matrix, but the IRF will be unaffected	**SF7** Dissolution rate	Proportionality is assumed between the production rate of oxidants and the dissolution rate of the fuel, with a proportionality constant pessimistically chosen on the basis of wide ranging experimental data and observations from nature	"What if?" case of fuel dissolution rate increased 10 (4.3a) and 100 fold (4.3b) with respect to Reference Case (PDF for fuel matrix dissolution rate)

Tab. A5.2.1: (Cont.)

Super-FEP	Associated uncertainties and design / system options	Significance of uncertainties	Safety-relevant aspects that are affected by uncertainties and design / system options	Treatment of uncertainties in assessment cases / realisations of safety-relevant aspects (case numbers in parentheses; PDF refers to probability distribution functions that have been defined for some parameters)	
				Reference Case (1.1a)	**Alternative cases**
			SF		
B.1.5 Criticality	Whether or not it can be completely ruled out	Ruled out by design and supporting calculations	**SF8** None – ruled out by design and supporting calculations	Not considered (discussion of calculation results in Chapter 5)	
			HLW glass		
B.2.1 Quantities of glass and associated radionuclide inventories	Low – compositions specified by the two reprocessors	Low – unless deviation from specified compositions is large	**HL1** Waste inventory in a single package and number of packages	Inventory based on specified compositions (likely / expected)	No alternative cases defined
B.2.2 Dissolution rate of glass	Long-term rates based on extrapolation of much shorter-term experiments; creation of additional surfaces for dissolution by fracturing of glass	Although sensitivity of dose to dissolution rate is expected to be small, a specific assessment case with an increased dissolution rate is analysed because the glass matrix is an important barrier	**HL2** Dissolution rate	Long-term rates taken directly from experiments (likely / expected); fracturing represented in terms of equivalent spheres (see Section 6.3.3)	Pessimistic case with glass dissolution rate increased ~ 100 fold (1.1e) (PDF for glass dissolution rate)

Tab. A5.2.1: (Cont.)

Super-FEP	**Associated uncertainties and design / system options**	**Significance of uncertainties**	**Safety-relevant aspects that are affected by uncertainties and design / system options**	**Treatment of uncertainties in assessment cases / realisations of safety-relevant aspects** **(case numbers in parentheses; PDF refers to probability distribution functions that have been defined for some parameters)**	
				Reference Case (1.1a)	**Alternative cases**
SF / HLW canisters					
B.3.5 Breaching of steel canisters	**B.3.5.1** The conditions under which mechanical failure of corroded canisters will occur; possibility of localised corrosion processes	Sensitivity analyses indicate small effects on overall performance, although performance of canisters (a pillar of safety) is affected	**CN2** Time of occurrence of breaching	Canisters breached at 10 000 a (pessimistic assumption)	Parameter variation with respect to Reference Case – further reduced canister lifetime of 1000 a (1.1c)
	B.3.5.2 The remote possibility of breaching prior to 1000 a, and the possibility of initially defective steel canisters	Early failure has low probability (1 in 1000 canisters), thus early releases would be small	**CN2** Time of occurrence of breaching	See above	No alternative cases defined (see, however, "canister material", B.3.7)
	B.3.5.3 Distribution of canister breaching times	Gives rise to attenuation of releases due to spreading in time	**CN1** Distribution of breaching times	All canisters breached simultaneously (conservative) *The spreading of radionuclide releases in time due to the fact that SF / HLW canisters would not be breached simultaneously is omitted (conservative)*	No alternative cases defined
B.3.6 Gas generation by steel canister corrosion	See "The creation of gas pathways", B.7.1.1		**CN3** Gas generation rate for SF / HLW	See "The creation of gas pathways", B.7.1.1	
B.3.7 Canister material	Design option of a copper canister with steel insert for SF (or alternative material to mitigate / avoid gas production)	Expected to give an extended period of complete containment and to largely eliminate gas generation in the case of SF	**CN4** Time of occurrence of breaching (time of occurrence affected by canister material) **CN5** Presence of initial defects (likelihood affected by canister material)	Steel canisters	Copper / steel canisters, which are breached simultaneously at 100 000 a (5.3a), or a case in which one canister has an initial pinhole defect, with full breaching at 100 000 a (5.3b/c)

Tab. A5.2.1: (Cont.)

Super-FEP	**Associated uncertainties and design / system options**	**Significance of uncertainties**	**Safety-relevant aspects that are affected by uncertainties and design / system options**	**Treatment of uncertainties in assessment cases / realisations of safety-relevant aspects (case numbers in parentheses; PDF refers to probability distribution functions that have been defined for some parameters)**	
				Reference Case (1.1a)	**Alternative cases**
			SF / HLW near field		
B.4.1 The long resaturation time of the repository and its surroundings	The rate of the resaturation process	Delays commencement of corrosion and dissolution processes – likely to be of low importance for SF / HLW except in the case of earlier than expected canister breaching	**NF1** The rate of the resaturation process	*SF / HLW parts of repository are conservatively assumed to be resaturated at time of repository closure (reserve FEP)*	No alternative cases defined
B.4.2 Geochemical immobilisation and retardation in the near field	**B.4.2.1** Thermodynamic data and water chemistry	Relevant to the evaluation of solubility limits and sorption coefficients, and thus to retention and decay in the near field	**NF2** Solubility limitation (reservoir) **NF3** Solubility limitation (buffer) **NF4** Linear, equilibrium sorption	Solubility limits and sorption coefficients in the near field based on realistic near field geochemical dataset	Parameter variations for solubilities and sorption coefficients in the near field based on pessimistic geochemical dataset (1.1d) and for pessimistic sorption coefficients in the geosphere (1.1i) (PDF for solubilities and K_d values)
	B.4.2.1a Colloid filtration by bentonite	Small pore size eliminates colloid transport	**NF5** Colloid filtration by bentonite	No colloid transport	No alternative cases defined
	B.4.2.2 The extent of co-precipitation of radionuclides with secondary minerals derived from SF and glass dissolution and canister corrosion	Co-precipitation could significantly enhance retention and decay in the near field, but the necessary data for modelling is unavailable for most radionuclides	**NF6** The extent of co-precipitation with secondary minerals	Co-precipitation of radium is taken into account *Co-precipitation of other radionuclides is conservatively omitted (reserve FEP)*	No alternative cases defined

Tab. A5.2.1: (Cont.)

Super-FEP	**Associated uncertainties and design / system options**	**Significance of uncertainties**	**Safety-relevant aspects that are affected by uncertainties and design / system options**	**Treatment of uncertainties in assessment cases / realisations of safety-relevant aspects (case numbers in parentheses; PDF refers to probability distribution functions that have been defined for some parameters)**	
				Reference Case (1.1a)	**Alternative cases**
			SF / HLW near field		
B.4.2 Geochemical immobilisation and retardation in the near field	**B.4.2.3** The extent of sorption of radionuclides on canister corrosion products	Could significantly enhance retention and decay in the near field, but the necessary data for modelling is unavailable	**NF7** The extent of sorption on canister corrosion products	*Sorption of radionuclides on canister corrosion products conservatively omitted (reserve FEP)*	No alternative cases defined
	B.4.2.4 The natural concentrations of isotopes in bentonite porewater	Could reduce the effective solubilities of some radionuclides	**NF8** The effects on solubility limitation of the natural concentrations of isotopes	*Natural concentrations of isotopes conservatively neglected when evaluating whether solubility limits are exceeded and precipitation occurs (reserve FEP)*	No alternative cases defined
B.4.3 Migration of radiolytic oxidants generated at SF surfaces into bentonite buffer	Degree to which these oxidants are scavenged by reductants in the system	Scoping calculations indicate that only a small proportion of the bentonite would be affected and sensitivity analyses indicate that degradation of properties of a small part of the bentonite is insignificant with respect to overall performance	**NF9** Proportion of the buffer affected and the magnitude of the effects on geochemical immobilisation	Oxidants consumed by steel – no migration into the bentonite (likely / expected)	"What if?" case (4.4a) of radiolytic oxidants affecting the bentonite, bounded by a redox front

Tab. A5.2.1: (Cont.)

Super-FEP	Associated uncertainties and design / system options	Significance of uncertainties	Safety-relevant aspects that are affected by uncertainties and design / system options	Treatment of uncertainties in assessment cases / realisations of safety-relevant aspects (case numbers in parentheses; PDF refers to probability distribution functions that have been defined for some parameters)	
				Reference Case (1.1a)	**Alternative cases**
SF / HLW near field					
B.4.4 Thermal alteration of the bentonite buffer adjacent to the SF / HLW canisters	Existence / extent of any thermally altered region	Some detrimental effects on transport-relevant properties within affected region cannot be excluded; sensitivity analyses indicate that degradation of properties of a small part of the bentonite is insignificant with respect to overall performance	**NF10** Proportion of the buffer affected and the magnitude of the effects on buffer transport properties	No significant alteration occurs (likely / expected)	Alternative conceptualisation within the Reference Scenario – inner half of bentonite thermally altered, with pore diffusion coefficient (D_p) set equal to that of free water; no effects on sorption (1.3a)
B.4.5 Transport resistances provided by internal spaces (fractures) within the waste forms, by the breached SF / HLW canisters and by corrosion products	The magnitude and time-dependence of these resistances	Increases radionuclide transport times, but likely to be a small effect compared to the overall transport resistance of the clay barrier (bentonite buffer and Opalinus Clay)	**NF11** The magnitude of transport resistance of initial defects **NF12** The magnitude and time-dependence of other transport resistances	*Transport resistances conservatively omitted except for Cu canister cases (reserve FEP) (5.3b/c)*	No alternative cases defined
B.4.6 Tunnel liner	Design option of concrete or polymer liners for emplacement tunnels in case increased tunnel support required	Effects on bentonite expected to be small	**NF13** Requirement for a liner	No liner required (likely / expected)	No alternative cases defined

Tab. A5.2.1: (Cont.)

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				Reference Case (1.1a)	**Alternative cases**
SF / HLW near field					
B.4.7 Hydraulic transport characteristics of bentonite	Compaction of bentonite by tunnel convergence	Not significant, as convergence expected to be concurrent with resaturation	**NF19** Compaction of bentonite by tunnel convergence	Decreased bentonite thickness due to tunnel convergence	No alternative cases defined (PDF for D_e)
B.4.7.1 Gas transport characteristics of bentonite	Uncertainties in corrosion rate	Water transport unaffected by gas buildup and transport, except in the case of gas-induced porewater displacement from void space in canisters	**NF20** Gas-induced release of dissolved radionuclides		Alternative conceptualisation within the Reference Scenario (1.8 a)
ILW					
B.3.1 Quantities of waste and associated radionuclide inventories	Uncertainty in inventories low, but two different waste specifications considered	Low – unless deviation from specified compositions is large	**IL1** Waste inventory in a single package and number of packages	Inventory based on cemented waste option	Inventory based on high force compaction option (5.2a)
B.3.2 Breaching of ILW steel drums and emplacement containers	The timing of drum / container breaching	Affects period of total containment	**IL2** Time of occurrence of breaching	*Complete containment by drums / containers omitted (reserve FEP)* – Release from ILW delayed until 100 a after emplacement due to slow resaturation of near field	No alternative cases defined
B.3.3 Corrosion / dissolution of ILW	Rate of corrosion / dissolution of waste matrix and rate of release of radionuclides	The delayed release of radionuclides due to the slow corrosion rate of ILW metallic materials (e.g. hulls and ends) potentially significant	**IL3** Corrosion rate of metallic components **IL4** Corrosion / dissolution rate of remaining ILW components	Immediate release of all radionuclides in ILW into near-field porewater 100 a after emplacement of wastes *The delayed release of radionuclides due to the slow corrosion rate of ILW metallic materials (e.g. hulls and ends) is conservatively neglected (reserve FEP)*	No alternative cases defined

Tab. A5.2.1: (Cont.)

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				Reference Case (1.1a)	**Alternative cases**
ILW					
B.3.3.2 Immobilisation and retardation in the ILW near field	Thermodynamic data and water chemistry	Relevant to the evaluation of solubility limits and sorption coefficients, and thus to retention and decay in the near field	**IL5** Linear, equilibrium sorption and solubility limitation	Solubility limits and sorption coefficients in the ILW near field based on realistic dataset *Sorption of nuclides on canister corrosion products conservatively neglected (reserve FEP)*	Parameter variations with respect to Reference Case – solubility limits and sorption coefficients in the near field based on pessimistic geochemical dataset (1.1d, 1.1i) (PDF for solubilities in near field and K_d values in near and far field) "What if?" case for redox front from compacted hulls (4.4a)
B.3.4 Gas generation	See "The creation of gas pathways", B.7.1.1		**IL6** Gas generation rates for ILW	See "The creation of gas pathways", B.7.1.1	
B.4.8 Hydraulic and gas transport characteristics of the ILW near field	Inflow rate of water; displacement of water by gas into rock and along tunnels	Influences rate of gas pressure buildup and timing of gas pathway formation in Opalinus Clay	**IL9** Porewater displacement by gas		Alternative conceptualisation within the Reference Scenario (1.8b)
B.3.3.1 Compaction of waste / mortar (see B.4.7)	Timing of convergence arising from void reduction of breached corroded containers		**IL10** Timing of convergence arising from void reduction of breached, corroded canisters		Alternative conceptualisation dealing with rapid and very slow convergence (1.7a/b)
B.3.3.3 The long resaturation time of the ILW tunnels	The rate of the resaturation process	Delays commencement of corrosion and dissolution processes	**IL11** The rate of the resaturation process	Release from ILW commences at 100 a after emplacement *The long resaturation time of the repository and its surroundings, which delays the commencement of corrosion and dissolution processes is conservatively neglected (reserve FEP)*	No alternative cases defined

Tab. A5.2.1: (Cont.)

<table>
<tr><th rowspan="2">Super-FEP</th><th rowspan="2">Associated uncertainties and design / system options</th><th rowspan="2">Significance of uncertainties</th><th rowspan="2">Safety-relevant aspects that are affected by uncertainties and design / system options</th><th colspan="2">Treatment of uncertainties in assessment cases / realisations of safety-relevant aspects
(case numbers in parentheses; PDF refers to probability distribution functions that have been defined for some parameters)</th></tr>
<tr><th>Reference Case (1.1a)</th><th>Alternative cases</th></tr>
<tr><td colspan="6">Tunnels / ramp / shaft and seals</td></tr>
<tr><td rowspan="6">B.5.1
Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)</td><td rowspan="2">B.5.1.1
The hydraulic conductivity of the EDZs with respect to that of the surrounding undisturbed rock</td><td rowspan="2">Relatively high hydraulic conductivity of the EDZ could allow dissolved radionuclides to migrate along the tunnels / ramp / shaft, driven by the natural hydraulic gradient</td><td>TS1
Transport paths provided by the tunnels / ramp / shaft</td><td rowspan="2">The self-sealing capacity of the host rock means that any EDZ with enhanced hydraulic conductivity is a transient feature, and can be neglected (likely / expected)</td><td rowspan="2">Alternative conceptualisation within the Reference Scenario – release of radionuclides affected by the ramp / shaft and their surrounding EDZs (1.6a/b)</td></tr>
<tr><td>TS2
Stationary flow</td></tr>
<tr><td rowspan="2">B.5.1.2
The driving force for flow along the EDZs provided by tunnel convergence</td><td rowspan="2">As above, but with tunnel convergence providing the driving force for migration along the tunnels / ramp / shaft</td><td>TS3
Transient flow</td><td rowspan="2">As above</td><td rowspan="2">Alternative conceptualisation within the Reference Scenario – convergence-induced release of radionuclides affected by the ramp / shaft and their surrounding EDZs, two different modelling approaches (1.7a/b)</td></tr>
<tr><td>OP2
Transient flow</td></tr>
<tr><td rowspan="2">B.5.1.3
The driving force for flow along the EDZs provided by near field gas, as well as the rate of near field gas production (see also "The migration of repository-induced gas", B.7.1)</td><td rowspan="2">As above, but with near field gas pressure providing the driving force for migration along the tunnels / ramp / shaft</td><td>TS3
Transient flow</td><td rowspan="2">As above</td><td rowspan="2">Alternative conceptualisation within the Reference Scenario – gas-induced release of dissolved radionuclides affected by the ramp / shaft and their surrounding EDZs, two different waste forms (SF and ILW) and for each waste form, two rates of water flow (1.8a/b)</td></tr>
<tr><td>OP2
Transient flow</td></tr>
<tr><td>B.5.2
The seals and the surrounding rock (see also "The creation of gas pathways", B.7.1.1)</td><td>The possibility of sealed zones being bypassed by relatively permeable EDZs</td><td>The bypassing of seals could allow dissolved radionuclides to migrate preferentially along the tunnels / ramp / shaft, driven by near field gas pressure</td><td>TS7
Transport resistance of the seals and the surrounding rock</td><td>Seals remain effective (likely / expected)</td><td>"What if?" cases (4.5a/b) of gas-induced release of dissolved radionuclides from ILW along ramp only, two different rates of water flow</td></tr>
</table>

Tab. A5.2.1: (Cont.)

Super-FEP	Associated uncertainties and design / system options	Significance of uncertainties	Safety-relevant aspects that are affected by uncertainties and design / system options	Treatment of uncertainties in assessment cases / realisations of safety-relevant aspects (case numbers in parentheses; PDF refers to probability distribution functions that have been defined for some parameters)	
				Reference Case (1.1a)	**Alternative cases**
			Opalinus Clay and confining units		
B.6.1 Low groundwater flow rate through undisturbed Opalinus Clay (see also "Low groundwater flow rate along the sealed tunnel / ramp / shaft, and through the surrounding excavation disturbed zones", B.5.1)	**B.6.1.1** The groundwater flow rate through the Opalinus Clay, which is affected by uncertainties of about an order of magnitude	Sensitivity analyses indicate that releases from Opalinus Clay of ^{129}I and ^{79}Se are affected by uncertainties in groundwater flow rate	**OP1** Stationary flow	Groundwater flow rate of 2×10^{-14} m s^{-1} (likely / expected)	Parameter variations with respect to Reference Case – groundwater flow rate in Opalinus Clay increased 10-fold (1.1f) and decreased 10-fold due to threshold hydraulic gradient (1.1g) (PDF for groundwater flow rate) "What if?" case (4.1a) 100-fold increase with respect to Reference Case (RC) "What if?" case for no advection in rock (4.8a) "What if?" case (4.7a/b/c) – RC flow rate, 10-fold increase, 100-fold increase combined with pessimistic near field / geosphere geochemical dataset
	B.6.1.2 The effects of gas pressure buildup in the near field, tunnel convergence and ice loads on the hydraulic gradient	See above	**OP2** Transient flow	The effects of gas pressure buildup in the near field, tunnel convergence and ice loads are insignificant (likely / expected)	Alternative conceptualisation within the Reference Scenario – glacially induced flow in the Opalinus Clay (1.4a)
	B.6.1.3 The eventual increase of hydraulic conductivity caused by erosion of the overburden	Ruled out within the one million year period of primary interest in the safety assessment	**OP5** Long-term changes (e.g. due to erosion of overburden)	Not considered (qualitative discussion in Chapter 5)	

Tab. A5.2.1: (Cont.)

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				Reference Case (1.1a)	**Alternative cases**
			Opalinus Clay and confining units		
B.6.1a Length of vertical transport path from emplacement tunnels to overlying and underlying formations	Variability in path length	Relevant to transport time through Opalinus Clay and to degree of dispersion	**OP6** Transport paths provided by the Opalinus Clay and confining units	40 m path length (minimum value)	"What if?" case based on 30 m path length (4.11a) (PDF for transport path length)
B.6.2 Geochemical immobilisation and retardation in the Opalinus Clay and confining units	**B.6.2.1** Sorption mechanisms and groundwater composition, diffusivity	Relevant to the evaluation of diffusion rates and sorption coefficients, and thus to retention and decay in the Opalinus Clay and confining units	**OP7** Linear, equilibrium sorption	Sorption coefficients and diffusivities in the Opalinus Clay based on realistic geochemical dataset	Sorption coefficients in the Opalinus Clay based on pessimistic geochemical dataset (1.1h), pessimistic solubility limits and sorption coefficients in the near field (1.1i) and pessimistic geosphere diffusion constants (1.1j) (PDF for K_d values and diffusion constants in Opalinus Clay) "What if?" case for $K_d = 0$ for ^{129}I in bentonite and Opalinus Clay (4.10a)
	B.6.2.2 The effectiveness of long-term immobilisation processes (precipitation / co-precipitation) in the geosphere	Could increase time available for decay during transport to the surface environment	**OP8** Immobilisation processes	*Long-term immobilisation processes omitted (reserve FEP – conservative, except if a change in geochemical conditions leads to remobilisation of previously immobilised radionuclides)*	No alternative cases defined

Tab. A5.2.1: (Cont.)

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				Reference Case (1.1a)	**Alternative cases**
Opalinus Clay and confining units					
B.6.3 Homogeneity	**B.6.3.1** The possibility of low transmissivity (i.e. 10^{-10} $m^2 s^{-1}$ or less) undetected discontinuities in the Opalinus Clay	Although not totally excluded on the basis of current scientific understanding (Chapter 5), these are shown by the sensitivity analyses to have negligible impact on the performance of the Opalinus Clay as a transport barrier, except possibly in the case of organic ^{14}C	**OP9** Transport paths provided by transmissive discontinuities, faults and repository-induced fractures in the clay	No discontinuities with significant transmissivities are present in the Opalinus Clay (likely / expected)	"What if?" cases (4.2a/b/c) of a discontinuity of transmissivity 10^{-10} $m^2 s^{-1}$ intersecting the repository, variants according to whether ILW or SF / HLW parts of the repository affected and, for SF / HLW, the number of canisters affected
	B.6.3.2 The possibility of higher-transmissivity discontinuities, faults and repository-induced fractures	Ruled out because of the self-sealing capacity of the clay	**OP9** Transport paths provided by transmissive discontinuities, faults and repository-induced fractures in the clay	Not considered	"What if?" cases for discontinuity with transmissivity 10^{-9} $m^2 s^{-1}$ intersecting SF / HLW near field (4.2d/e) and ILW near field (4.2f)

Tab. A5.2.1: (Cont.)

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				Reference Case (1.1a)	**Alternative cases**
			Opalinus Clay and confining units		
B.6.4 Migration of high pH plume from ILW backfill into Opalinus Clay	The depth of migration, and associated physical and chemical changes in the clay	The maximum possible depth of migration, based on mass balance, is about 4 m (Section 5.4.4); even if it is hypothetically assumed that this results in a complete loss of geochemical retardation over this distance, the sensitivity analyses show that the impact on the performance of the Opalinus Clay as a transport barrier is small	**OP10** The depth of migration, and associated physical and chemical changes in the clay	Not considered (qualitative discussion in Section 5.4.4)	
B.6.5 Radionuclide transport through the confining units and regional aquifers	Transport-relevant properties of the confining units and regional aquifers	Slow transport could increase time available for decay during transport to the surface environment	**OP11** Transport paths provided by the confining units and regional aquifers	Decay during transport through the confining units / aquifers omitted (conservative)	Alternative conceptualisation within the Reference Scenario – decay during vertical transport through the confining units (1.5a) or horizontal transport in local aquifers (1.5b) taken into account

Tab. A5.2.1: (Cont.)

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				Reference Case (1.1a)	**Alternative cases**
The barrier system (general)					
B.7.1 The migration of repository induced gas	**B.7.1.1** The possibility that gas pathways are created through host rock and the uncertainty in gas permeability that might allow the transport of ^{14}C in a volatile form with flowing gas	Affects rate of transport of ^{14}C released by SF and ILW which has the potential to form volatile species	**SF4** Proportion of organic ^{14}C in volatile form upon release **NF21** Dilatant gas pathway formation (SF / HLW near field) **NF22** Gas dissolution and diffusion **IL8** Gas dissolution and diffusion **BS1** Gas dissolution and diffusion in the Opalinus Clay (incl. tunnel EDZs) **BS5** Gas dissolution and diffusion in the low-permeability upper confining units **BS6** Capillary leakage through low-permeability upper confining units **BS4** Porewater displacement in the Wedelsandstein **BS2** Capillary leakage in the Opalinus Clay **BS3** Pathway dilation in the Opalinus Clay	Gas pathways unimportant (likely / expected)	Alternative conceptualisation within scenario addressing transport of radionuclides as volatile species – "tight seals" (2.1a/b/c)

Tab. A5.2.1: (Cont.)

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				Reference Case (1.1a)	**Alternative cases**
			The barrier system (general)		
B.7.1 The migration of repository induced gas	**B.7.1.2** The possibility that the EDZs would allow the tunnels / ramp / shaft to provide gas pathways and the uncertainties in gas permeability	Affects properties of pathways	**TS6** Formation of dilatant gas pathways through the sealing zone	See above	Alternative conceptualisation within scenario addressing transport of radionuclides as volatile species – "leaky seals" (2.2a/b/c)
	B.7.1.3 The rate of gas generation by corrosion of the SF / HLW canisters	Affects rate of transport along gas pathways	**CN3** Gas generation rate for SF / HLW	See above	No alternative cases defined
	B.7.1.4 Rapid transport of radionuclides as volatile species through continuous gas path	Affects rate of transport along gas pathways	**BS3** Pathway dilation in the Opalinus Clay	See above	"What if?" case (4.6a-c) in which ^{14}C is transported unretarded through the host rock
	B.7.1.5 The rate of generation of gas by ILW		**IL6** Gas generation rates for ILW	See above	No alternative cases defined
	B.7.1.6 Extent of preferential release of organic ^{14}C from SF cladding	Could affect release of radionuclides with the potential to form volatile species along gas pathways	**SF2** Partitioning between fuel matrix, cladding and IRF	See above	Some ^{14}C assigned to the IRF (all affected cases)

Tab. A5.2.1: (Cont.)

Super-FEP	Associated uncertainties and design / system options	Significance of uncertainties	Safety-relevant aspects that are affected by uncertainties and design / system options	Treatment of uncertainties in assessment cases / realisations of safety-relevant aspects (case numbers in parentheses; PDF refers to probability distribution functions that have been defined for some parameters)	
				Reference Case (1.1a)	**Alternative cases**
The barrier system (general)					
B.7.2 Future human actions	**B.7.2.1** Possibility of future drilling of a borehole inadvertently affecting the barrier system	It is likely that any borehole would either be sealed, or collapse and self seal, and so would not provide a radionuclide transport path; most significant if unsealed and supported borehole penetrates the repository	**BS7** Borehole penetration of the repository	No borehole is drilled in the future that affects the barrier system	Borehole penetration of the repository is considered as one conceptualisation of the scenario addressing future human actions, with and without a SF canister being directly hit (3.1a-g)
	B.7.2.2 Possibility of future extraction of drinking water from a deep well drilled into the Malm aquifer and the production rate of such a well should it be created	Could lead to ingestion of radionuclides with less dilution than if they had reached the surface environment	**BS8** Drinking water extraction from the Malm aquifer	No deep well for drinking water is created in the Malm aquifer	Drinking water extraction from the Malm aquifer, with different capture efficiencies of the well (3.2a/b)
	B.7.2.3 Possibility of the repository being abandoned before it is backfilled and sealed	Could lead to preferential transport of radionuclides through collapsed access tunnels	**BS9** Abandonment of repository before backfilling / sealing	The repository is successfully backfilled and sealed as planned	Preferential transport of radionuclides from repository occurs through collapsed tunnels (3.3a)

Tab. A5.2.1: (Cont.)

Super-FEP	Associated uncertainties and design / system options	Significance of uncertainties	Safety-relevant aspects that are affected by uncertainties and design / system options	Treatment of uncertainties in assessment cases / realisations of safety-relevant aspects (case numbers in parentheses; PDF refers to probability distribution functions that have been defined for some parameters)	
				Reference Case (1.1a)	**Alternative cases**
The surface environment					
B.8 Climatic evolution	The nature and timing of climate change	Affects dilution in the surface environment and the exposure pathways that are relevant; it also affects geomorphological evolution (see B.9)	**SE1** The nature and timing of climate change	Present-day climatic conditions are assumed to persist for all calculated times (stylised conceptualisation) – also referred to as (6.2a)	Alternative stylised conceptualisations in which a dry warm climate (6.2b), humid warm climate (6.2c) and periglacial climate (6.2d) are assumed to persist for all calculated times
B.9 Geomorphological evolution	Properties of the discharge area for groundwater conveying radionuclides	Affects radionuclide transport / uptake in the surface environment	**SE2** Properties of the exfiltration area for groundwater conveying radionuclides	Discharge to section of the Rhine valley where the groundwater table is at some distance from the soil (likely / expected)	Discharge where the groundwater table is close to the soil – either to a sedimentation area (6.1b) or to wetland (6.1c); discharge to a spring at the side of a valley (6.1d)

Tab. A5.3.1: List of scenarios, "what if?" cases, design and system options and illustration of the effects of biosphere uncertainty with associated conceptualisation and parameter variations

Alternative scenarios addressing scenario uncertainty	Alternative conceptualisations addressing conceptual uncertainty	Parameter variations addressing parameter uncertainty
1. Reference Scenario Release of dissolved radionuclides	1.1 Reference conceptualisation	1.1a Reference Case (RC)
		1.1b Variability in canister inventory
		1.1c Reduced canister lifetime
		1.1d Pessimistic near-field geochemical dataset
		1.1e Increased glass dissolution rate in HLW
		1.1f Increased water flow rate in geosphere (10-fold increase)
		1.1g Decreased water flow rate in geosphere (10-fold decrease)
		1.1h Pessimistic geosphere sorption constants
		1.1i Pessimistic near-field and geosphere geochemical dataset
		1.1j Pessimistic geosphere diffusion constants
		1.1k Pessimistic treatment of ^{14}C (organic) in SF
	1.2 Solubility-limited dissolution of SF	1.2a Base Case only
	1.3 Bentonite thermal alteration	1.3a Base Case only
	1.4 Glacially-induced flow in the Opalinus Clay	1.4a Base Case only
	1.5 Additional barrier provided by confining units	1.5a Vertical transport through confining units
		1.5b Horizontal transport in local aquifers
	1.6 Radionuclide release affected by ramp / shaft	1.6a Base Case
		1.6b Increased hydraulic conductivity of EDZ (100-fold increase)
	1.7 Convergence-induced release affected by ramp (ILW)	1.7a Steady-state hydraulics
		1.7b Water pulse
	1.8 Gas-induced release of dissolved radionuclides affected by ramp / shaft	1.8a Base Case
		1.8b Increased water flow rate in ILW
2. Alternative Scenario 1 Release of volatile radionuclides along gas pathways	2.1 Release of ^{14}C from SF and ILW as volatile species in the gas phase not affected by ramp / shaft ("tight seals")	2.1a-c Three different gas permeability values
	2.2 Release of ^{14}C from SF and ILW as volatile species in the gas phase affected by ramp / shaft ("leaky seals")	2.2a-c Three different gas permeability values
3. Alternative Scenario 2 Release of radionuclides affected by human actions	3.1 Borehole penetration	3.1a-d Penetration of SF / HLW / ILW emplacement tunnel (parameter variations related to the water flow rate through the borehole and the number of canisters affected)
		3.1e-g Direct hit of a SF canister (parameter variations related to the water flow rate through the borehole)
	3.2 Deep groundwater extraction from Malm aquifer (production of well as dilution)	3.2a/b Two different degrees of plume capture efficiency (10 %, 100 %)
	3.3 Abandoned repository	3.3a Base Case only

Tab. A5.3.1: (Cont.)

Alternative scenarios addressing scenario uncertainty	Alternative conceptualisations addressing conceptual uncertainty	Parameter variations addressing parameter uncertainty
4. "What if" cases to investigate robustness of the disposal system	4.1 High water flow rate	4.1a Increased water flow rate in geosphere (100-fold increase)
	4.2 Transport along transmissive discontinuities	4.2a/b Number of SF / HLW canisters affected ($T = 10^{-10}$ m^2 s^{-1})
		4.2c ILW ($T = 10^{-10}$ m^2 s^{-1})
		4.2d/e Number of SF / HLW canisters affected ($T = 10^{-9}$ m^2 s^{-1})
		4.2f ILW ($T = 10^{-9}$ m^2 s^{-1})
	4.3 SF: Increased fuel dissolution rate	4.3a 10-fold increase with respect to RC
		4.3b 100-fold increase with respect to RC
	4.4 Redox front (SF / ILW compacted hulls)	4.4a Base Case only
	4.5 ILW: Gas-induced release of dissolved radionuclides through the ramp only	4.5a/b Two different water flow rates
	4.6 Unretarded transport of ^{14}C released as volatile species through host rock; retardation in confining units taken into account	4.6a-c Three different gas permeability values
	4.7 Poor near field and pessimistic near-field / geosphere geochemical dataset	4.7a RC flow rate
		4.7b 10-fold increase of flow rate
		4.7c 100-fold increase of flow rate
	4.8 No advection in geosphere (diffusive transport only)	4.8a Base Case only
	4.9 SF: Increased cladding corrosion rate	4.9a 10-fold increase with respect to RC
	4.10 K_d(I) for NF and geosphere = 0	4.10a Base Case only
	4.11 Decreased transport distance in Opalinus Clay (30 m)	4.11a Base Case only
5. Design and system options	5.1 Increased waste arisings (300 GWa(e))	5.1a Base Case only
	5.2 ILW high force compacted waste option	5.2a Base Case only
	5.3 SF canister with Cu shell	5.3a Canister breaching at 10^5 years
		5.3b Initial defect (small initial pinhole, full breaching at 10^5 years)
		5.3c Initial defect (large initial pinhole, full breaching at 10^5 years)
6. Illustration of effects of biosphere uncertainty	6.1 Reference and alternative geomorphology	6.1a Reference area (RC)
		6.1b Sedimentation area
		6.1c Wetland
		6.1d Exfiltration to spring located at valley side
	6.2 Reference and alternative climates	6.2a Present-day climate (RC)
		6.2b Drier / warmer than present-day climate
		6.2c Wetter / warmer than present-day climate
		6.2d Periglacial climate

Tab. A5.4.1: Interaction matrix for Super-FEPs and their associated uncertainties

Grey field	Diagonal element of interaction matrix. For diagonal elements, the last column indicates the treatment of the Super-FEP and associated uncertainties.
1.1b (type of assumption)	Interaction explicitly considered in case 1.1b
Type of assumption	Identical to abbreviations used in Nagra (2002b), Ch. 10
LE	Conceptual assumption corresponds to the **l**ikely / **e**xpected characteristics and evolution of the system – any deviations are expected to be unimportant
PCA	**P**essimistic **c**onceptual **a**ssumption within the range of possibilities that is reasonably to be expected
WRP	**W**ithin the **r**ange of **p**ossibilities, but likelihood not currently possible to evaluate – other (and sometimes more pessimistic) assumptions may not be unreasonable
WI	"**W**hat **i**f?" assumption for system evolution that is outside the range of possibilities that is reasonably to be expected
ST	**St**ylised conceptualisation of system characteristics and evolution
NA	Interaction possible but not analysed
NA (RFEP1)	Reserve FEP (RFEP) with reference to Super-FEP / associated uncertainty (1)
NA (RFEP2)	Reserve FEP (RFEP) with reference to Super-FEP / associated uncertainty (2)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
SF				
B.1.1	**B.1.1.1**	**B.1.1**	**B.1.1.1**	
Quantities and burnup of fuel and associated radionuclide inventories, including the instant release fraction (IRF)	The possibility for increased nuclear power production	Quantities and burnup of fuel and associated radionuclide inventories, including the instant release fraction (IRF)	The possibility for increased nuclear power production	5.1a (PCA)
			B.1.1.2	
			The current trend to higher burnups	1.1b (PCA)
		B.2.1		
		Quantities of glass and associated radionuclide inventories	Low – compositions specified by the two reprocessors	NA (no additional reprocessing assumed)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
		B.3.5	**B.3.5.2**	
		Breaching of steel canisters	The remote possibility of breaching prior to 1000 a, and the possibility of initially defective steel canisters	NA (5.3b-c assumes single defective copper canister)
		B.3.7		
		Canister material	Design option of a copper canister with steel insert for SF (or alternative material to mitigate / avoid gas production)	5.3a (WRP) to mitigate/avoid gas production
		B.3.1		
		Quantities of waste and associated radionuclide inventories	Uncertainty in inventories low, but two different waste specifications considered	NA (no additional reprocessing assumed)
		B.7.1	**B.7.1.3**	
		The migration of repository induced gas	The rate of gas generation by corrosion of the SF / HLW canisters	NA (gas generation increases linearly with number of canisters)
			B.7.1.5	
			The rate of generation of gas by ILW	NA (no additional reprocessing assumed)
		B.7.2	**B.7.2.1**	
		Future human actions	Possibility of future drilling of a borehole inadvertently affecting the barrier system	3.1a-g (ST) (single hit assumed)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
	B.1.1.2	**B.1.1**	**B.1.1.1**	
	The current trend to higher burnups	Quantities and burnup of fuel and associated radio-nuclide inventories, including the instant release fraction (IRF)	The possibility for increased nuclear power production	1.1b (PCA)
			B.1.1.2	
			The current trend to higher burnups	1.1b (PCA)
			B.1.1.2a	
			Chemical state of ^{14}C released from SF	1.1k (PCA)
			B.1.1.3	
			The limited information available on the IRF of high burnup UO_2 fuel and MOX fuel	1.1b (PCA)
		B.1.5		
		Criticality	Whether or not it can be completely ruled out	NA (higher burnup is beneficial)
		B.4.3		
		Migration of radiolytic oxidants generated at SF surfaces into bentonite buffer	Degree to which these oxidants are scavenged by reductants in the system	Effects of higher activity covered by 4.4a (WI)
		B.4.4		
		Thermal alteration of the bentonite buffer adjacent to the SF / HLW canisters	Existence / extent of any thermally altered region	Effects of higher temperatures covered by 1.3a (PCA)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
	B.1.1.2a	**B.1.1**	**B.1.1.1**	
	Chemical state of ^{14}C released from SF	Quantities and burnup of fuel and associated radio-nuclide inventories, including the instant release fraction (IRF)	The possibility for increased nuclear power production	All relevant cases
			B.1.1.2a	
			Chemical state of ^{14}C released from SF	1.1k (PCA)
		B.4.2	**B.4.2.1**	
		Geochemical immobilisation and retardation in the near field	Thermodynamic data and water chemistry	All relevant cases
		B.7.1	**B.7.1.1**	
		The migration of repository induced gas	The possibility that gas pathways are created through host rock and the uncer-tainty in gas permea-bility that might allow the transport of ^{14}C in a volatile form with flowing gas	2.1a/b/c (PCA) 2.2a/b/c (PCA)
			B.7.1.2	
			The possibility that the EDZs would allow the tunnels / ramp / shaft to provide gas pathways and the uncertainties in gas permeability	2.2a/b/c (PCA)
			B.7.1.4	
			Rapid transport of radionuclides as volatile species through continuous gas path	4.6a/b/c (WI)
			B.7.1.6	
			Extent of preferential release of organic ^{14}C from SF cladding	1.1k (PCA)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
	B.1.1.3	**B.1.1**	**B.1.1.3**	
	The limited information available on the IRF of high burnup UO_2 fuel and MOX fuel	Quantities and burnup of fuel and associated radio-nuclide inventories, including the instant release fraction (IRF)	The limited information available on the IRF of high burnup UO_2 fuel and MOX fuel	1.1b (PCA)
		B.7.1	**B.7.1.6**	
		The migration of repository induced gas	Extent of preferential release of organic ^{14}C from SF cladding	Covered by 1.1k (PCA)
B.1.2		**B.1.1**	**B.1.1.2a**	
Corrosion of cladding (see also "The creation of gas pathways", B.7.1.1)	Whether prefer-ential release of organic ^{14}C from the cladding occurs; corrosion rate of cladding	Quantities and burnup of fuel and associated radio-nuclide inventories, including the instant release fraction (IRF)	Chemical state of ^{14}C released from SF	1.1k (PCA)
		B.1.2		
		Corrosion of cladding (see also "The creation of gas pathways", B.7.1.1)	Whether preferential release of organic ^{14}C from the cladding occurs; corrosion rate of cladding	4.7a/b/c (WI) 4.9a (WI)
		B.3.3		
		Corrosion / dissolution of ILW	Rate of corrosion / dissolution of waste matrix and rate of release of radionuclides	All relevant cases (instantaneous release assumed)
		B.7.1	**B.7.1.6**	
		The migration of repository induced gas	Extent of preferential release of organic ^{14}C from SF cladding	All relevant cases (some ^{14}C assigned to IRF) / for gas production: NA

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
B.1.3		**B.1.3**		
Breaching of cladding	The possibility of early fracturing of the cladding, preventing an extended period of complete containment following canister breaching	Breaching of cladding	The possibility of early fracturing of the cladding, preventing an extended period of complete containment following canister breaching	NA (RFEP)
B.1.4	**B.1.4.1**	**B.1.4**	**B.1.4.1**	
Dissolution of fuel matrix	Whether the rate of dissolution is controlled by the rate of production of radiolytic oxidants or (if reducing conditions prevail at the fuel surface) by the solubility of U(IV)	Dissolution of fuel matrix	Whether the rate of dissolution is controlled by the rate of production of radiolytic oxidants or (if reducing conditions prevail at the fuel surface) by the solubility of U(IV)	1.2a (LE)
		B.4.2	**B.4.2.2**	
		Geochemical immobilisation and retardation in the near field	The extent of co-precipitation of radionuclides with secondary minerals derived from SF and glass dissolution and canister corrosion	NA (RFEP2)
	B.1.4.2	**B.1.4**	**B.1.4.2**	
	If the rate of dissolution is controlled by the rate of production of radiolytic oxidants, the proportion of the oxidants that is available for reaction at the fuel surface (not recombined, e.g. with radiolytic reductants)	Dissolution of fuel matrix	If the rate of dissolution is controlled by the rate of production of radiolytic oxidants, the proportion of the oxidants that is available for reaction at the fuel surface (not recombined, e.g. with radiolytic reductants)	4.3a/b (WI)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
		B.4.2	**B.4.2.2**	
		Geochemical immobilisation and retardation in the near field	The extent of co-precipitation of radionuclides with secondary minerals derived from SF and glass dissolution and canister corrosion	NA (RFEP2)
		B.4.3		
		Migration of radiolytic oxidants generated at SF surfaces into bentonite buffer	Degree to which these oxidants are scavenged by reductants in the system	4.4a (WI), assuming oxidising conditions throughout near field
B.1.5		**B.1.5**		
Criticality	Whether or not it can be completely ruled out	Criticality	Whether or not it can be completely ruled out	NA (ruled out by design and supporting calculations)
		HLW glass		
B.2.1		**B.2.1**		
Quantities of glass and associated radionuclide inventories	Low – compositions specified by the two reprocessors	Quantities of glass and associated radionuclide inventories	Low – compositions specified by the two reprocessors	NA (analysis of COGEMA and BNFL glasses only)
B.2.2		**B.2.2**		
Dissolution rate of glass	Long-term rates based on extrapolation of much shorter-term experiments; creation of additional surfaces for dissolution by fracturing of glass	Dissolution rate of glass	Long-term rates based on extrapolation of much shorter-term experiments; creation of additional surfaces for dissolution by fracturing of glass	1.1e (PCA) 4.7a/b/c (WI)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
SF / HLW canisters				
B.3.5	**B.3.5.1**	**B.1.2**		
Breaching of steel canisters	The conditions under which mechanical failure of corroded canisters will occur; possibility of localised corrosion processes	Corrosion of cladding (see also "The creation of gas pathways", B.7.1.1)	Whether preferential release of organic ^{14}C from the cladding occurs; corrosion rate of cladding	1.1c (PCA), no water ingress prior to canister breaching
		B.1.4	**B.1.4.1**	
		Dissolution of fuel matrix	Whether the rate of dissolution is controlled by the rate of production of radiolytic oxidants or (if reducing conditions prevail at the fuel surface) by the solubility of U(IV)	1.1c (PCA), no water ingress prior to canister breaching
			B.1.4.2	
			If the rate of dissolution is controlled by the rate of production of radiolytic oxidants, the proportion of the oxidants that is available for reaction at the fuel surface (not recombined, e.g. with radiolytic reductants)	4.7a/b/c (WI)
		B.1.5		
		Criticality	Whether or not it can be completely ruled out	NA (no water ingress prior to canister breaching)
		B.2.2		
		Dissolution rate of glass	Long-term rates based on extrapolation of much shorter-term experiments; creation of additional surfaces for dissolution by fracturing of glass	1.1c/e (PCA)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		B.3.5	**B.3.5.1**	
		Breaching of steel canisters	The conditions under which mechanical failure of corroded canisters will occur; possibility of localised corrosion processes	1.1c (PCA)
		B.4.2	**B.4.2.3**	
		Geochemical immobilisation and retardation in the near field	The extent of sorption of radio-nuclides on canister corrosion products	NA (RFEP)
		B.4.5		
		Transport resistances provided by internal spaces (fractures) within the waste forms, by the breached SF / HLW canisters and by corrosion products	The magnitude and time-dependence of these resistances	NA (RFEP)
	B.3.5.2	**B.1.2**		
	The remote possibility of breaching prior to 1000 a, and the possibility of initially defective steel canisters	Corrosion of cladding (see also "The creation of gas pathways", B.7.1.1)	Whether preferential release of organic ^{14}C from the cladding occurs; corrosion rate of cladding	4.7a/b/c (WI)
		B.1.4	**B.1.4.2**	
		Dissolution of fuel matrix	If the rate of disso-lution is controlled by the rate of pro-duction of radiolytic oxidants, the propor-tion of the oxidants that is available for reaction at the fuel surface (not recom-bined, e.g. with radiolytic reductants)	4.7a/b/c (WI)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
		B.2.2		
		Dissolution rate of glass	Long-term rates based on extrapolation of much shorter-term experiments; creation of additional surfaces for dissolution by fracturing of glass	4.7a/b/c (WI)
		B.3.5	**B.3.5.2**	
		Breaching of steel canisters	The remote possibility of breaching prior to 1000 a, and the possibility of initially defective steel canisters	4.7a/b/c (WI)
	B.3.5.3	**B.1.2**		
	Distribution of canister breaching times	Corrosion of cladding (see also "The creation of gas pathways", B.7.1.1)	Whether preferential release of organic ^{14}C from the cladding occurs; corrosion rate of cladding	NA (RFEP1)
		B.1.4	**B.1.4.1**	
		Dissolution of fuel matrix	Whether the rate of dissolution is controlled by the rate of production of radiolytic oxidants or (if reducing conditions prevail at the fuel surface) by the solubility of U(IV)	NA (RFEP1)
			B.1.4.2	
			If the rate of dissolution is controlled by the rate of production of radiolytic oxidants, the proportion of the oxidants that is available for reaction at the fuel surface (not recombined, e.g. with radiolytic reductants)	NA (RFEP1)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		B.2.2		
		Dissolution rate of glass	Long-term rates based on extrapolation of much shorter-term experiments; creation of additional surfaces for dissolution by fracturing of glass	NA (RFEP1)
		B.3.5	**B.3.5.3**	
		Breaching of steel canisters	Distribution of canister breaching times	NA (RFEP)
		B.3.7		
		Canister material	Design option of a copper canister with steel insert for SF (or alternative material to mitigate / avoid gas production)	NA (RFEP2)
B.3.6		**B.3.5**	**B.3.5.1**	
Gas generation by steel canister corrosion	See "The creation of gas pathways", B.7.1.1	Breaching of steel canisters	The conditions under which mechanical failure of corroded canisters will occur; possibility of localised corrosion processes	Covered by 1.1c (PCA)
			B.3.5.3	
			Distribution of canister breaching times	NA (RFEP2)
		B.3.6		
		Gas generation by steel canister corrosion	See "The creation of gas pathways", B.7.1.1	See B.7.1.1
		B.3.7		
		Canister material	Design option of a copper canister with steel insert for SF (or alternative material to mitigate / avoid gas production)	NA (RFEP2)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		B.7.1	**B.7.1.1**	
		The migration of repository induced gas	The possibility that gas pathways are created through host rock and the uncertainty in gas permeability that might allow the transport of ^{14}C in a volatile form with flowing gas	1.8a (WRP) 1.8b (PCA) 2.1a/b/c (PCA) 2.2a/b/c (PCA)
			B.7.1.2	
			The possibility that the EDZs would allow the tunnels / ramp / shaft to provide gas pathways and the uncertainties in gas permeability	2.2a/b/c (PCA)
			B.7.1.3	
			The rate of gas generation by corrosion of the SF / HLW canisters	All gas-related cases
			B.7.1.4	
			Rapid transport of radionuclides as volatile species through continuous gas path	4.6a/b/c (WI)
		B.7.2	**B.7.2.1**	
		Future human actions	Possibility of future drilling of a borehole inadvertently affecting the barrier system	NA (exposure of drilling personnel outside scope)
			B.7.2.3	
			Possibility of the repository being abandoned before it is backfilled and sealed	NA (mitigation of gas pressure buildup)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
B.3.7		**B.1.5**		
Canister material	Design option of a copper canister with steel insert for SF (or alternative material to mitigate / avoid gas production)	Criticality	Whether or not it can be completely ruled out	NA
		B.3.5	**B.3.5.1**	
		Breaching of steel canisters	The conditions under which mechanical failure of corroded canisters will occur; possibility of localised corrosion processes	5.3a (WRP)
			B.3.5.2	
			The remote possibility of breaching prior to 1000 a, and the possibility of initially defective steel canisters	5.3b/c (PCA)
			B.3.5.3	
			Distribution of canister breaching times	NA (RFEP2)
		B.3.6		
		Gas generation by steel canister corrosion	See "The creation of gas pathways", B.7.1.1	See B.7.1.1
		B.3.7		
		Canister material	Design option of a copper canister with steel insert for SF (or alternative material to mitigate / avoid gas production)	5.3a (WRP) 5.3b/c (PCA)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
		B.4.2	**B.4.2.3**	
		Geochemical immobilisation and retardation in the near field	The extent of sorption of radionuclides on canister corrosion products	NA (RFEP2)
		B.4.3		
		Migration of radiolytic oxidants generated at SF surfaces into bentonite buffer	Degree to which these oxidants are scavenged by reductants in the system	NA (no significant amounts of radiolytic oxidants)
		B.4.5		
		Transport resistances provided by internal spaces (fractures) within the waste forms, by the breached SF / HLW canisters and by corrosion products	The magnitude and time-dependence of these resistances	5.3b/c (PCA)
		B.4.7.1		
		Gas transport characteristics of bentonite	Uncertainties in corrosion rate	NA (gas generation largely eliminated for SF copper canister)
		B.7.1	**B.7.1.1**	
		The migration of repository induced gas	The possibility that gas pathways are created through host rock and the uncertainty in gas permeability that might allow the transport of ^{14}C in a volatile form with flowing gas	NA (gas generation largely eliminated for SF copper canister)
			B.7.1.2	
			The possibility that the EDZs would allow the tunnels / ramp / shaft to provide gas pathways and the uncertainties in gas permeability	NA (gas generation largely eliminated for SF copper canister)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
			B.7.1.3	
			The rate of gas generation by corrosion of the SF / HLW canisters	NA (gas generation largely eliminated for SF copper canister)
			B.7.1.4	
			Rapid transport of radionuclides as volatile species through continuous gas path	NA (gas generation largely eliminated for SF copper canister)
		B.7.2	**B.7.2.1**	
		Future human actions	Possibility of future drilling of a borehole inadvertently affecting the barrier system	NA
SF / HLW near field				
B.4.1		**B.1.4**	**B.1.4.1**	
The long resaturation time of the repository and its surroundings	The rate of the resaturation process	Dissolution of fuel matrix	Whether the rate of dissolution is controlled by the rate of production of radiolytic oxidants or (if reducing conditions prevail at the fuel surface) by the solubility of U(IV)	NA (RFEP1)
			B.1.4.2	
			If the rate of dissolution is controlled by the rate of production of radiolytic oxidants, the proportion of the oxidants that is available for reaction at the fuel surface (not recombined, e.g. with radiolytic reductants)	NA (RFEP1)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		B.2.2		
		Dissolution rate of glass	Long-term rates based on extrapolation of much shorter-term experiments; creation of additional surfaces for dissolution by fracturing of glass	NA (RFEP1)
		B.3.5	**B.3.5.1**	
		Breaching of steel canisters	The conditions under which mechanical failure of corroded canisters will occur; possibility of localised corrosion processes	NA (RFEP1)
			B.3.5.2	
			The remote possibility of breaching prior to 1000 a, and the possibility of initially defective steel canisters	NA (RFEP1)
		B.3.7		
		Canister material	Design option of a copper canister with steel insert for SF (or alternative material to mitigate / avoid gas production)	NA (RFEP1)
		B.4.1		
		The long resaturation time of the repository and its surroundings	The rate of the resaturation process	NA (RFEP)
		B.4.4		
		Thermal alteration of the bentonite buffer adjacent to the SF / HLW canisters	Existence / extent of any thermally altered region	1.3a (PCA, consideration of dry bentonite)
		B.4.7.1		
		Gas transport characteristics of bentonite	Uncertainties in corrosion rate	NA (RFEP1)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
		B.5.1	**B.5.1.1**	
		Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)	The hydraulic conductivity of the EDZs with respect to that of the surrounding undisturbed rock	NA (RFEP1)
			B.5.1.2	
			The driving force for flow along the EDZs provided by tunnel convergence	1.7a (PCA, compaction / resaturation occur in parallel)
			B.5.1.3	
			The driving force for flow along the EDZs provided by near field gas, as well as the rate of near field gas production (see also "The migration of repository induced gas", B.7.1)	1.8a (WRP) 1.8b (PCA) 4.5a/b (WI)
		B.5.2		
		The seals and the surrounding rock (see also "The creation of gas pathways", B.7.1.1)	The possibility of sealed zones being bypassed by relatively permeable EDZs	See B.7.1.1
		B.6.1	**B.6.1.2**	
		Low groundwater flow rate through undisturbed Opalinus Clay (see also "Low ground-water flow rate along the sealed tunnels / ramp / shaft, and through the sur-rounding excavation disturbed zones", B.5.1)	The effects of gas pressure buildup in the near field, tunnel convergence and ice loads on the hydrau-lic gradient	Delay of gas pressure buildup considered in all relevant cases

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		B.7.1	**B.7.1.1**	
		The migration of repository induced gas	The possibility that gas pathways are created through host rock and the uncertainty in gas permeability that might allow the transport of ^{14}C in a volatile form with flowing gas	Resaturation considered in all gas-related cases
			B.7.1.2	
			The possibility that the EDZs would allow the tunnels / ramp / shaft to provide gas pathways and the uncertainties in gas permeability	Resaturation considered in all gas-related cases
			B.7.1.3	
			The rate of gas generation by corrosion of the SF / HLW canisters	Resaturation considered in all gas-related cases
			B.7.1.4	
			Rapid transport of radionuclides as volatile species through continuous gas path	Resaturation considered in all gas-related cases
			B.7.1.5	
			The rate of generation of gas by ILW	Included in all cases (PCA)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
B.4.2	**B.4.2.1**	**B.4.2**	**B.4.2.1**	
Geochemical immobilisation and retardation in the near field	Thermodynamic data and water chemistry	Geochemical immobilisation and retardation in the near field	Thermodynamic data and water chemistry	1.1d/i (PCA) 4.7a/b/c (WI) 4.10a (WI)
		B.6.2	**B.6.2.1**	
		Geochemical immobilisation and retardation in the Opalinus Clay and confining units	Sorption mechanisms and groundwater composition, diffusivity	4.7a/b/c (WI)
			B.6.2.2	
			The effectiveness of long-term immobilisation processes (precipitation / co-precipitation) in the geosphere	4.7a/b/c (WI)
	B.4.2.1a	**B.4.2**	**B.4.2.1**	
	Colloid filtration by bentonite	Geochemical immobilisation and retardation in the near field	Thermodynamic data and water chemistry	NA (small pore size eliminates colloid transport)
			B.4.2.1a	
			Colloid filtration by bentonite	NA (small pore size eliminates colloid transport)
		B.6.2	**B.6.2.1**	
		Geochemical immobilisation and retardation in the Opalinus Clay and confining units	Sorption mechanisms and groundwater composition, diffusivity	NA (small pore size eliminates colloid transport)
			B.6.2.2	
			The effectiveness of long-term immobilisation processes (precipitation / co-precipitation) in the geosphere	NA (small pore size eliminates colloid transport)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
	B.4.2.2	**B.4.2**	**B.4.2.1**	
	The extent of co-precipitation of radionuclides with secondary minerals derived from SF and glass dissolution and canister corrosion	Geochemical immobilisation and retardation in the near field	Thermodynamic data and water chemistry	NA (RFEP1)
			B.4.2.2	
			The extent of co-precipitation of radionuclides with secondary minerals derived from SF and glass dissolution and canister corrosion	NA (RFEP)
	B.4.2.3	**B.4.2**	**B.4.2.1**	
	The extent of sorption of radionuclides on canister corrosion products	Geochemical immobilisation and retardation in the near field	Thermodynamic data and water chemistry	NA (RFEP1)
			B.4.2.3	
			The extent of sorption of radio-nuclides on canister corrosion products	NA (RFEP)
	B.4.2.4	**B.4.2**	**B.4.2.1**	
	The natural concentrations of isotopes in bentonite porewater	Geochemical immobilisation and retardation in the near field	Thermodynamic data and water chemistry	NA (RFEP1)
			B.4.2.4	
			The natural concentrations of isotopes in bentonite porewater	NA (RFEP)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
		B.6.2	**B.6.2.1**	
		Geochemical immobilisation and retardation in the Opalinus Clay and confining units	Sorption mechanisms and groundwater composition, diffusivity	NA (similar geochemical conditions in bentonite and Opalinus Clay)
			B.6.2.2	
			The effectiveness of long-term immobili-sation processes (precipitation / co-precipitation) in the geosphere	NA (similar geochemical conditions in bentonite and Opalinus Clay)
B.4.3		**B.4.2**	**B.4.2.1**	
Migration of radiolytic oxi-dants generated at SF surfaces into bentonite buffer	Degree to which these oxidants are scavenged by reductants in the system	Geochemical immobilisation and retardation in the near field	Thermodynamic data and water chemistry	4.4a (WI, K_ds and solubility limits for oxidising conditions)
		B.4.3		
		Migration of radiolytic oxidants generated at SF surfaces into bentonite buffer	Degree to which these oxidants are scavenged by reductants in the system	4.4a (WI)
		B.6.2	**B.6.2.1**	
		Geochemical immobilisation and retardation in the Opalinus Clay and confining units	Sorption mechanisms and groundwater composition, diffusivity	4.4a (WI, no migration of radiolytic oxidants into Opalinus Clay)
			B.6.2.2	
			The effectiveness of long-term immobili-sation processes (precipitation / co-precipitation) in the geosphere	4.4a (WI, solubility limitation in Opalinus Clay conservatively neglected)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
B.4.4		**B.4.2**	**B.4.2.1**	
Thermal alteration of the bentonite buffer adjacent to the SF / HLW canisters	Existence / extent of any thermally altered region	Geochemical immobilisation and retardation in the near field	Thermodynamic data and water chemistry	1.3a (PCA, no effect on bentonite K_d values assumed, but increased diffusion coefficient)
			B.4.2.1a	
			Colloid filtration by bentonite	NA (small pore size in bentonite eliminates colloid transport)
		B.4.4		
		Thermal alteration of the bentonite buffer adjacent to the SF / HLW canisters	Existence / extent of any thermally altered region	1.3a (PCA)
		B.4.7		
		Hydraulic transport characteristics of bentonite	Compaction of bentonite by tunnel convergence	NA (outer half of bentonite not altered)
		B.4.7.1		
		Gas transport characteristics of bentonite	Uncertainties in corrosion rate	NA (outer half of bentonite not altered)
		B.5.1	**B.5.1.2**	
		Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)	The driving force for flow along the EDZs provided by tunnel convergence	NA (major part of bentonite not altered)
		B.6.2	**B.6.2.1**	
		Geochemical immobilisation and retardation in the Opalinus Clay and confining units	Sorption mechanisms and groundwater composition, diffusivity	1.3a (PCA), no thermal alterations in Opalinus Clay
			B.6.2.2	
			The effectiveness of long-term immobilisation processes (precipitation / co-precipitation) in the geosphere	1.3a (PCA), no thermal alterations in Opalinus Clay

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
B.4.5		**B.4.1**		
Transport resistances provided by internal spaces (fractures) within the waste forms, by the breached SF / HLW canisters and by corrosion products	The magnitude and time-dependence of these resistances	The long resaturation time of the repository and its surroundings	The rate of the resaturation process	NA (transport resistance for water ingress conservatively neglected)
		B.4.2	**B.4.2.3**	
		Geochemical immobilisation and retardation in the near field	The extent of sorption of radionuclides on canister corrosion products	NA (RFEP2)
		B.4.5		
		Transport resistances provided by internal spaces (fractures) within the waste forms, by the breached SF / HLW canisters and by corrosion products	The magnitude and time-dependence of these resistances	5.3b/c (PCA)
B.4.6		**B.4.1**		
Tunnel liner	Design option of concrete or polymer liners for emplacement tunnels in case increased tunnel support required	The long resaturation time of the repository and its surroundings	The rate of the resaturation process	NA (no liner required)
		B.4.2	**B.4.2.1**	
		Geochemical immobilisation and retardation in the near field	Thermodynamic data and water chemistry	NA (no liner required)
		B.4.6		
		Tunnel liner	Design option of concrete or polymer liners for emplacement tunnels in case increased tunnel support required	NA (no liner required)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		B.5.1	**B.5.1.1**	
		Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)	The hydraulic conductivity of the EDZs with respect to that of the surrounding undisturbed rock	NA (no liner required)
			B.5.1.2	
			The driving force for flow along the EDZs provided by tunnel convergence	NA (no liner required)
			B.5.1.3	
			The driving force for flow along the EDZs provided by near field gas, as well as the rate of near field gas production (see also "The migration of repository induced gas", B.7.1)	NA (no liner required)
B.4.7		**B.4.1**		
Hydraulic transport characteristics of bentonite	Compaction of bentonite by tunnel convergence	The long resaturation time of the repository and its surroundings	The rate of the resaturation process	NA (instantaneous resaturation assumed)
		B.4.7		
		Hydraulic transport characteristics of bentonite	Compaction of bentonite by tunnel convergence	NA (decreased bentonite thickness assumed)
		B.5.1	**B.5.1.1**	
		Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)	The hydraulic conductivity of the EDZs with respect to that of the surrounding undisturbed rock	1.6a (WRP) 1.6b (PCA)
			B.5.1.2	
			The driving force for flow along the EDZs provided by tunnel convergence	NA (decreased bentonite thickness assumed)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
		B.5.2		
		The seals and the surrounding rock (see also "The creation of gas pathways", B.7.1.1)	The possibility of sealed zones being bypassed by relatively permeable EDZs	1.6a (WRP) 1.6b (PCA)
		B.7.1	**B.7.1.3**	
		The migration of repository induced gas	The rate of gas generation by corrosion of the SF / HLW canisters	NA (unlimited availability of water assumed)
		B.7.2	**B.7.2.3**	
		Future human actions	Possibility of the repository being abandoned before it is backfilled and sealed	3.3a (PCA)
B.4.7.1		**B.4.7.1**		
Gas transport characteristics of bentonite	Uncertainties in corrosion rate	Gas transport characteristics of bentonite	Uncertainties in corrosion rate	NA
		B.5.1	**B.5.1.3**	
		Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)	The driving force for flow along the EDZs provided by near field gas, as well as the rate of near field gas production (see also "The migration of repository induced gas", B.7.1)	NA
		B.5.2		
		The seals and the surrounding rock (see also "The creation of gas pathways", B.7.1.1)	The possibility of sealed zones being bypassed by relatively permeable EDZs	NA

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		B.7.1	**B.7.1.1**	
		The migration of repository induced gas	The possibility that gas pathways are created through host rock and the uncertainty in gas permeability that might allow the transport of ^{14}C in a volatile form with flowing gas	NA
			B.7.1.2	
			The possibility that the EDZs would allow the tunnels / ramp / shaft to provide gas pathways and the uncertainties in gas permeability	2.2a/b/c (PCA)
			B.7.1.4	
			Rapid transport of radionuclides as volatile species through continuous gas path	4.6a/b/c (WI)
		B.7.2	**B.7.2.1**	
		Future human actions	Possibility of future drilling of a borehole inadvertently affecting the barrier system	NA (effects of gas on borehole penetration neglected)
			B.7.2.3	
			Possibility of the repository being abandoned before it is backfilled and sealed	NA (effects of gas on abandoned repository neglected)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		ILW		
B.3.1		**B.3.1**		
Quantities of waste and associated radionuclide inventories	Uncertainty in inventories low, but two different waste specifica-tions considered	Quantities of waste and associated radionuclide inventories	Uncertainty in inventories low, but two different waste specifica-tions considered	5.2a (WRP)
		B.3.3		
		Corrosion / dissolution of ILW	Rate of corrosion / dissolution of waste matrix and rate of release of radionuclides	NA (instantaneous dissolution assumed)
		B.3.4		
		Gas generation	See "The creation of gas pathways", B.7.1.1	See B.7.1.1
		B.3.3.1		
		Compaction of waste / mortar (see B.4.7)	Timing of conver-gence arising from void reduction of breached, corroded containers	NA (less void space in high force compacted waste option)
		B.7.1	**B.7.1.1**	
		The migration of repository induced gas	The possibility that gas pathways are created through host rock and the uncer-tainty in gas perme-ability that might allow the transport of ^{14}C in a volatile form with flowing gas	NA (insignificant difference between the two waste options)
			B.7.1.2	
			The possibility that the EDZs would allow the tunnels / ramp / shaft to pro-vide gas pathways and the uncertainties in gas permeability	NA (insignificant difference between the two waste options)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
			B.7.1.4	
			Rapid transport of radionuclides as volatile species through continuous gas path	NA (insignificant difference between the two waste options)
			B.7.1.5	
			The rate of generation of gas by ILW	NA (insignificant difference between the two waste options)
B.3.2		**B.3.2**		
Breaching of ILW steel drums and emplacement containers	The timing of drum / container breaching	Breaching of ILW steel drums and emplacement containers	The timing of drum / container breaching	4.7a/b/c (WI)
		B.3.3		
		Corrosion / dissolution of ILW	Rate of corrosion / dissolution of waste matrix and rate of release of radionuclides	NA (delay neglected, RFEP1)
		B.3.4		
		Gas generation	See "The creation of gas pathways", B.7.1.1	See B.7.1.1
		B.3.3.1		
		Compaction of waste / mortar (see B.4.7)	Timing of convergence arising from void reduction of breached, corroded containers	1.7a/b (PCA)
		B.7.1	**B.7.1.1**	
		The migration of repository induced gas	The possibility that gas pathways are created through host rock and the uncertainty in gas permeability that might allow the transport of ^{14}C in a volatile form with flowing gas	2.1a/b/c (PCA, instantaneous breaching)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
			B.7.1.2	
			The possibility that the EDZs would allow the tunnels / ramp / shaft to provide gas pathways and the uncertainties in gas permeability	2.2a/b/c (PCA, instantaneous breaching)
			B.7.1.4	
			Rapid transport of radionuclides as volatile species through continuous gas path	4.6a/b/c (WI, instantaneous breaching)
		B.7.2	**B.7.2.3**	
		Future human actions	Possibility of the repository being abandoned before it is backfilled and sealed	3.3a (PCA)
B.3.3		**B.3.3**		
Corrosion / dissolution of ILW	Rate of corrosion / dissolution of waste matrix and rate of release of radionuclides	Corrosion / dissolution of ILW	Rate of corrosion / dissolution of waste matrix and rate of release of radionuclides	NA (instantaneous dissolution, reserve FEP)
		B.3.4		
		Gas generation	See "The creation of gas pathways", B.7.1.1	See B.7.1.1
		B.7.1	**B.7.1.1**	
		The migration of repository induced gas	The possibility that gas pathways are created through host rock and the uncertainty in gas permeability that might allow the transport of ^{14}C in a volatile form with flowing gas	2.1a/b/c (PCA, instantaneous dissolution)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
			B.7.1.2	
			The possibility that the EDZs would allow the tunnels / ramp / shaft to provide gas pathways and the uncertainties in gas permeability	2.2a/b/c (PCA, instantaneous dissolution)
			B.7.1.4	
			Rapid transport of radionuclides as volatile species through continuous gas path	4.6a/b/c (WI, instantaneous dissolution)
			B.7.1.5	
			The rate of generation of gas by ILW	All gas-related cases
		B.7.2	**B.7.2.3**	
		Future human actions	Possibility of the repository being abandoned before it is backfilled and sealed	3.3a (PCA)
B.3.3.2		**B.3.3.2**		
Immobilisation and retardation in the ILW near field	Thermodynamic data and water chemistry	Immobilisation and retardation in the ILW near field	Thermodynamic data and water chemistry	1.1d/i (PCA) 4.4a (WI) 4.7a/b/c (WI)
		B.6.2	**B.6.2.1**	
		Geochemical immobilisation and retardation in the Opalinus Clay and confining units	Sorption mechanisms and groundwater composition, diffusivity	1.1h (PCA)
			B.6.2.2	
			The effectiveness of long-term immobili-sation processes (precipitation / co-precipitation) in the geosphere	1.1h (PCA)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
		B.6.4		
		Migration of high pH plume from ILW backfill into Opalinus Clay	The depth of migration, and associated physical and chemical changes in the clay	NA (effect of ILW water chemistry on Opalinus Clay neglected)
B.3.4		**B.3.4**		
Gas generation	See "The creation of gas pathways", B.7.1.1	Gas generation	See "The creation of gas pathways", B.7.1.1	See B.7.1.1
B.4.8		**B.4.8**		
Hydraulic and gas transport characteristics of the ILW near field	Inflow rate of water; displace-ment of water by gas into rock and along tunnels	Hydraulic and gas transport characteristics of the ILW near field	Inflow rate of water; displace-ment of water by gas into rock and along tunnels	1.8a (WRP) 1.8b (PCA)
		B.3.3.3		
		The long resaturation time of the ILW tunnels	The rate of the resaturation process	1.8a (WRP) 1.8b (PCA)
		B.5.1	**B.5.1.3**	
		Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)	The driving force for flow along the EDZs provided by near field gas, as well as the rate of near field gas production (see also "The migration of repository induced gas", B.7.1)	1.8a (WRP) 1.8b (PCA)
		B.5.2		
		The seals and the surrounding rock (see also "The creation of gas pathways", B.7.1.1)	The possibility of sealed zones being bypassed by relatively permeable EDZs	4.5a/b (WI)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
		B.6.1	**B.6.1.2**	
		Low groundwater flow rate through undisturbed Opalinus Clay (see also "Low ground-water flow rate along the sealed tunnels / ramp / shaft, and through the sur-rounding excavation disturbed zones", B.5.1)	The effects of gas pressure buildup in the near field, tunnel convergence and ice loads on the hydraulic gradient	1.8a (WRP) 1.8b (PCA)
		B.7.1	**B.7.1.1**	
		The migration of repository induced gas	The possibility that gas pathways are created through host rock and the uncer-tainty in gas perme-ability that might allow the transport of ^{14}C in a volatile form with flowing gas	2.1a/b/c (PCA)
			B.7.1.2	
			The possibility that the EDZs would allow the tunnels / ramp / shaft to pro-vide gas pathways and the uncertainties in gas permeability	2.2a/b/c (PCA)
			B.7.1.4	
			Rapid transport of radionuclides as volatile species through continuous gas path	4.6a/b/c (WI)
		B.7.2	**B.7.2.1**	
		Future human actions	Possibility of future drilling of a borehole inadvertently affecting the barrier system	3.1a/c/d (WRP)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
B.3.3.1		**B.3.2**		
Compaction of waste / mortar (see B.4.7)	Timing of convergence arising from void reduction of breached, corroded containers	Breaching of ILW steel drums and emplacement containers	The timing of drum / container breaching	1.7a/b (PCA)
		B.3.3.1		
		Compaction of waste / mortar (see B.4.7)	Timing of convergence arising from void reduction of breached, corroded containers	1.7a/b (PCA)
		B.3.3.3		
		The long resaturation time of the ILW tunnels	The rate of the resaturation process	1.7a/b (PCA, compaction / resaturation occur in parallel)
		B.5.1	**B.5.1.2**	
		Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)	The driving force for flow along the EDZs provided by tunnel convergence	1.7a (PCA)
		B.6.1	**B.6.1.2**	
		Low groundwater flow rate through undisturbed Opalinus Clay (see also "Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones", B.5.1)	The effects of gas pressure buildup in the near field, tunnel convergence and ice loads on the hydraulic gradient	1.7a/b (PCA)
B.3.3.3		**B.3.2**		
The long resaturation time of the ILW tunnels	The rate of the resaturation process	Breaching of ILW steel drums and emplacement containers	The timing of drum / container breaching	All relevant cases (100 years resaturation time assumed)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		B.3.3		
		Corrosion / dissolution of ILW	Rate of corrosion / dissolution of waste matrix and rate of release of radio-nuclides	All relevant cases (100 years resaturation time assumed)
		B.4.8		
		Hydraulic and gas transport characteristics of the ILW near field	Inflow rate of water; displacement of water by gas into rock and along tunnels	1.8a (WRP) 1.8b (PCA)
		B.3.3.1		
		Compaction of waste / mortar (see B.4.7)	Timing of convergence arising from void reduction of breached, corroded containers	1.7a/b (PCA, compaction / resaturation occur in parallel)
		B.3.3.3		
		The long resaturation time of the ILW tunnels	The rate of the resaturation process	All relevant cases (100 years resaturation time assumed)
		B.7.1	**B.7.1.1**	
		The migration of repository induced gas	The possibility that gas pathways are created through host rock and the uncertainty in gas permeability that might allow the transport of ^{14}C in a volatile form with flowing gas	Resaturation considered in all gas-related cases
			B.7.1.2	
			The possibility that the EDZs would allow the tunnels / ramp / shaft to provide gas pathways and the uncertainties in gas permeability	Resaturation considered in all gas-related cases

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
			B.7.1.4	
			Rapid transport of radionuclides as volatile species through continuous gas path	Resaturation considered in all gas-related cases
			B.7.1.5	
			The rate of generation of gas by ILW	NA (no delay in gas generation assumed)
Tunnels / ramp / shaft and seals				
B.5.1	**B.5.1.1**	**B.5.1**	**B.5.1.1**	
Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)	The hydraulic conductivity of the EDZs with respect to that of the surrounding undisturbed rock	Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)	The hydraulic conductivity of the EDZs with respect to that of the surrounding undisturbed rock	1.6a (WRP) 1.6b (PCA)
		B.5.2		
		The seals and the surrounding rock (see also "The creation of gas pathways", B.7.1.1)	The possibility of sealed zones being bypassed by relatively permeable EDZs	4.5a/b (WI)
		B.6.1a		
		Length of vertical transport path from emplacement tunnels to overlying and underlying formations	Variability in path length	All relevant cases (reference path length of 40 m)
		B.7.1	**B.7.1.2**	
		The migration of repository induced gas	The possibility that the EDZs would allow the tunnels / ramp / shaft to provide gas pathways and the uncertainties in gas permeability	2.2a/b/c (PCA)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		B.7.2	**B.7.2.1**	
		Future human actions	Possibility of future drilling of a borehole inadvertently affecting the barrier system	3.1a-d (WRP)
			B.7.2.3	
			Possibility of the repository being abandoned before it is backfilled and sealed	3.3a (PCA)
		B.5.2		
		The seals and the surrounding rock (see also "The creation of gas pathways", B.7.1.1)	The possibility of sealed zones being bypassed by relatively permeable EDZs	1.7a (PCA)
		B.6.1	**B.6.1.2**	
		Low groundwater flow rate through undisturbed Opalinus Clay (see also "Low ground-water flow rate along the sealed tunnels / ramp / shaft, and through the sur-rounding excavation disturbed zones", B.5.1)	The effects of gas pressure buildup in the near field, tunnel convergence and ice loads on the hydraulic gradient	1.7a/b (PCA)
		B.7.2	**B.7.2.1**	
		Future human actions	Possibility of future drilling of a borehole inadvertently affecting the barrier system	NA (stylised approach in case 3.1)
			B.7.2.3	
			Possibility of the repository being abandoned before it is backfilled and sealed	NA (stylised approach in case 3.3a)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
	B.5.1.3	**B.5.1**	**B.5.1.3**	
	The driving force for flow along the EDZs provided by near field gas, as well as the rate of near field gas production (see also "The migration of repository induced gas", B.7.1)	Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)	The driving force for flow along the EDZs provided by near field gas, as well as the rate of near field gas production (see also "The migration of repository induced gas", B.7.1)	1.8a (WRP) 1.8b (PCA)
		B.5.2		
		The seals and the surrounding rock (see also "The creation of gas pathways", B.7.1.1)	The possibility of sealed zones being bypassed by relatively permeable EDZs	4.5a/b (WI)
		B.6.1	**B.6.1.2**	
		Low groundwater flow rate through undisturbed Opalinus Clay (see also "Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones", B.5.1)	The effects of gas pressure buildup in the near field, tunnel convergence and ice loads on the hydraulic gradient	1.8a (WRP) 1.8b (PCA)
		B.7.1	**B.7.1.1**	
		The migration of repository induced gas	The possibility that gas pathways are created through host rock and the uncertainty in gas permeability that might allow the transport of ^{14}C in a volatile form with flowing gas	2.1a/b/c (PCA)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
			B.7.1.2	
			The possibility that the EDZs would allow the tunnels / ramp / shaft to provide gas pathways and the uncertainties in gas permeability	2.2a/b/c (PCA)
			B.7.1.4	
			Rapid transport of radionuclides as volatile species through continuous gas path	Covered by 4.6a/b/c (WI)
		B.7.2	**B.7.2.1**	
		Future human actions	Possibility of future drilling of a borehole inadvertently affecting the barrier system	NA (stylised approach in case 3.1)
			B.7.2.3	
			Possibility of the repository being abandoned before it is backfilled and sealed	NA (stylised approach in case 3.3a)
B.5.2		**B.5.2**		
The seals and the surrounding rock (see also "The creation of gas pathways", B.7.1.1)	The possibility of sealed zones being bypassed by relatively permeable EDZs	The seals and the surrounding rock (see also "The creation of gas pathways", B.7.1.1)	The possibility of sealed zones being bypassed by relatively permeable EDZs	4.5a/b (WI)
		B.7.1	**B.7.1.2**	
		The migration of repository induced gas	The possibility that the EDZs would allow the tunnels / ramp / shaft to provide gas pathways and the uncertainties in gas permeability	2.2a/b/c (PCA) 4.5a/b (WI)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		B.7.2	**B.7.2.1**	
		Future human actions	Possibility of future drilling of a borehole inadvertently affecting the barrier system	NA (stylised approach in case 3.1)
			B.7.2.3	
			Possibility of the repository being abandoned before it is backfilled and sealed	NA (stylised approach in case 3.3a)
Opalinus Clay and confining units				
B.6.1	**B.6.1.1**	**B.3.5**	**B.3.5.1**	
Low ground-water flow rate through undis-turbed Opalinus Clay (see also "Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones", B.5.1)	The groundwater flow rate through the Opalinus Clay, which is affected by uncertainties of about an order of magnitude	Breaching of steel canisters	The conditions under which mechanical failure of corroded canisters will occur; possibility of localised corrosion processes	NA (unlimited availability of water conservatively assumed)
		B.4.1		
		The long resatura-tion time of the repository and its surroundings	The rate of the resaturation process	NA (instantaneous resaturation assumed)
		B.4.4		
		Thermal alteration of the bentonite buffer adjacent to the SF / HLW canisters	Existence / extent of any thermally altered region	1.3a (PCA, consideration of dry bentonite)
		B.4.7		
		Hydraulic transport characteristics of bentonite	Compaction of bentonite by tunnel convergence	NA (delay in tunnel convergence conser-vatively neglected)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
		B.3.2		
		Breaching of ILW steel drums and emplacement containers	The timing of drum / container breaching	All relevant cases (100 years resaturation time assumed)
		B.3.3		
		Corrosion / dissolution of ILW	Rate of corrosion / dissolution of waste matrix and rate of release of radio-nuclides	All relevant cases (100 years resaturation time assumed)
		B.4.8		
		Hydraulic and gas transport character-istics of the ILW near field	Inflow rate of water; displacement of wa-ter by gas into rock and along tunnels	All relevant cases (100 years resaturation time assumed)
		B.3.3.3		
		The long resaturation time of the ILW tunnels	The rate of the resaturation process	All relevant cases (100 years resaturation time assumed)
		B.5.1	**B.5.1.1**	
		Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)	The hydraulic conductivity of the EDZs with respect to that of the surrounding undisturbed rock	1.6a (WRP) 1.6b (PCA)
		B.6.1	**B.6.1.1**	
		Low groundwater flow rate through undisturbed Opalinus Clay (see also "Low ground-water flow rate along the sealed tunnels / ramp / shaft, and through the sur-rounding excavation disturbed zones", B.5.1)	The groundwater flow rate through the Opalinus Clay, which is affected by uncertainties of about an order of magnitude	1.1f (PCA) 1.1g (WRP) 4.1a (WI) 4.7a/b/c (WI) 4.8a (WI)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		B.6.4		
		Migration of high pH plume from ILW backfill into Opalinus Clay	The depth of migration, and associated physical and chemical changes in the clay	NA (limited depth of migration)
		B.7.1	**B.7.1.1**	
		The migration of repository induced gas	The possibility that gas pathways are created through host rock and the uncertainty in gas permeability that might allow the transport of ^{14}C in a volatile form with flowing gas	NA (low groundwater flow rate limits advective transport of dissolved gas)
			B.7.1.3	
			The rate of gas generation by corrosion of the SF / HLW canisters	NA (unlimited availability of water assumed)
			B.7.1.5	
			The rate of generation of gas by ILW	NA (unlimited availability of water assumed)
	B.6.1.2	**B.6.1**	**B.6.1.1**	
	The effects of gas pressure buildup in the near field, tunnel convergence and ice loads on the hydraulic gradient	Low groundwater flow rate through undisturbed Opalinus Clay (see also "Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones", B.5.1)	The groundwater flow rate through the Opalinus Clay, which is affected by uncertainties of about an order of magnitude	1.4a (WRP) 1.7a/b (PCA) 1.8a (WRP) 1.8b (PCA)
			B.6.1.2	
			The effects of gas pressure buildup in the near field, tunnel convergence and ice loads on the hydraulic gradient	1.4a (WRP) 1.7a/b (PCA) 1.8a (WRP) 1.8b (PCA)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		B.6.3	**B.6.3.2**	
		Homogeneity	The possibility of higher-transmissivity discontinuities, faults and repository induced fractures	Fracturing of host rock is excluded in 1.4/1.7/1.8
		B.7.1	**B.7.1.1**	
		The migration of repository induced gas	The possibility that gas pathways are created through host rock and the uncertainty in gas permeability that might allow the transport of ^{14}C in a volatile form with flowing gas	2.1a/b/c (PCA)
			B.7.1.4	
			Rapid transport of radionuclides as volatile species through continuous gas path	4.6a/b/c (WI)
		B.7.2	**B.7.2.1**	
		Future human actions	Possibility of future drilling of a borehole inadvertently affecting the barrier system	NA (stylised approach in case 3.1)
	B.6.1.3	**B.6.1**	**B.6.1.1**	
	The eventual increase of hydraulic conductivity caused by erosion of the overburden	Low groundwater flow rate through undisturbed Opalinus Clay (see also "Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones", B.5.1)	The groundwater flow rate through the Opalinus Clay, which is affected by uncertainties of about an order of magnitude	NA (ruled out within period of interest)
			B.6.1.3	
			The eventual increase of hydraulic conductivity caused by erosion of the overburden	NA (ruled out within period of interest)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		B.6.1a		
		Length of vertical transport path from emplacement tunnels to overlying and underlying formations	Variability in path length	NA (ruled out within period of interest)
		B.7.1	**B.7.1.1**	
		The migration of repository induced gas	The possibility that gas pathways are created through host rock and the uncertainty in gas permeability that might allow the transport of ^{14}C in a volatile form with flowing gas	NA (ruled out within period of interest)
			B.7.1.4	
			Rapid transport of radionuclides as volatile species through continuous gas path	NA (ruled out within period of interest)
B.6.1a		**B.6.1a**		
Length of vertical transport path from emplacement tunnels to overlying and underlying formations	Variability in path length	Length of vertical transport path from emplacement tunnels to overlying and underlying formations	Variability in path length	4.11a (WI, path length of 30m)
		B.7.1	**B.7.1.4**	
		The migration of repository induced gas	Rapid transport of radionuclides as volatile species through continuous gas path	Covered by case 4.6a/b/c (WI)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
B.6.2	**B.6.2.1**	**B.4.2**	**B.4.2.1**	
Geochemical immobilisation and retardation in the Opalinus Clay and confining units	Sorption mechanisms and groundwater composition, diffusivity	Geochemical immobilisation and retardation in the near field	Thermodynamic data and water chemistry	1.1i (PCA)
			B.4.2.4	
			The natural concentrations of isotopes in bentonite porewater	1.1i (PCA)
		B.6.2	**B.6.2.1**	
		Geochemical immobilisation and retardation in the Opalinus Clay and confining units	Sorption mechanisms and groundwater composition, diffusivity	1.1h (PCA) 1.1i (PCA) 1.1j (PCA) 4.7a/b/c (WI) 4.10a (WI)
		B.6.4		
		Migration of high pH plume from ILW backfill into Opalinus Clay	The depth of migration, and associated physical and chemical changes in the clay	NA (limited depth of migration)
		B.6.5		
		Radionuclide transport through the confining units and regional aquifers	Transport-relevant properties of the confining units and regional aquifers	1.5a (LE) 1.5b (WRP)
		B.7.2	**B.7.2.1**	
		Future human actions	Possibility of future drilling of a borehole inadvertently affecting the barrier system	NA (unretarded transport through borehole assumed in cases 3.1a-g)
	B.6.2.2	**B.6.2**	**B.6.2.2**	
	The effectiveness of long-term immobilisation processes (precipitation / co-precipitation) in the geosphere	Geochemical immobilisation and retardation in the Opalinus Clay and confining units	The effectiveness of long-term immobilisation processes (precipitation / co-precipitation) in the geosphere	NA (RFEP)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
		B.6.4		
		Migration of high pH plume from ILW backfill into Opalinus Clay	The depth of migration, and associated physical and chemical changes in the clay	NA (limited depth of migration)
		B.6.5		
		Radionuclide transport through the confining units and regional aquifers	Transport-relevant properties of the confining units and regional aquifers	1.5a (LE) 1.5b (WRP)
B.6.3	**B.6.3.1**	**B.4.1**		
Homogeneity	The possibility of low transmissivity (i.e. 10^{-10} m^2 s^{-1} or less) undetected discontinuities in the Opalinus Clay	The long resaturation time of the repository and its surroundings	The rate of the resaturation process	NA (instantaneous resaturation assumed)
		B.3.3.3		
		The long resaturation time of the ILW tunnels	The rate of the resaturation process	All relevant cases (100 years resaturation time assumed)
		B.6.3	**B.6.3.1**	
		Homogeneity	The possibility of low transmissivity (i.e. 10^{-10} m^2 s^{-1} or less) undetected discontinuities in the Opalinus Clay	4.2a/b/c (WI)
		B.6.4		
		Migration of high pH plume from ILW backfill into Opalinus Clay	The depth of migration, and associated physical and chemical changes in the clay	NA (migration of pH plume along discontinuity neglected)
		B.7.1	**B.7.1.4**	
		The migration of repository induced gas	Rapid transport of radionuclides as volatile species through continuous gas path	Covered by case 4.6a/b/c (WI)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
	B.6.3.2	**B.4.1**		
	The possibility of higher-transmissivity discontinuities, faults and repository induced fractures	The long resaturation time of the repository and its surroundings	The rate of the resaturation process	NA (instantaneous resaturation assumed)
		B.3.3.3		
		The long resaturation time of the ILW tunnels	The rate of the resaturation process	All relevant cases (100 years resaturation time assumed)
		B.6.3	**B.6.3.2**	
		Homogeneity	The possibility of higher-transmissivity discontinuities, faults and repository induced fractures	4.2d/e/f (WI)
		B.6.4		
		Migration of high pH plume from ILW backfill into Opalinus Clay	The depth of migration, and associated physical and chemical changes in the clay	NA (migration of pH plume along discontinuity neglected)
		B.7.1	**B.7.1.4**	
		The migration of repository induced gas	Rapid transport of radionuclides as volatile species through continuous gas path	Covered by case 4.6a/b/c (WI)
B.6.4		**B.6.4**		
Migration of high pH plume from ILW backfill into Opalinus Clay	The depth of migration, and associated physical and chemical changes in the clay	Migration of high pH plume from ILW backfill into Opalinus Clay	The depth of migration, and associated physical and chemical changes in the clay	NA (limited penetration depth has no effect on radionuclide transport)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
B.6.5		**B.6.5**		
Radionuclide transport through the confining units and regional aquifers	Transport-relevant properties of the confining units and regional aquifers	Radionuclide transport through the confining units and regional aquifers	Transport-relevant properties of the confining units and regional aquifers	1.5a (LE) 1.5b (WRP)
		B.7.1	**B.7.1.4**	
		The migration of repository induced gas	Rapid transport of radionuclides as volatile species through continuous gas path	4.6a/b/c (WI), gas storage in Wedelsandstein
		B.7.2	**B.7.2.1**	
		Future human actions	Possibility of future drilling of a borehole inadvertently affecting the barrier system	NA (unretarded transport through borehole assumed in cases 3.1a-g)
The barrier system (general)				
B.7.1	**B.7.1.1**	**B.6.1**	**B.6.1.1**	
The migration of repository induced gas	The possibility that gas pathways are created through host rock and the uncertainty in gas permeability that might allow the transport of ^{14}C in a volatile form with flowing gas	Low groundwater flow rate through undisturbed Opalinus Clay (see also "Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones", B.5.1)	The groundwater flow rate through the Opalinus Clay, which is affected by uncertainties of about an order of magnitude	Possible increase of hydraulic conductivity of host rock by formation of gas pathways is covered by cases 1.1f (PCA), 4.1a (WI), 4.7a/b/c (WI)
		B.6.5		
		Radionuclide transport through the confining units and regional aquifers	Transport-relevant properties of the confining units and regional aquifers	2.1a/b/c (PCA) 4.6 (WI)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		B.7.1	**B.7.1.1**	
		The migration of repository induced gas	The possibility that gas pathways are created through host rock and the uncertainty in gas permeability that might allow the transport of ^{14}C in a volatile form with flowing gas	2.1a/b/c (PCA)
		B.7.2	**B.7.2.1**	
		Future human actions	Possibility of future drilling of a borehole inadvertently affecting the barrier system	NA (stylised approach in case 3.1)
			B.7.2.3	
			Possibility of the repository being abandoned before it is backfilled and sealed	NA (stylised approach in case 3.3a)
		B.9		
		Geomorphological evolution	Properties of the discharge area for groundwater conveying radionuclides	2.1a/b/c (PCA) drinking water pathway only
	B.7.1.2	**B.5.1**	**B.5.1.1**	
	The possibility that the EDZs would allow the tunnels / ramp / shaft to provide gas pathways and the uncertainties in gas permeability	Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)	The hydraulic conductivity of the EDZs with respect to that of the surrounding undisturbed rock	Possible increase of hydraulic conductivity of EDZ by formation of gas pathways is covered by case 1.6b (PCA)
		B.5.2		
		The seals and the surrounding rock (see also "The creation of gas pathways", B.7.1.1)	The possibility of sealed zones being bypassed by relatively permeable EDZs	See B.7.1

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		B.6.5		
		Radionuclide transport through the confining units and regional aquifers	Transport-relevant properties of the confining units and regional aquifers	2.2a/b/c (PCA)
		B.7.1	**B.7.1.2**	
		The migration of repository induced gas	The possibility that the EDZs would allow the tunnels / ramp / shaft to provide gas pathways and the uncertainties in gas permeability	2.2a/b/c (PCA)
		B.7.2	**B.7.2.1**	
		Future human actions	Possibility of future drilling of a borehole inadvertently affecting the barrier system	NA (stylised approach in case 3.1)
			B.7.2.3	
			Possibility of the repository being abandoned before it is backfilled and sealed	NA (stylised approach in case 3.3a)
		B.9		
		Geomorphological evolution	Properties of the discharge area for groundwater conveying radionuclides	2.2a/b/c (PCA) drinking water pathway only
	B.7.1.3	**B.3.6**		
	The rate of gas generation by corrosion of the SF / HLW canisters	Gas generation by steel canister corrosion	See "The creation of gas pathways", B.7.1.1	See B.7.1
		B.3.7		
		Canister material	Design option of a copper canister with steel insert for SF (or alternative material to mitigate / avoid gas production)	May necessitate measures to mitigate / avoid gas generation (5.3a)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		B.4.1		
		The long resaturation time of the repository and its surroundings	The rate of the resaturation process	NA (delay of resaturation, reserve FEP)
		B.4.7.1		
		Gas transport characteristics of bentonite	Uncertainties in corrosion rate	All gas-related cases (micro-fractures in bentonite created)
		B.5.1	**B.5.1.3**	
		Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)	The driving force for flow along the EDZs provided by near field gas, as well as the rate of near field gas production (see also "The migration of repository induced gas", B.7.1)	All gas-related cases (gas pressure buildup by gas generation)
		B.6.1	**B.6.1.2**	
		Low groundwater flow rate through undisturbed Opalinus Clay (see also "Low ground-water flow rate along the sealed tunnels / ramp / shaft, and through the sur-rounding excavation disturbed zones", B.5.1)	The effects of gas pressure buildup in the near field, tunnel convergence and ice loads on the hydraulic gradient	All gas-related cases (gas pressure buildup by gas generation)
		B.7.1	**B.7.1.3**	
		The migration of repository induced gas	The rate of gas generation by corrosion of the SF / HLW canisters	All gas-related cases (gas generation cor-responds to reference steel corrosion rate)
	B.7.1.4	**B.6.3**	**B.6.3.2**	
	Rapid transport of radionuclides as volatile species through continuous gas path	Homogeneity	The possibility of higher-transmissi-vity discontinuities, faults and repository induced fractures	Covered by 4.6a/b/c (WI)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		B.6.5		
		Radionuclide transport through the confining units and regional aquifers	Transport-relevant properties of the confining units and regional aquifers	4.6a/b/c (WI)
		B.7.1	**B.7.1.4**	
		The migration of repository induced gas	Rapid transport of radionuclides as volatile species through continuous gas path	4.6a/b/c (WI)
		B.7.2	**B.7.2.1**	
		Future human actions	Possibility of future drilling of a borehole inadvertently affecting the barrier system	NA (stylised approach in case 3.1)
			B.7.2.3	
			Possibility of the repository being abandoned before it is backfilled and sealed	NA (stylised approach in case 3.3a)
		B.9		
		Geomorphological evolution	Properties of the discharge area for groundwater conveying radionuclides	4.6a/b/c (WI) drinking water pathway only
	B.7.1.5	**B.3.2**		
	The rate of generation of gas by ILW	Breaching of ILW steel drums and emplacement containers	The timing of drum / container breaching	All ILW gas-related cases assume start of gas production at repository closure
		B.3.3.3		
		The long resaturation time of the ILW tunnels	The rate of the resaturation process	All gas-related cases (delay of resaturation taken into account)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		B.5.1	**B.5.1.3**	
		Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)	The driving force for flow along the EDZs provided by near field gas, as well as the rate of near field gas production (see also "The migration of repository induced gas", B.7.1)	All gas-related cases (gas pressure buildup by gas generation)
		B.6.1	**B.6.1.2**	
		Low groundwater flow rate through undisturbed Opalinus Clay (see also "Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones", B.5.1)	The effects of gas pressure buildup in the near field, tunnel convergence and ice loads on the hydraulic gradient	All gas-related cases (gas pressure buildup by gas generation)
		B.7.1	**B.7.1.5**	
		The migration of repository induced gas	The rate of generation of gas by ILW	All gas-related cases (realistic gas generation rates assumed)
	B.7.1.6	**B.1.2**		
	Extent of preferential release of organic ^{14}C from SF cladding	Corrosion of cladding (see also "The creation of gas pathways", B.7.1.1)	Whether preferential release of organic ^{14}C from the cladding occurs; corrosion rate of cladding	See B.7.1.1
		B.3.4		
		Gas generation	See "The creation of gas pathways", B.7.1.1	See B.7.1
		B.7.1	**B.7.1.1**	
		The migration of repository induced gas	The possibility that gas pathways are created through host rock and the uncertainty in gas permeability that might allow the transport of ^{14}C in a volatile form with flowing gas	2.1a/b/c (PCA)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
			B.7.1.2	
			The possibility that the EDZs would allow the tunnels / ramp / shaft to provide gas pathways and the uncertainties in gas permeability	2.2a/b/c (PCA)
			B.7.1.4	
			Rapid transport of radionuclides as volatile species through continuous gas path	4.6a/b/c (WI)
			B.7.1.6	
			Extent of preferential release of organic ^{14}C from SF cladding	All affected cases (some ^{14}C assigned to the IRF)
B.7.2	**B.7.2.1**	**B.3.5**	**B.3.5.1**	
Future human actions	Possibility of future drilling of a borehole inadvertently affecting the barrier system	Breaching of steel canisters	The conditions under which mechanical failure of corroded canisters will occur; possibility of localised corrosion processes	3.1e-g (direct hit of canister)
		B.4.2	**B.4.2.1**	
		Geochemical immobilisation and retardation in the near field	Thermodynamic data and water chemistry	3.1e-g (sorption / solubility limitation in vicinity of penetrated canister neglected)
			B.4.2.1a	
			Colloid filtration by bentonite	NA (stylised approach in 3.1 neglects colloid transport along borehole)
		B.3.2		
		Breaching of ILW steel drums and emplacement containers	The timing of drum / container breaching	3.1a/c/d (direct hit of ILW emplacement tunnel 500 a after closure)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	Associated uncertainties and design / system option (1)	Super-FEP (2)	Associated uncertainties and design / system option (2)	Treatment of effect of Super-FEP (1) on (2)
		B.3.3.2		
		Immobilisation and retardation in the ILW near field	Thermodynamic data and water chemistry	3.1a/c/d (refererence values assumed)
		B.4.8		
		Hydraulic and gas transport characteristics of the ILW near field	Inflow rate of water; displacement of water by gas into rock and along tunnels	3.1a/c/d (range of water fluxes in borehole considered)
		B.3.3.3		
		The long resaturation time of the ILW tunnels	The rate of the resaturation process	3.1a/c/d (assumed to be fully saturated at time of borehole penetration)
		B.6.2	**B.6.2.1**	
		Geochemical immobilisation and retardation in the Opalinus Clay and confining units	Sorption mechanisms and groundwater composition, diffusivity	3.1 (retardation along borehole neglected)
		B.6.5		
		Radionuclide transport through the confining units and regional aquifers	Transport-relevant properties of the confining units and regional aquifers	3.1 (transport from borehole via Malm aquifer to biosphere assumed)
		B.7.1	**B.7.1.4**	
		The migration of repository induced gas	Rapid transport of radionuclides as volatile species through continuous gas path	NA (no consideration of transport of ^{14}C driven by gas pressure along borehole)
		B.7.2	**B.7.2.1**	
		Future human actions	Possibility of future drilling of a borehole inadvertently affecting the barrier system	3.1a-d (WRP) 3.1e-g (PCA)
		B.9		
		Geomorphological evolution	Properties of the discharge area for groundwater conveying radionuclides	Discharge to reference area considered in case 3.1 (radiological exposure to drilling personnel outside scope)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
	B.7.2.2	**B.6.5**		
	Possibility of future extraction of drinking water from a deep well drilled into the Malm aquifer and the production rate of such a well should it be created	Radionuclide transport through the confining units and regional aquifers	Transport-relevant properties of the confining units and regional aquifers	3.2a/b (no retardation in confining units and Malm aquifer)
		B.7.2	**B.7.2.2**	
		Future human actions	Possibility of future extraction of drinking water from a deep well drilled into the Malm aquifer and the production rate of such a well should it be created	3.2a/b (PCA)
		B.9		
		Geomorphological evolution	Properties of the discharge area for groundwater conveying radionuclides	3.2a/b (capture efficiency of well 10 % and 100 %, drinking water pathway only)
	B.7.2.3	**B.5.1**	**B.5.1.1**	
	Possibility of the repository being abandoned before it is backfilled and sealed	Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)	The hydraulic conductivity of the EDZs with respect to that of the surrounding undisturbed rock	3.3a (PCA) increased hydraulic conductivity in collapsed tunnel sections
		B.7.1	**B.7.1.4**	
		The migration of repository induced gas	Rapid transport of radionuclides as volatile species through continuous gas path	4.6a/b/c cover gas transport through abandoned tunnel sections
		B.7.2	**B.7.2.3**	
		Future human actions	Possibility of the repository being abandoned before it is backfilled and sealed	3.3a (PCA)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
		B.9		
		Geomorphological evolution	Properties of the discharge area for groundwater conveying radionuclides	Discharge to reference area considered in case 3.3a (transport through abandoned tunnels / ramp considered unlikely)
The surface environment				
B.8		**B.6.1**	**B.6.1.2**	
Climatic evolution	The nature and timing of climate change	Low groundwater flow rate through undisturbed Opalinus Clay (see also "Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones", B.5.1)	The effects of gas pressure buildup in the near field, tunnel convergence and ice loads on the hydraulic gradient	1.4a (WRP), repeated future ice loading considered
			B.6.1.3	
			The eventual increase of hydraulic conductivity caused by erosion of the overburden	NA (ruled out within period of interest)
		B.6.5		
		Radionuclide transport through the confining units and regional aquifers	Transport-relevant properties of the confining units and regional aquifers	NA (dilution in regional aquifers neglected, reserve FEP)
		B.7.2	**B.7.2.2**	
		Future human actions	Possibility of future extraction of drinking water from a deep well drilled into the Malm aquifer and the production rate of such a well should it be created	Dry climate may necessitate use of deep well water (3.2a/b, PCA)

Tab. A5.4.1: (Cont.)

Super-FEP (1)	**Associated uncertainties and design / system option (1)**	**Super-FEP (2)**	**Associated uncertainties and design / system option (2)**	**Treatment of effect of Super-FEP (1) on (2)**
		B.8		
		Climatic evolution	The nature and timing of climate change	6.2a (LE) 6.2b/c/d (ST)
		B.9		
		Geomorphological evolution	Properties of the discharge area for groundwater conveying radionuclides	6.1a (LE) 6.1b/c/d (ST), similar geomorphology assumed for reference and alternative climates
B.9		**B.9**		
Geomorpho-logical evolution	Properties of the discharge area for groundwater conveying radionuclides	Geomorpho-logical evolution	Properties of the discharge area for groundwater conveying radionuclides	6.1a (LE) 6.1b/c/d (ST)

Tab. A5.5.1: FEPs that are conservatively omitted in defining the assessment cases, including reserve FEPs

It should be noted that the distinction between reserve FEPs and other FEPs that are treated conservatively is a matter of judgement, and some of the latter may in fact turn out to be reserve FEPs that can be mobilised in the future. Taken from Nagra (2002a, Tab. 6.8-3).

Reserve FEPs
The co-precipitation of radionuclides with secondary minerals derived from SF, glass and canister corrosion (except for co-precipitation of radium).
Sorption of radionuclides on canister corrosion products.
Natural concentrations of isotopes in solution in bentonite porewater, which could reduce the effective solubilities of some radionuclides.
Long-term immobilisation processes (precipitation / co-precipitation) in the geosphere.
The long resaturation time of the repository and its surroundings, which delays the commencement of corrosion and dissolution processes (likely to be of negligible importance for SF / HLW except in the case of earlier than expected canister breaching).
The delayed release of radionuclides, due to the slow corrosion rate of ILW metallic materials (e.g. hulls and ends), as well as a period of complete containment by ILW steel drums and emplacement containers.
Irreversible sorption of radionuclides in the near field or in the geosphere (e.g. surface mineralisation).
Degassing of volatile $^{14}CH_4$ in the biosphere.
Other FEPs that are treated conservatively
A period of complete containment provided by the SF Zircaloy cladding following canister breaching (conservatively omitted in all cases).
The conditions under which mechanical failure of the corroded canisters will occur (the Reference case breaching time of 10^4 years errs on the side of pessimism).
The spreading of radionuclide releases in time due to the fact that SF / HLW canisters would not be breached simultaneously (conservatively assumed that all canisters are breached simultaneously, except in cases addressing initial defects in the copper / steel canister design option).
The transport resistance provided by internal spaces (fractures) within the waste forms, by the breached SF / HLW canisters and by corrosion products (conservatively omitted in all cases).
The spreading of radionuclide releases in space and time due to the lateral extent of the repository and the three-dimensional nature of diffusive transport (transport paths from the repository to the biosphere are assumed to be 1-D and identical in length in all cases).
The barrier efficiency of regional aquifers (conservatively omitted in all cases).

Appendix 6: Audits and checks of OPA FEPs against the key safety-relevant phenomena, Super-FEPs and assessment cases

A6.1 Introduction

Tab. A6.1.1 shows the audit of key safety-relevant phenomena (KSRPs) against OPA FEPs and the allocation of safety-relevant OPA FEPs to Super-FEPs and assessment cases, as described in Section 4.3 of the main text. For completeness, it also indicates the screening of OPA FEPs as described in Section 3.4 of the main text. Thus the table provides a complete trace of the treatment of each OPA FEP in the safety assessment.

Tab. A6.1.1 has the following structure:

- The first three columns show the OPA FEP category number, FEP number within the category and FEP name. The OPA FEP numbering scheme is explained in Section 3.2 of the main text and in Appendix 2.

- The 4th column indicates those OPA FEPs that are screened out. The reasons for screening out are given in Tab. 3.4-1 in the main text. If screened out, they do not appear in subsequent columns.

- The 5th column indicates the audit of KSRPs against OPA FEPs. That is, it indicates the KSRPs which include each OPA FEP. The KSRPs are indicated by their "A" codes as given in Tab. A4.1.1 in this report (Tab. 5.7-1 in the Safety Report). OPA FEPs are often captured by several KSRPs in which different aspects or implications of the OPA FEP may be addressed. In some cases OPA FEPs are identified as "not safety-relevant", for reasons given in Chapters 4 and 5 of the Safety Report. In this case they generally do not appear in subsequent columns.

- The 6th and 7th column indicate how each KSRP is represented by the Super-FEPs and the assessment cases, consistent with the derivation already given in Appendix 4, Tab. A4.1.2. The "B" code letters are as given in Tab. A5.2.1 in this report (Tab. 6.8-1 in the Safety Report).

Note:
Tabs. A4.1.1 and A5.2.1 in this report are based on, but contain additional information compared to, Tabs. 5.7-1 and 6.8-1 in the Safety Report, respectively. Tab. A5.3.1 in this report is identical to Tab. 6.8-2 in the Safety Report.

Tab. A6.1.1: Audit of the key safety-relevant phenomena (KSRP) and checks of allocation of the OPA FEPs to Super-FEPs and assessment cases

Table notes:

KSRP Key safety-relevant phenomena
SR Safety Report (Nagra 2002a)
FMR FEP Management Report (this report)
SC Screened out (reason given in Tab. 3.4-1; see also the complete listing of OPA FEPs, Tab. A2.1.1)
NSR Not relevant to long-term safety (justification given in Chapters 4 and 5 of the Safety Report)
A Codes beginning with an "A" identify the key safety-relevant phenomena (KSRPs) as given in Appendix 4, Tab. A4.1.1
B Codes beginning with a "B" identify the Super-FEPs as given in Appendix 5, Tab. A5.2.1
R Reserve FEP
I Intrinsic attribute of deep geological disposal to which no specific Super-FEP and / or KSRP is assigned
BIO Biosphere attributes to which no specific Super-FEP and / or KSRP is assigned
(d) Process explicitly included, and / or magnitude, rate or other properties of the FEP directly provide input parameters in all cases (alternative assumptions regarding the FEP give rise to alternative parameter values in the cases indicated)
(s) Process explicitly included, and / or magnitude, rate or other properties of the FEP directly provide input parameters in specific cases (but not the Reference Case)
(i) Magnitude, rate or other properties of the FEP affect input parameters indirectly in all cases
(j) Magnitude, rate or other properties of the FEP affect input parameters indirectly in specific cases (but not the Reference Case)
(a) Controls or affects certain model assumptions in all relevant cases (e.g. appropriate design and closure and adequate quality control are assumed)
(x) Judged unimportant or irrelevant to main model chain parameters or assumptions (e.g. on the basis of side calculations), or effects conservatively omitted in all cases

Cat. no.	**FEP no.**	**OPA FEP name**	**Screened out?**	**KSRP** **SR Tab. 5.7-1** **FMR Tab. A4.1.1**	**Super-FEPs** **SR Tab. 6.8-1** **FMR Tab. A5.2.1**	**Assessment Cases** **SR Tab. 6.8-2** **FMR Tab. A5.3.1**
0.	**1.**	**SITE AND DISPOSAL CONCEPT**				
0.	1.1	Waste form and packaging		A.1.0, A.12.1	I	(d)
0.	1.2	Waste emplacement and repository		A.1.0, A.1.0.1	I	(i)
0.	1.3	Host geology		A.10, A.11	I	(d)
0.	1.4	Local and regional surface environment		A.16.2	I	(d)
0.	1.5	Geographical location		A.16.2	I	(d)
0.	1.6	Appropriate repository design and closure		A.1.0	I	(a)
0.5	1.01	Radioactive decay		A.1.1, A.2.1, A.7.1	I	(d)
0.5	1.02	Speciation		A.4.1, A.5.1, A.10.2b, A.7.3, A.7.4	I	(i)
0.5	1.03	Gaseous and volatile isotopes		A.1.2, A.10.3, A.8.3	B.7.1.4	(s) 4.6, 2.1, 2.2
1.0	**1.**	**SITING**				
1.0	1.01	Repository site		A.10, A.11, A.16.2	I	(i)
1.0	1.02	Host rock / geology – regional character		A.10, A.11	I	(d)
1.0	1.03	Host rock / geology – at repository location		A.10, A.11	I	(d)
1.0	1.04	Surface environment		A.16	I	(d)

Tab. A6.1.1: (Cont.)

Cat. no.	FEP no.	OPA FEP name	Screened out?	KSRP SR Tab. 5.7-1 FMR Tab. A4.1.1	Super-FEPs SR Tab. 6.8-1 FMR Tab. A5.2.1	Assessment Cases SR Tab. 6.8-2 FMR Tab. A5.3.1
1.0	**2.**	**WASTE**				
1.0	2.01	Overall waste inventory		A.1.0	I	(d)
1.0	2.02	HLW reference inventory		A.1.0, A.2.1	B.2.1	(d)
1.0	2.03	SF reference inventory		A.1.0, A.1.1	B.1.1	(d)
1.0	2.04	ILW reference inventory		A.7.1	B.3.1	(d)
1.0	2.05	Alternative inventory / waste allocation assumptions		A.1.1, A.7.1	B.3.1, B.2.1, B.1.1	(s) 5.1, 5.2
1.0	**3.**	**FACILITY, DESIGN & OPERATION**				
1.0	3.01	Repository layout / constraints		A.1.0	I	(i)
1.0	3.02	SF / HLW emplacement panels – reference design		A.1.0, A.1.0.1	I	(i)
1.0	3.03	SF / HLW emplacement panels – alternative design	SC			
1.0	3.04	ILW emplacement tunnels – reference design		A.1.0, A.1.0.1	I	(i)
1.0	3.05	ILW emplacement tunnels – alternative design	SC			
1.0	3.06	Operations / excavation / emplacement schedule		A.1.0	I	(i)
1.0	3.07	Closure and sealing		A.1.0	I	(i)
1.0	3.08	Effect of construction and operation phase		NSR	-	(x)
1.0	3.09	Retrievability	SC			
1.0	3.10	Monitoring (part of design basis)		I	I	(x)
2.1	**1.**	**FEATURES AND CHARACTERISTICS (HLW)**				
2.1	1.01	Typical waste unit – vitrified HLW		A.2.1	I	(d)
2.1	1.02	Waste form (glass)		A.2.1, A.2.2	I	(d)
2.1	1.03	Stainless steel fabrication flask (incl. void space)		A.2.1, A.2.2, A.4.1	B.4.2	(d)
2.1	1.04	Glass cracking and surface area		A.2.1, A.2.2	B.2.2	(d)
2.1	1.05	Heat output (RN decay heat)		A.2.1	I	(i)
2.1	**2.**	**ENVIRONMENTAL PROCESSES (HLW)**				
2.1	2.01	Glass recrystallisation		NSR	-	(x)
2.1	2.02	Phase separation		NSR	-	(x)
2.1	2.03	Temperature evolution		A.2.1, A.2.2	B.2.1	(a)
2.1	2.04	Radiation damage		A.2.2	B.2.2	(i)
2.1	2.05	Glass alteration / dissolution		A.2.2	B.2.2	(d)
2.1	2.06	Rate of glass dissolution		A.2.2	B.2.2	(d)
2.1	2.07	Congruent dissolution		A.2.2	B.2.2	(d)
2.1	2.08	Selective leaching		A.2.2	B.2.2	(x)
2.1	2.09	Iron corrosion products / clay minerals and glass dissolution		A.2.2	B.2.2	(x)
2.1	2.10	Precipitation of silicates / silica gel and glass dissolution		A.2.2	B.2.2, B.4.2.2 (R)	(x)
2.1	2.11	Radiolysis		NSR	-	(x)
2.1	2.12	He gas production		NSR	-	(x)
2.1	2.13	Microbial activity and effects		NSR	-	(x)

Tab. A6.1.1: (Cont.)

Cat. no.	FEP no.	OPA FEP name	Screened out?	KSRP SR Tab. 5.7-1 FMR Tab. A4.1.1	Super-FEPs SR Tab. 6.8-1 FMR Tab. A5.2.1	Assessment Cases SR Tab. 6.8-2 FMR Tab. A5.3.1
2.1	**3.**	**RADIONUCLIDE PROCESSES (HLW)**				
2.1	3.01	Radionuclide release from glass		A.2.1, A.2.2	B.2.1, B.2.2	(d)
2.1	3.02	Elemental (and RN) solubility limits		A.4.1	B.4.2.1, B.4.2.2	(d)
2.1	3.03	Co-precipitates / solid solutions (of RNs)		A.4.1	B.4.2.2	(d)
2.1	3.05	Colloids formation (RN bearing)		A.5.1, A.10.2b (NSR)	B.4.2.1a (NSR)	(x)
2.1	3.06	Solute transport resistance		-	B.4.5 (R)	(x)
2.1	**4.**	**SPECIAL ISSUES (HLW)**				
2.1	4.01	Quality control		A.1.0.1 (NSR)	I	(a)
2.1	4.02	Handling accidents	SC			
2.1	4.03	Fuel mixing at reprocessing – variant specification		A.1.0.1 , A.2.1	B.2.1	(i)
2.1	4.04	Nuclear criticality		NSR	-	(x)
2.2	**1.**	**FEATURES AND CHARACTERISTICS (SF)**				
2.2	1.01	Typical waste unit – spent fuel		A.1.1	B.1.1	(d)
2.2	1.02	UO2 fuel matrix		A.1.1	B.1.1	(d)
2.2	1.03	Zircaloy cladding and structural elements		A.1.2	B.1.2, B.1.3	(d)
2.2	1.04	Filling material and voids		A.4.1	B.4.2	(i)
2.2	1.05	Heat output (RN decay heat)		A.1.1	I	(i)
2.2	1.06	Distribution of radionuclides in spent fuel		A.1.1 to A.1.4	B.1.1 to B.1.4	(d)
2.2	1.07	Chemically toxic contaminants	SC			
2.2	1.08	Fuel cracking and surface area		A.1.3, A.1.4	B.1.4	(d)
2.2	**2.**	**ENVIRONMENTAL PROCESSES (SF)**				
2.2	2.01	Temperature evolution		A.1.1, A.1.4	B.1.1, B.1.4	(a)
2.2	2.02	Saturation / water content		A.1.4	B.1.4	(a)
2.2	2.03	Gas generation in intact canister		NSR	-	(x)
2.2	2.03.1	Fuel matrix dissolution		A.1.4	B.1.4	(d)
2.2	2.04	Zircaloy corrosion		A.1.2	B.1.2	(d)
2.2	2.05	Cladding integrity		A.1.2	B.1.3 (R)	(a)
2.2	2.06	Galvanic effects		A.1.2	B.1.3	(x)
2.2	2.07	Alpha-radiolysis – production of oxidants and hydrogen, and recombination		A.1.1, A.1.4	B.1.4	(i)
2.2	2.08	Beta / gamma-radiolysis effects		A.1.1, A.1.4	B.1.4	(j) 1.1c
2.2	2.09	Radiation damage		(NSR) A.1.2, A.1.4	-	(x)
2.2	2.10	Fuel alteration product formation		(NSR) A.1.4, A.4.1	-	(x)
2.2	2.11	Canister corrosion products		A.1.4, A.3.3	B.1.4, B.4.2.2, B.4.2.3 (R)	(i)
2.2	2.11.1	Volume expansion		A.3.4	B.3.5.1 (NSR)	(x)
2.2	2.12	Microbial activity and effects		NSR	-	(x)
2.2	2.13	Zircaloy corrosion / hydrogen gas production		A.1.2, A.3.2	B.1.2, B.5.1.3, B.6.1.2, B.4.7.1	(x)

Tab. A6.1.1: (Cont.)

Cat. no.	FEP no.	OPA FEP name	Screened out?	KSRP SR Tab. 5.7-1 FMR Tab. A4.1.1	Super-FEPs SR Tab. 6.8-1 FMR Tab. A5.2.1	Assessment Cases SR Tab. 6.8-2 FMR Tab. A5.3.1
2.2	**3.**	**RADIONUCLIDE PROCESSES (SF)**				
2.2	3.01	Radionuclide release from fuel		A.1.2 to A.1.4	B.1.1 to B.1.4	(d)
2.2	3.02	RN release from cladding and structural materials		A.1.2	B.1.2	(d) 4.9
2.2	3.03	Radionuclide elemental solubilities and precipitation		A.4.1	B.4.2.1	(d)
2.2	3.05	Co-precipitation of radionuclides		A.4.1	B.4.2.2	(d)
2.2	3.06	Sorption of radionuclides inside canister		A.3.3	B.4.2.3(R)	(x)
2.2	3.07	Complexation of radionuclides		A.4.1	B.4.2.1	(i)
2.2	3.08	Formation of radionuclide-bearing colloids		A.5.1 (NSR)	B.4.2.1a	(x)
2.2	3.09	Gaseous radionuclide release		A.1.2, A.10.3	B.1.2, B.7.1	(s) 4.6, 2.1, 2.2
2.2	**4.**	**SPECIAL ISSUES (SF)**				
2.2	4.01	Quality control of the inventory of fuel in a canister		A.1.1	B.1.1	(a)
2.2	4.02	Handling accidents	SC			
2.2	4.03	Damaged fuel	SC			
2.2	4.04	Nuclear criticality		A.1.5 (NSR)	B.1.5 (NSR)	(x)
2.2	4.05	Extreme temperature of cladding		A.1.2 (NSR)	-	(x)
2.2	4.06	Cracking of fuel pellets by He buildup		A.1.3 (NSR)	-	(x)
2.3	**1.**	**FEATURES AND CHARACTERISTICS (ILW)**				
2.3	1.01	ILW waste types		A.7.1, A.15.1	B.3.1	(d) 5.2
2.3	1.01.1	ILW waste groups		A.7.1, A.15.1	B.3.1	(d)
2.3	1.02	Typical waste package / emplacement containers		A.7.1, A.15.1	B.3.1	(d)
2.3	1.03	Chemically toxic components	SC			
2.3	1.04	Compacted waste (hulls / ends)		A.7.1, A.15.1	B.3.1	(i)
2.3	1.05	Conditioning materials		A.7.1, A.15.1	B.3.1 to B.3.3	(i)
2.3	1.06	Waste packages		A.7.1, A.7.2, A.15.1	B.3.1	(i)
2.3	1.06.1	Backfill		A.7.6a, A.7.2, A.7.3	B.3.3.2, B.4.8	(d)
2.3	1.06.2	Voids		A.7.5, A.7.6, A.7.7, A.7.6a	B.3.3.1	(j) 1.7
2.3	1.07	Heat output		A.7.1 (NSR)	-	(i)
2.3	1.08	Organics		A.1.0, A.7.4, A.7.2, A.7.6	B.3.3.2, B.3.4	(i)
2.3	1.09	Extraneous materials (including microbes / biological materials)		NSR	-	(x)

Tab. A6.1.1: (Cont.)

Cat. no.	FEP no.	OPA FEP name	Screened out?	KSRP SR Tab. 5.7-1 FMR Tab. A4.1.1	Super-FEPs SR Tab. 6.8-1 FMR Tab. A5.2.1	Assessment Cases SR Tab. 6.8-2 FMR Tab. A5.3.1
2.3	**2.**	**ENVIRONMENTAL PROCESSES (ILW)**				
2.3	2.01	Resaturation of repository		A.7.2, A.7.8	B.3.2, B.3.3.3	(a)
2.3	2.01.1	Host rock creep: effect on near field (tunnel convergence)		A.7.7	B.3.3.1	(j) 1.7
2.3	2.02	Temperature evolution of near field		A.7.1 (NSR)	-	(x)
2.3	2.03	Chemical evolution – pH		A.7.3, A.8.1	B.3.3.2, B.6.4	(i)
2.3	2.04	Chemical evolution – redox		A.7.3	B.3.3.2	(i)
2.3	2.04.1	Galvanic effects		A.7.6 (NSR), A.7.2	-	(x)
2.3	2.04.2	Degradation of backfill		A.7.7 (NSR)	-	(x)
2.3	2.05	Radiolysis		A.7.3 , A.7.5	B.3.3.2	(j) 4.4
2.3	2.05.1	Alpha-radiolysis		A.7.3, A.7.5	B.3.3.2	(j) 4.4
2.3	2.05.2	Beta / gamma-radiolysis		NSR	-	(x)
2.3	2.06	Corrosion of metallic components		A.7.6	B.3.4	(j) 4.6, 2.1, 2.2, 1.8
2.3	2.06.1	Volume expansion		NSR	-	(x)
2.3	2.07	Degradation / failure of disposal containers and emplacement packages		A.7.2	B.3.2	(i)
2.3	2.08	Gas generation and transport		A.7.6, A.9.1	B.3.4, B.4.8, B.7.1.5, B.5.2	(s) 4.6, 2.1, 2.2
2.3	2.09	Effect of temperature on chemical processes		A.7.1 (NSR)	-	(x)
2.3	2.10	Microbial activity and effects		A.7.3, A.7.4	B.3.3.2	(x)
2.3	**3.**	**RADIONUCLIDE PROCESSES (ILW)**				
2.3	3.00	RN transport			I	(d)
2.3	3.00.1	Diffusive transport		A.7.5	I	(d)
2.3	3.00.2	Flow and advective transport		A.7.5	I	(d)
2.3	3.01	Radionuclide release through waste form degradation		A.7.2	B.3.2, B.3.3	(d)
2.3	3.02	Instant release fraction		A.7.2	B.3.2, B.3.3	(d)
2.3	3.03	Release of volatile radionuclides over gas pathway		A.10.3, A.8.3, A.9.1	B.7.1.1, B.7.1.2, B.7.1.4	(s) 4.6, 2.1, 2.2
2.3	3.03.1	Gas dissolution in porewater		A.9.1	B.6.1, B.7.1.1, B.7.1.4, B.4.8	(s) 4.6, 2.1, 2.2, 1.8
2.3	3.03.2	Sorption on cement materials		A.7.3, A.7.4	B.3.3.2	(d)
2.3	3.04	Sorption on and co-precipitation with corrosion products		A.7.3 (R)	-	(x)
2.3	3.05	Co-precipitation with calcite		R	-	(x)
2.3	3.05.1	Complexation		A.7.3, A.7.4	B.3.3.2	(i)
2.3	3.06	Colloid generation		A.10.2b (NSR)	-	(x)

Tab. A6.1.1: (Cont.)

Cat. no.	FEP no.	OPA FEP name	Screened out?	KSRP SR Tab. 5.7-1 FMR Tab. A4.1.1	Super-FEPs SR Tab. 6.8-1 FMR Tab. A5.2.1	Assessment Cases SR Tab. 6.8-2 FMR Tab. A5.3.1
2.3	**4.**	**SPECIAL ISSUES (ILW)**				
2.3	4.00.1	Quality control		A.7.1, A.15.1	B.3.1	(a)
2.3	4.00.2	Handling accidents	SC			
2.3	4.01	Effects of co-disposal with SF / HLW	SC			
2.3	4.03	Nuclear criticality	SC			
3.1	**1.**	**FEATURES AND CHARACTERISTICS (SF / HLW canister)**				
3.1	1.01	Cast steel canister (vitrified waste)		A.1.0.1	I	(d)
3.1	1.01.1	Cast steel canister (spent fuel)		A.1.0.1	I	(d)
3.1	1.01.2	Cu / steel canister (spent fuel)		A.1.0.1	B.3.7	(s) 5.3
3.1	1.02	Canister thickness / specification (vitrified waste canister)		A.1.0.1	I	(d)
3.1	1.02.1	Canister thickness / specification (cast steel spent fuel canister)		A.1.0.1	I	(d)
3.1	1.02.2	Canister thickness / specification (Cu / steel canister)		A.1.0.1	B.3.7	(s) 5.3
3.1	**2.**	**ENVIRONMENTAL PROCESSES (Canister)**				
3.1	2.01	Canister temperature evolution (vitrified waste)		A.3.1	B.3.5	(a)
3.1	2.01.1	Canister temperature evolution (spent fuel)		A.3.1	B.3.5	(a)
3.1	2.02	Corrosion on wetting (steel canister – vitrified waste or spent fuel)		A.3.1	B.3.5	(i)
3.1	2.02.1	Corrosion on wetting (Cu / steel canister)		A.13.1	B.3.7	(i) 5.3
3.1	2.03	Oxic uniform corrosion (steel canister – vitrified waste / spent fuel)		A.3.1	B.3.5	(i)
3.1	2.03.1	Oxic uniform corrosion (Cu / steel canister – spent fuel)		A.13.1	B.3.7	(i) 5.3
3.1	2.04	Microbially-mediated corrosion (steel canister – vitrified waste / spent fuel)		A.3.1	B.3.5	(i)
3.1	2.04.1	Microbially-mediated corrosion (Cu / steel canister)		A.13.1	B.3.7	(i) 5.3
3.1	2.05	Anoxic corrosion (steel canister – vitrified waste / spent fuel)		A.3.1	B.3.5	(i)
3.1	2.05.1	Anoxic corrosion (Cu / steel canister)		A.13.1	B.3.7	(i) 5.3
3.1	2.06	Localised corrosion (steel canister – vitrified waste / spent fuel)		A.3.1	B.3.5	(i)
3.1	2.06.1	Localised corrosion (Cu / steel canister – spent fuel)		A.13.1	B.3.7	(i) 5.3
3.1	2.07	Total extent of corrosion (steel canister – vitrified waste / spent fuel)		A.3.1	B.3.5	(i)
3.1	2.07.1	Total corrosion (steel canister – spent fuel)		A.3.1	B.3.5	(i)
3.1	2.07.2	Total corrosion (Cu / steel canister – spent fuel)		A.13.1	B.3.7	(i) 5.3

Tab. A6.1.1: (Cont.)

Cat. no.	FEP no.	OPA FEP name	Screened out?	KSRP SR Tab. 5.7-1 FMR Tab. A4.1.1	Super-FEPs SR Tab. 6.8-1 FMR Tab. A5.2.1	Assessment Cases SR Tab. 6.8-2 FMR Tab. A5.3.1
3.1	**2.**	**ENVIRONMENTAL PROCESSES (Canister)**				
3.1	2.08	Stress corrosion cracking (steel canister – vitrified waste / spent fuel)		A.3.1	B.3.5	(i)
3.1	2.09	Other canister degradation processes (steel and Cu / steel canisters)		A.13.1, A.3.1	B.3.5, B.3.7	(i)
3.1	2.10	Radiation shielding		A.3.1 (NSR)	-	(x)
3.1	2.11	Canister breaching – reference (steel canister – vitrified waste / SF)		A.3.1	B.3.5	(d)
3.1	2.11.1	Canister breaching – reference (Cu / steel canister – spent fuel)		A.13.1	B.3.7	(s) 5.3
3.1	2.13	Chemical buffering (canister corrosion products)		A.3.3, A.4.1	B.4.2.1, B.4.2.3	(i)
3.1	2.14	Hydrogen production (steel canister – vitrified waste / spent fuel)		A.3.2, A.13.2	B.3.6, B.7.1.3	(s) 4.6, 2.1, 2.2, 1.8
3.1	2.14.1	Hydrogen production (Cu / steel canister – spent fuel)		NSR	-	(x)
3.1	2.15	Effect of hydrogen on corrosion		A.3.2 (NSR)	-	(x)
3.1	2.16	Corrosion products – physical effects (steel canister – vitrified waste / SF)		A.3.4 (NSR)	-	(x)
3.1	2.16.1	Corrosion products – physical effects (Cu / steel canister – spent fuel)		A.13.1	B.3.7	(j) 5.3b/c
3.1	**3.**	**RADIONUCLIDE PROCESSES (Canister)**				
3.1	3.01	Residual canister – crack / hole effects (vitrified waste)		A.3.1	B.4.5 (R)	(x)
3.1	3.02	Residual canister – crack / hole effects (spent fuel)		A.3.1, A.13.1	B.4.5 (R)	(s) 5.3b/c
3.1	3.03	Radionuclide sorption on and co-precipitation with canister corrosion products		A.3.3	B.4.2.2, B.4.2.3 (R)	(x)
3.1	**4.**	**SPECIAL ISSUES (Canister)**				
3.1	4.01	Quality control		A.3.1, A.13.1	B.3.7, B.3.5	(a)
3.1	4.02	Mis-sealed canister		A.13.1	B.3.7	(s) 5.3b/c
4.1	**1.**	**FEATURES AND CHARACTERISTICS (Bentonite buffer)**				
4.1	1.01	Bentonite emplacement and composition		A.1.0.1	B.4.7	(a)
4.1	1.01.1	Pellets		A.1.0.1	B.4.7	(x)
4.1	1.01.2	Corrosion of structural elements in HCB blocks	SC			
4.1	1.02	Bentonite swelling pressure		A.5.1, A.5.2	B.4.7	(a)
4.1	1.03	Bentonite plasticity		A.5.1, A.5.2	B.4.7	(a)
4.1	1.04	Buffer permeability		A.5.1	B.4.7	(a)
4.1	1.05	Bentonite porewater chemistry		A.5.1, A.4.1	B.4.2	(i)
4.1	1.06	Gas permeability		A.5.5	B.4.7.1	(a)
4.1	1.07	Inhomogeneities (properties and evolution)		A.5.1 (NSR)	-	(x)

Tab. A6.1.1: (Cont.)

Cat. no.	FEP no.	OPA FEP name	Screened out?	KSRP SR Tab. 5.7-1 FMR Tab. A4.1.1	Super-FEPs SR Tab. 6.8-1 FMR Tab. A5.2.1	Assessment Cases SR Tab. 6.8-2 FMR Tab. A5.3.1
4.1	**2.**	**ENVIRONMENTAL PROCESSES (Bentonite buffer)**				
4.1	2.01	Thermal evolution		A.5.2	B.4.4	(a) or (s) 1.3
4.1	2.02	Bentonite saturation		A.5.1, A.5.0	B.4.1 (R)	(a)
4.1	2.03	Mineralogical alteration – short term		A.5.2, A.5.1	B.4.4	(j) 1.3
4.1	2.04	Mineralogical alteration – long term		A.5.2, A.5.1	B.4.4	(j) 1.3
4.1	2.05	Bentonite cementation		A.5.2, A.5.1	B.4.4	(j) 1.3
4.1	2.06	Bentonite-iron interactions (canister)		A.5.2, A.5.1	B.4.4	(j) 1.3
4.1	2.06.1	Bentonite-Cu interactions		NSR	-	(x)
4.1	2.07	Microbial activity	SC	A.5.6 (NSR)		
4.1	2.08	Radiolysis		A.5.4	B.4.3	(s) 4.4
4.1	2.09	Bentonite erosion	SC	A.5.1 (NSR)		
4.1	2.10	Interaction with cement components		A.1.0.1 (NSR)	-	(x)
4.1	2.11	Gas fracturing		A.5.5	B.4.7, B.4.7.1	(a)
4.1	**3.**	**RADIONUCLIDE PROCESSES (Bentonite buffer)**				
4.1	3.01	Radionuclide transport through buffer		A.5.1	B.4.7, B.4.2.1	(d)
4.1	3.02	Radionuclide retardation		A.5.1	B.4.2	(d)
4.1	3.03	Elemental solubility / precipitation		A.4.1	B.4.2.1, B.4.2.2, B.4.2.4	(d)
4.1	3.04	Colloid filtration		A.5.1	B.4.2.1a	(a)
4.1	3.05	Interaction and diffusion between canisters		-	-	(x)
4.1	**4.**	**SPECIAL ISSUES**				
4.1	4.01	Quality Control		A.1.0.1 (NSR)	-	(a)
4.1	4.03	Organics / contamination of bentonite		A.1.0.1 (NSR)	-	(x)
4.1	4.04	Canister sinking		NSR	-	(x)
5.3	**1.**	**FEATURES AND CHARACTERISTICS (ILW backfill and liner)**				
5.3	1.01	Backfill material		A.1.0.1	B.4.8	(d)
5.3	1.02	Backfill emplacement		A.1.0.1	B.3.3.2	(a)
5.3	1.03	Hydraulic and gas permeability		A.7.5, A.7.6a	B.4.8	(i)
5.3	1.04	Effects of initial (operating) conditions		A.1.0.1 (NSR)	-	(x)
5.3	1.05	Lining material		A.1.0.1	I	(x)
5.3	1.05.1	Drainage system	SC			
5.3	1.05.3	Seals		A.1.0.1	I	(a)
5.3	1.05.4	Cement additives		A.1.0.1, A.7.4	B.3.3.2	(x)
5.3	1.05.5	Organics		A.7.4	B.3.3.2	(i)
5.3	1.06	Rock bolts		A.7.6	B.3.4	(j) 1.8, 2.2, 4.5
5.3	1.07	Joints and cracks in backfill / liner		A.1.0.1 (NSR)	-	(x)
5.3	1.08	Voids in backfill / liner		A.1.0.1 (NSR)	-	(x)

Tab. A6.1.1: (Cont.)

Cat. no.	FEP no.	OPA FEP name	Screened out?	KSRP SR Tab. 5.7-1 FMR Tab. A4.1.1	Super-FEPs SR Tab. 6.8-1 FMR Tab. A5.2.1	Assessment Cases SR Tab. 6.8-2 FMR Tab. A5.3.1
5.3	**2.**	**ENVIRONMENTAL PROCESSES (ILW backfill and liner)**				
5.3	2.01	Cement hydration		NSR		(x)
5.3	2.02	Temperature evolution		A.7.1 (NSR)	-	(a)
5.3	2.03	Mechanical strength / stability		A.7.7	B.3.3.1, B.5.1.2	(a) or (j) 1.7
5.3	2.04	Mechanical evolution and external forces		A.7.7	B.3.3.1, B.5.1.2	(j) 1.7
5.3	2.04.1	Effect of liner on rock creep		A.7.7	B.3.3.1, B.5.1.2	(j) 1.7
5.3	2.05	Saturation / hydraulic evolution		A.7.8, A.7.2, A.7.5, A.7.6a	B.4.8, B.3.3.3	(a)
5.3	2.06	Chemical degradation		A.7.3	B.3.3.2	(i)
5.3	2.07	Degradation due to reaction with sulphate		NSR	-	(x)
5.3	2.08	Degradation due to reaction with magnesium		NSR	-	(x)
5.3	2.08.1	Degradation due to other reactions		NSR	-	(x)
5.3	2.09	Volume expanding materials		NSR	-	(x)
5.3	2.10	Pore-structure heterogeneity and evolution		NSR	-	(x)
5.3	2.10.1	Compaction		A.7.7	B.3.3.1, B.5.1.2	(s) 1.7
5.3	2.11	Formation of advective paths		NSR	-	(x)
5.3	2.12	Biofilms		A.7.6, A.7.4	B.3.3.2	(x)
5.3	2.13	Colloid formation through backfill degradation		A.7.5, A.10.2b (NSR)	-	(x)
5.3	2.14	Effects of temperature gradients		A.7.1 (NSR)	-	(x)
5.3	2.15	2-phase flow		A.7.6, A.9.1	B.7.1, B.4.8, B.5.1.3	(s) 1.8, 2.2, 4.5
5.3	**3.**	**RADIONUCLIDE PROCESSES (ILW backfill and liner)**				
5.3	3.01	Diffusive transport through backfill and liner		A.7.5	I	(d)
5.3	3.02	Flow and advective transport through backfill and liner		A.7.5, A.8.2	I	(d)
5.3	3.03	Radionuclide sorption in backfill and liner		A.7.4, A.7.5	B.3.3.2	(d)
5.3	3.04	Sorption / incorporation of radio-nuclides on colloids and microbes		A.7.5, A.10.2b (NSR)	-	(x)
5.3	3.05	Solubility		A.7.3	B.3.3.2	(d)
5.3	3.06	Co-precipitation (of RNs)		A.7.3 (R)	-	(x)
5.3	3.07	Complexation		A.7.3, A.7.4	B.3.3.2	(i)
5.3	**4.**	**SPECIAL ISSUES (ILW backfill and liner)**				
5.3	4.01	Quality control		A.1.0.1 (NSR)	-	(a)
5.3	4.02	Poor emplacement		A.1.0.1 (NSR)	-	(x)
5.3	4.03	Interfaces, cracks and slabbing		A.1.0.1 (NSR)	-	(x)
5.3	4.04	Seismic effects		NSR	-	(x)

Tab. A6.1.1: (Cont.)

Cat. no.	FEP no.	OPA FEP name	Screened out?	KSRP SR Tab. 5.7-1 FMR Tab. A4.1.1	Super-FEPs SR Tab. 6.8-1 FMR Tab. A5.2.1	Assessment Cases SR Tab. 6.8-2 FMR Tab. A5.3.1
6.1	**1.**	**FEATURES AND CHARACTERISTICS (Bentonite – HR interface)**				
6.1	1.01	Excavation disturbed zone (EDZ)		A.6.1	B.5.1.1	(s) 1.6
6.1	1.01.1	Rock bolts and mesh	SC			
6.1	1.02	Open contact joints		A.6.1	B.5.1.1	(x)
6.1	1.03	Effective hydraulic properties		A.6.1	B.5.1.1	(s) 1.6
6.1	1.04	Mineralogy		A.5.1, A.10.2b	B.6.2	(i)
6.1	1.05	Groundwater composition		A.5.1, A.10.2b	B.6.2.1	(i)
6.1	1.06	Natural organics		A.10.2b	B.6.2.1	(x)
6.1	1.07	Microbial activity	SC			
6.1	1.08	Hydraulic gradient		A.6.1	B.5.1.2, B.5.1.3	(s) 1.6, 1.7, 1.8, 4.5
6.1	1.09	Water flow at bentonite – host rock interface		A.6.1	B.5.1	(s) 1.6, 1.7, 1.8, 4.5
6.1	**2.**	**ENVIRONMENTAL PROCESSES (Bentonite – HR interface)**				
6.1	2.01	Desaturation / resaturation of EDZ		A.5.0	B.4.1	(x)
6.1	2.02	Thermal evolution		A.5.0, A.6.1	B.4.4	(a)
6.1	2.03	Geomechanical processes		A.6.3	B.4.7	(i)
6.1	2.04	Effect of bentonite swelling on EDZ		A.6.3	B.5.1	(a)
6.1	2.05	Swelling of clay-minerals in EDZ		A.6.1, A.6.3	B.5.1.1	(a)
6.1	2.06	Compaction of EDZ		A.6.1, A.6.3	B.5.1	(a)
6.1	2.07	Geochemical alteration		A.5.4, A.14.1 (NSR)	B.4.3, B.4.6	(x)
6.1	2.08	Fluid and heat fluxes by coupled processes (Onsager)		A.5.3 (NSR)	-	(x)
6.1	2.09	Gas transport		A.6.2, A.5.5, A.10.3	B.5.1.3, B.7.1	(s) 1.8, 2.1, 2.2, 4.6
6.1	2.10	Colloid production and effects		A.5.1, A.10.2b (NSR)	B.4.2.1a	(x)
6.1	**3.**	**RADIONUCLIDE PROCESSES (Bentonite – HR interface)**				
6.1	3.01	Radionuclide migration pathways		A.8.2	B.5.2, B.5.1.1	(a)
6.1	3.02	Radionuclide sorption		A.10.2b	B.6.2.1	(d)
6.1	3.03	Elemental solubility		A.4.1	B.6.2.2	(x)
6.1	3.04	Advective / dispersive / diffusive transport		A.6.1	I	(d)
6.1	3.05	Matrix diffusion		A.10.4	B.6.3.1	(s) 4.2
6.1	3.06	Gas-induced transport		A.6.2	B.5.1.3, B.7.1	(s) 1.8, 2.1, 2.2, 4.6
6.1	3.07	Colloid-facilitated transport		A.5.1, A.10.2b (NSR)	-	(x)
6.1	3.08	Convergence-induced transport		A.6.3	B.5.1.2, B.4.7	(x)
6.1	3.09	Transport by coupled processes (Onsager)		A.5.3 (NSR)	-	(x)
6.1	**4.**	**SPECIAL ISSUES (Bentonite – HR interface)**				

Tab. A6.1.1: (Cont.)

Cat. no.	FEP no.	OPA FEP name	Screened out?	KSRP SR Tab. 5.7-1 FMR Tab. A4.1.1	Super-FEPs SR Tab. 6.8-1 FMR Tab. A5.2.1	Assessment Cases SR Tab. 6.8-2 FMR Tab. A5.3.1
6.3	**1.**	**FEATURES AND CHARACTERISTICS (Concrete – HR interface)**				
6.3	1.01	Excavation disturbed zone (EDZ)		A.7.5, A.7.6a	B.4.8	(d)
6.3	1.01.1	Rock bolts	SC			
6.3	1.03	Effective hydraulic properties		A.7.5, A.7.6a	B.4.8	(d)
6.3	1.04	Mineralogy		A.8.1 (NSR)	B.6.4	(x)
6.3	1.05	Groundwater composition		A.8.1	B.6.4	(x)
6.3	1.06	Natural organics		A.10.2b, A.8.1	B.6.2.1, B.6.4	(x)
6.3	1.07	Microbial activity	SC			
6.3	1.08	Hydraulic gradient		A.7.5, A7.6a	B.4.8	(d)
6.3	1.09	Water flow at concrete – host rock interface		A.7.5, A.7.6a	B.4.8	(d)
6.3	**2.**	**ENVIRONMENTAL PROCESSES (Concrete – HR interface)**				
6.3	2.01	Desaturation / resaturation of EDZ		A.7.6a, A.7.8	C	(a)
6.3	2.02	Thermal evolution		A.7.1 (NSR)	-	(x)
6.3	2.03	Geomechanical processes		A.7.7	B.5.1.2, B.3.3.1	(j) 1.7
6.3	2.05	Swelling of clay-minerals in EDZ		A.7.7	B.5.1.2	(j) 1.7
6.3	2.06	Compaction of EDZ		A.7.7	B.5.1.2	(s) 1.7
6.3	2.07	Geochemical alteration		A.8.1	B.6.4	(x)
6.3	2.08	Fluid and heat fluxes by coupled processes (Onsager)		A.10.2 (NSR)	-	(x)
6.3	2.09	Gas transport		A.9.1	B.5.1.3, B.5.2, B.7.1	(s) 1.8, 4.5, 2.1, 2.2, 4.6
6.3	2.10	Colloid production and effects		A.7.5, A.10.2b (NSR)	-	(x)
6.3	**3.**	**RADIONUCLIDE PROCESSES (Concrete – HR interface)**				
6.3	3.01	Radionuclide migration pathways		A.7.5	B.4.8	(d)
6.3	3.02	Radionuclide sorption		A.7.5	B.3.3.2	(d)
6.3	3.03	Elemental solubility		A.7.3	B.3.3.2	(x)
6.3	3.04	Advective / dispersive / diffusive transport		A.7.5	B.4.8	(d)
6.3	3.05	Matrix diffusion		A.7.5	B.6.3.1	(x)
6.3	3.06	Gas-induced transport		A.7.6a	B.5.1.3, B.7.1, B.5.2, B.4.8	(s) 1.8, 4.5, 2.1, 2.2, 4.6
6.3	3.07	Colloid-facilitated transport		A.7.5, A.10.2b (NSR)	-	(x)
6.3	3.08	Convergence-induced transport		A.7.7	B.5.1.2, B.3.3.1	(s) 1.7
6.3	3.09	Transport by coupled processes (Onsager)		A.10.2a (NSR)	-	(x)
6.3	**4.**	**SPECIAL ISSUES (Concrete – HR interface)**				

Tab. A6.1.1: (Cont.)

Cat. no.	FEP no.	OPA FEP name	Screened out?	KSRP SR Tab. 5.7-1 FMR Tab. A4.1.1	Super-FEPs SR Tab. 6.8-1 FMR Tab. A5.2.1	Assessment Cases SR Tab. 6.8-2 FMR Tab. A5.3.1
7.	**1.**	**FEATURES AND CHARACTERISTICS (OPA host rock)**				
7.	1.01	Discontinuities		A.10.4	B.6.3	(s) 4.2
7.	1.02	OPA matrix		A.10.1, A.10.2b	B.6.1a, B.6.2	(d)
7.	1.03	Effective hydraulic properties		A.10.1, A.10.2a	B.6.1	(d)
7.	1.04	Mineralogy		A.10.2b	B.6.2.1	(i)
7.	1.05	Groundwater composition		A.10.2b	B.6.2.1	(i)
7.	1.06	Natural organics		A.10.2b	B.6.2.1	(i)
7.	1.07	Stress regime		A.10.2a, A.6.3, A.11.1	B.6.1.1, B.6.1.2, B.3.3.1	(j) 1.4, 1.7
7.	1.08	Hydraulic gradient		A.10.2a, A.10.3	B.6.1	(d) 1.1f, 1.1g, 4.1
7.	1.09	Heterogeneity within OPA		A.10.4	B.6.3	(j) 4.2
7.	1.10	Calcite veins	SC			
7.	1.11	Overpressures		A.10.2a	B.6.1	(j) 1.1f
7.	**2.**	**ENVIRONMENTAL PROCESSES (OPA host rock)**				
7.	2.01	Thermal effects		A.5.2 (NSR)	-	(x)
7.	2.03	Swelling of clay		A.10.4	B.6.3.2	(a)
7.	2.04	Geochemical alteration		A.8.1 (NSR)	-	(x)
7.	2.05	Microbial activity	SC			
7.	2.06	Effects of gas on OPA		A.10.3	B.6.1.2, B.7.1.1/4	(j) 1.4, 2.1, 4.6
7.	2.07	Groundwater flow		A.10.2a	B.6.1.1/3	(d) 1.1f, 1.1g, 4.1, 4.8
7.	2.08	Gas transport		A.10.3	B.6.1.2, B.7.1.1/4	(s) 2.1, 4.6
7.	2.09	Colloid transport		A.10.2 (NSR)	-	(x)
7.	2.10	Effect of colloids on OPA properties		A.10.2 (NSR)	-	(x)
7.	2.11	Density-driven groundwater flow (thermal and saline)		A.10.2a (NSR)	-	(x)
7.	2.12	Fluid fluxes by coupled processes (Onsager)		A.10.2a (NSR)	-	(x)
7.	**3.**	**RADIONUCLIDE PROCESSES (OPA host rock)**				
7.	3.01	Radionuclide migration pathways		A.10.2a, A.10.1, A.10.4	B.6.1a, B.6.3	(d) 4.2, 4.11
7.	3.02	Elemental solubility		A.10.2b	B.6.2.2 (NSR)	(x)
7.	3.03	Advective / dispersive / diffusive transport		A.10.2a, A.10.1, A.10.4	B.6.1, B.6.3	(d)
7.	3.04	Matrix diffusion		A.10.2a, A.10.4	B.6.3	(s) 4.2
7.	3.05	Radionuclide sorption		A.10.2b	B.6.2.1	(d) 1.1h, 1.1i, 4.7
7.	3.06	Dilution of radionuclides		A.10.1, A.10.2b	B.6.1a (NSR)	(x)
7.	3.07	Colloid-facilitated transport		A.10.2b (NSR)	-	(x)
7.	3.08	Gas-induced transport		A.10.3	B.6.1.2, B.7.1.1/4	(s) 1.4, 2.1, 4.6
7.	3.10	Transport by coupled processes (Onsager)		A.10.2a (NSR)	-	(x)

Tab. A6.1.1: (Cont.)

Cat. no.	FEP no.	OPA FEP name	Screened out?	KSRP SR Tab. 5.7-1 FMR Tab. A4.1.1	Super-FEPs SR Tab. 6.8-1 FMR Tab. A5.2.1	Assessment Cases SR Tab. 6.8-2 FMR Tab. A5.3.1
7.	**4.**	**SPECIAL ISSUES (OPA host rock)**				
7.	4.01	Exploratory boreholes		A.17.1, A.11.3	B.7.2.1	(s) 3.1
7.	4.03	Influx of oxidising water		A.10.1 (NSR)	-	(x)
7.	4.04	Intrusion of saline groundwater	SC			-
7.	4.05	Chemical plume from ILW		A.8.1	B.6.4 (NSR)	(x)
8.	**1.**	**FEATURES AND CHARACTERISTICS (Tunnels & shafts)**				
8.	1.01	Access tunnels, ramp and shaft		A.1.0	I	(a)
8.	1.02	Tunnel, ramp and shaft seals		A.1.0	I	(a)
8.	1.03	Effective hydraulic properties		A.8.2	B.5.1.1	(s) 1.6
8.	1.04	Hydraulic gradient		A.8.2	B.5.1.1	(s) 1.6
8.	**2.**	**ENVIRONMENTAL PROCESSES (Tunnels & shafts)**				
8.	2.01	Seal performance (during and after swelling)		A.8.2	B.5.2	(j) 4.5
8.	2.02	Tunnel backfill performance		A.8.2	B.5.2	(j) 4.5
8.	2.03	Drainage of water		A.8.2	B.5.1	(x)
8.	2.04	Preferential flow of water		A.8.2	B.5.1	(j)
8.	2.05	Colloid transport		A.5.1 (NSR)	-	(x)
8.	2.06	Gas transport		A.9.1, A.8.3	B.5.1.3, B.5.2, B.7.1.2	(s) 1.8, 2.2, 4.5
8.	2.07	Fluid fluxes by coupled processes (Onsager)		A.5.3 (NSR)	-	(x)
8.	2.08	Density-driven groundwater flow (thermal and saline)		A.8.2	B.5.1.1	(x)
8.	**3.**	**RADIONUCLIDE PROCESSES (Tunnels & shafts)**				
8.	3.01	Radionuclide migration pathways		A.8.2	B.5.1.1	(s) 1.6
8.	3.02	Elemental solubility	SC			
8.	3.03	Advective / dispersive / diffusive transport		A.8.2	I	(d)
8.	3.04	Matrix diffusion		A.8.2	B.5.1.1	(x)
8.	3.05	Radionuclide sorption		A.8.2	B.5.1.1	(s) 1.6
8.	3.06	Dilution of radionuclides		A.8.2	B.5.1.1	(x)
8.	3.07	Colloid-facilitated transport		A.5.1 (NSR)	-	(x)
8.	3.08	Gas-induced transport (of RNs)		A.9.1, A.8.3	B.5.1.3, B.5.2, B.7.1.2	(s) 1.8, 2.2, 4.5
8.	3.09	Convergence-induced transport		A.8.2	B.5.1.2	(s) 1.7
8.	3.10	Transport by coupled processes (Onsager)		A.5.3 (NSR)	-	(x)
8.	**4.**	**SPECIAL ISSUES (Tunnels & shafts)**				
8.	4.01	Oil or organic fluid spill	SC			
8.	4.02	Influx of oxidising water		A.8.2 (NSR)	-	(x)
8.	4.03	Intrusion of saline groundwater	SC			
8.	4.04	Chemical plume from ILW	SC			
8.	4.05	Alteration of backfill by liner of access tunnels		A.14.1	B.4.6	(x)

Tab. A6.1.1: (Cont.)

Cat. no.	FEP no.	OPA FEP name	Screened out?	KSRP SR Tab. 5.7-1 FMR Tab. A4.1.1	Super-FEPs SR Tab. 6.8-1 FMR Tab. A5.2.1	Assessment Cases SR Tab. 6.8-2 FMR Tab. A5.3.1
9.	**1.**	**GEOLOGY**				
9.	1.01	Lithostratigraphy		A.10, A.11	I	(a)
9.	1.02	Geological formation / history		A.10, A.11	I	(x)
9.	1.03.1	Sedimentology, mineralogy etc. – overlying formations		A.11	I	(x)
9.	1.03.3	Sedimentology, mineralogy etc. – underlying formations		A.11	I	(a)
9.	1.05	Regional stress regime		A.11.1	I	(a)
9.	1.06	Faults, distribution and properties		A.11.1	I	(a)
9.	1.07	Groundwater composition		A.11.2	B.6.5	(i)
9.	1.08	Natural resources		A.11.3 (NSR)	-	(x)
9.	**2.**	**HYDROGEOLOGIC MODEL(S)**				
9.	2.01	Hydrogeological units		A.11.2	B.6.5	(s) 1.5
9.	2.02	Effective hydraulic properties		A.11.2	B.6.5	(s) 1.5
9.	2.03	Recharge / discharge zones		A.11.2, A.16.2	B.6.5, B.9	(j) 1.5, 6.1
9.	2.04	Hydraulic gradient		A.11.2, A.16.2	B.6.5, B.9	(s) 1.5, 6.1
9.	2.05	Groundwater flowpaths		A.11.2, A.16.2	B.6.5, B.9	(s) 1.5, 6.1
9.	2.06	Density-driven groundwater flow (thermal and saline)		A.11.2 (NSR)	-	(x)
9.	**3.**	**RADIONUCLIDE MIGRATION (Geology & hydrology)**				
9.	3.01	Radionuclide migration pathways		A.11.2, A.16.2	B.6.5, B.9	(s) 1.5, 6.1
9.	3.02	Dilution of radionuclides		A.11.2, A.16.2	B.6.5, B.9	(s) 1.5, 6.1
9.	3.03	Sorption / retardation		A.11.2	B.6.5	(s) 1.5
10.	**1.**	**FEATURES AND CHARACTERISTICS (Biosphere)**				
10.	1.01	Topography and geomorphology		A.16.1/2	B.9	(i)
10.	1.02	Geosphere-biosphere interface		A.16.1/2	B.9	(d)
10.	1.03	Soils		A.16.1/2	B.9	(d)
10.	1.04	Aquifers		A.16.1/2	B.9	(d)
10.	1.05	Surface water bodies		A.16.1/2	B.9	(d)
10.	1.06	Atmosphere		A.16.1	B.7.1	(d)
10.	1.07	Animals		A.16.1/2	BIO	(i)
10.	1.08	Vegetation		A.16.1/2	BIO	(i)
10.	1.09	Climate		A.16.1/2	B.8	(s) 6.2b-d
10.	1.10	Present-day biosphere		A.16.1/2	B.8, B.9	(i)
10.	1.11	Agricultural practices		A.16.3	BIO	(i)
10.	1.12	Natural and semi-natural environments		A.16	B.8, B.9 , B.7.2	(j)
10.	1.13	Hunter / gathering lifestyle		A.16.1/3	B.8, B.7.2	(j) 6.2d

Tab. A6.1.1: (Cont.)

Cat. no.	FEP no.	OPA FEP name	Screened out?	KSRP SR Tab. 5.7-1 FMR Tab. A4.1.1	Super-FEPs SR Tab. 6.8-1 FMR Tab. A5.2.1	Assessment Cases SR Tab. 6.8-2 FMR Tab. A5.3.1
10.	**2.**	**ENVIRONMENTAL PROCESSES (Biosphere)**				
10.	2.01	Exfiltration to a biosphere aquifer		A.16.1/2	B.9	(d)
10.	2.02	Exfiltration to surface waters		A.16.1/2	B.9	(s) 6.1c
10.	2.03	Water resource exploitation		A.16.3	B.7.2.2	(s) 3.2,6.1d
10.	2.04	Filtration	SC			
10.	2.05	Surface water flow		A.16.1/2	B.9	(d)
10.	2.06	Groundwater flow		A.16.2	B.9	(d)
10.	2.07	Erosion / deposition		A.16.1/2	B.9	(d)
10.	2.08	Sedimentation		A.16.1/2	B.9	(d)
10.	2.09	Soil formation		A.16.1/2	B.9	(i)
10.	2.10	Interface effects		A.16.1/2	BIO	(x)
10.	2.11	Precipitation		A.16.1	B.8	(d)
10.	2.12	Evapotranspiration		A.16.1/2	B.8	(d)
10.	2.13	Capillary rise		A.16.1/2	B.9	(d)
10.	2.14	Percolation		A.16.1/2	B.9	(i)
10.	2.15	Irrigation		A.16.1/2	B.8, B.9	(d)
10.	2.16	Surface run-off		A.16.1/2	B.9	(i)
10.	2.17	Bioturbation		A.16.1/2	B.9	(d)
10.	2.18	Suspended sediment transport		A.16.1/2	B.9	(d)
10.	2.19	Earthworks (human actions, dredging etc.)		A.16	B.8, B.9, B.7.2	(d)
10.	2.20	Ploughing		A.16	B.8, B.9, B.7.2	(x)
10.	2.21	Exfiltration to spring		A.16.2	B.9	(s) 6.1d
10.	**3.00**	**RADIONUCLIDE MIGRATION PROCESSES (Biosphere)**				
10.	3.01	Radionuclide accumulation in sediments		A.16.1/2	B.9	(i)
10.	3.02	Radionuclide accumulation in soils		A.16.1/2	B.9	(i)
10.	3.03	Radionuclide transport as solute		A.16.1/2	B.9	(d)
10.	3.04	Radionuclide transport with solid material		A.16.1/2	B.9	(d)
10.	3.05	Radionuclide sorption		A.16.1/2	B.9	(d)
10.	3.06	Speciation and solubility		A.16.1/2	B.9	(i)
10.	3.07	Diffusion/dispersion		A.16.1/2	B.9	(x)
10.	3.08	Radionuclide volatilisation / aerosol / dust production		A.16	B.7.1, B.8	(x)
10.	3.09	Dilution of radionuclides in surface water (aquifer, river, lake, etc.)		A.16.1/2	B.9	(d)
10.	3.11	Uptake by crops		A.16	BIO	(d)
10.	3.12	Uptake by livestock		A.16	BIO	(d)
10.	3.13	Uptake in fish		A.16	BIO	(d)
10.	3.15	Foodchain equilibrium		A.16	BIO	(i)
10.	3.16	Secular equilibrium of radionuclide chains		A.16	BIO	(i)
10.	3.17	Removal mechanisms		A.16	BIO	(d)
10.	3.18	Food and water processing		A.16	BIO	(d)

Tab. A6.1.1: (Cont.)

Cat. no.	FEP no.	OPA FEP name	Screened out?	KSRP SR Tab. 5.7-1 FMR Tab. A4.1.1	Super-FEPs SR Tab. 6.8-1 FMR Tab. A5.2.1	Assessment Cases SR Tab. 6.8-2 FMR Tab. A5.3.1
10.	**3.20**	**RADIONUCLIDE EXPOSURE PROCESSES (Biosphere)**				
10.	3.21	Exposure pathways		A.16.3	BIO	(d)
10.	3.22	Age groups		A.16.3	BIO	(x)
10.	3.23	Dosimetry		A.16.3	BIO	(d)
10.	3.24	Human lifestyle		A.16.3	BIO	(d)
10.	3.25	Contaminated products (non-food)		NC	BIO	(x)
10.	3.26	Consumption of uncontaminated products		NC	BIO	(x)
10.	3.27	Radon pathways and doses		A.16	BIO	(x)
10.	**4.**	**SPECIAL ISSUES (Biosphere)**				
10.	4.01	Future biosphere conditions		A.16.1/2	BIO	(s) 6.2b-d
10.	4.02	Non-radiological effects	SC			
10.	4.03	Radiological effects on non-human biota	SC			
11.	**2.**	**ENVIRONMENTAL PROCESSES (Geological P&E)**				
11.	2.01	Regional vertical movements		A.11.1	B.6.1.3	(x)
11.	2.02	Regional horizontal movements		A.11.1	B.6.1.3	(x)
11.	2.03	Compaction of Opalinus Clay		A.10.1	B.6.1a	(s) 4.11
11.	2.04	Erosion		A.11.1	B.6.1.3	(x)
11.	2.05	Evolution of regional stress regime		A.11.1, A.10.4	B.6.3	(j) 4.2
11.	2.06	Neo-tectonic activity		A.11.1, A.10.4	B.6.3	(j) 4.2
11.	2.07	Self-sealing of faults		A.10.4	B.6.3.2	(a)
11.	2.08	Seismic activity		A.11.1 (NSR)	-	(x)
11.	2.09	Magmatic activity (volcanism and plutonism)		A.11.1 (NSR)	-	(x)
11.	2.10	Hydrothermal activity	SC			
12.	**1.**	**FEATURES AND CHARACTERISTICS (Climatic P&E)**				
12.	1.01	Present-day climatic conditions		A.16.1	B.8	(d)
12.	1.02	Future climatic conditions		A.16.1	B.8	(s) 6.2b-d
12.	1.03	Glacial climate		A.16.1 (NSR)	-	(x)
12.	1.04	Permafrost		A.16.1 (NSR)	-	(x)
12.	1.05	Tundra climate		A.16.1	B.8	(s) 6.2d
12.	1.06	Dry climate		A.16.1	B.8	(s) 6.2b/d
12.	1.07	Warm seasonal humid climate		A.16.1	B.8	(s) 6.2c
12.	1.08	Warm equable humid climate		A.16.1	B.8	(s) 6.2c
12.	1.09	Seasonality of climate		A.16.1	BIO	(x)
12.	**2.**	**ENVIRONMENTAL PROCESSES (Climatic P&E)**				
12.	2.02	Fluvial erosion / sedimentation		A.16.1/2	B.8, B.9	(i)
12.	2.03	Glacial erosion / sedimentation		A.16.1/2	B.8, B.9	(i)
12.	2.04	Glacial-fluvial erosion / sedimentation		A.16.1/2	B.8, B.9	(x)
12.	2.05	Ice sheet effects (loading, melt water recharge)		A.16.1/2, A.10.2a	B.8, B.9, B.6.1.2	(s) 6.2d, 1.4
12.	2.06	Effective moisture (recharge)		A.16.1	B.8	(d)
12.	2.09	Greenhouse effect		A.16.1	B.8	(s) 6.2c

Tab. A6.1.1: (Cont.)

Cat. no.	FEP no.	OPA FEP name	Screened out?	KSRP SR Tab. 5.7-1 FMR Tab. A4.1.1	Super-FEPs SR Tab. 6.8-1 FMR Tab. A5.2.1	Assessment Cases SR Tab. 6.8-2 FMR Tab. A5.3.1
13.	**1.**	**FUTURE HUMAN ACTIONS (Future human actions)**				
13.	1.01	Exploratory drilling		A.17.1	B.7.2.1	(j) 3.1
13.	1.02	Resource exploitation through boreholes		A.17.1	B.7.2.1	(j) 3.1
13.	1.03	Mining activities		A.11.3 (NSR)	-	-
13.	1.04	Geothermal exploitation		A.17.1	-	(x)
13.	1.05	Deep groundwater extraction		A.16.3	B.7.2.2	(s) 3.2
13.	1.06	Liquid waste injection		A.17.1	B.7.2.1	(j) 3.1
13.	2.01	Human-induced climate change		A.16.1	B.8	(j) 6.2c
13.	2.02	Surface pollution (soils, rivers)	SC			
13.	2.03	Groundwater pollution	SC			
13.	2.04	Water management schemes		A.16.3	B.7.2.2	(j) 3.2
13.	3.01	Intentional intrusion	SC			
13.	3.02	Inadvertent intrusion		A.17.1	B.7.2.1	(s) 3.1
13.	3.03	Repository records, markers	SC			
13.	3.04	Planning restrictions	SC			
13.	3.05	Abandonment of repository		A.18.1	B.7.2.3	(s) 3.3a

Appendix 7: Phenomena explicitly included in the main safety assessment codes

A7.1 Introduction

The main safety assessment codes comprise the *Reference Model Chain (RMC)* codes, together with the general-purpose transport code, FRAC3DVS, and the Gas Model. The RMC includes:

- The STMAN family of codes for modelling the release of radionuclides from the waste forms, transport through the engineered barriers and release to the geosphere, comprising:
    - SPENT, which is applicable to directly disposed spent fuel (SF);
    - STRENG, which is applicable to the vitrified high-level waste form (HLW); and
    - STALLION, which is applicable to long-lived intermediate-level waste (ILW);
- the PICNIC geosphere transport code; and
- the TAME biosphere code.

The purpose of this appendix is to summarise phenomena that are explicitly included in these codes. The broader topic of qualification of the codes to represent not only these but also other phenomena (often in a simplified or partial manner) is the subject of Appendix 8.

A7.2 The SPENT model

Tab. A7.2.1 summarises phenomena that are either modelled explicitly by SPENT, or their magnitude, timing, rate, spatial extent and performance (which may be evaluated by another model or code) directly determine one or more input parameters. The following model features or categories of phenomena are distinguished:

- The containment period and canister breaching modes;
- the release mechanisms for radionuclides from the fuel and the canister;
- transport through the buffer; and
- the interface with the host rock.

The final two aspects are common to all codes in the STMAN family.

Tab. A7.2.1: Phenomena explicitly included in the SPENT model

Model features	**Phenomena explicitly included in the SPENT model**
All	Radionuclide decay and ingrowth
The containment period and canister breaching modes	Waste inventory in a single package and number of packages
	Time of occurrence of SF canister breaching
	Presence of initial defects
	Transport resistance of initial defects
Fuel release mechanisms and the reservoir	Partitioning between fuel matrix, cladding and IRF
	Proportion of ^{14}C in organic form upon release
	Corrosion rate of cladding
	Dissolution rate of fuel matrix
	Solubility limitation
Transport through the buffer	Aqueous diffusion
	Linear equilibrium sorption
	Solubility limitation
Interface with the host rock	Effective flow rate at outer boundary

A7.3 The STRENG model

Tab. A7.3.1 summarises phenomena that are either modelled explicitly by STRENG, or their magnitude, timing, rate, spatial extent and performance (which may be evaluated by another model or code) directly determine one or more input parameters. The same model features are distinguished as in the case of SPENT, namely:

- The containment period and canister breaching modes;
- the release mechanisms for radionuclides from the waste form and the reservoir;
- transport through the buffer; and
- the interface with the host rock,

where the final two aspects are common to all codes in the STMAN family.

Tab. A7.3.1: Phenomena explicitly included in the STRENG model

Model features	**Phenomena explicitly included in the STRENG model**
All	Radionuclide decay and ingrowth
The containment period and canister breaching modes	Waste inventory in a single package and number of packages
	Time of occurrence of HLW canister breaching
	Presence of initial defects
	Transport resistance of initial defects
Glass release mechanisms and the reservoir	Dissolution rate of glass
	Solubility limitation
Transport through the buffer	Aqueous diffusion
	Linear equilibrium sorption
	Solubility limitation
Interface with the host rock	Effective flow rate at outer boundary

A7.4 The STALLION model

Tab. A7.4.1 summarises phenomena that are either modelled explicitly by STALLION, or their magnitude, timing, rate, spatial extent and performance (which may be evaluated by another model or code) directly determine one or more input parameters. The following model features or categories of phenomena are distinguished:

- The containment period;
- the behaviour of radionuclides in the cementitious region; and
- the interface with the host rock.

Again, the final two aspects are common to all codes in the STMAN family. STALLION also includes the possibility of modelling transport through a buffer region surrounding the cementitious region. This is, however, redundant in the present study [14] and is therefore not included in Tab. A7.4.1.

Tab. A7.4.1: Phenomena explicitly included in the STALLION model

Model features	**Phenomena explicitly included in the STALLION model**
All	Radionuclide decay and ingrowth
The containment period	Waste inventory in a single package and number of packages
	Time of occurrence of breaching (ILW steel drums and emplacement containers)
The behaviour of radionuclides in the cementitious region	Corrosion rate of metallic components
	Linear equilibrium sorption
	Solubility limitation
Interface with the host rock	Effective flow rate

[14] In practice, for numerical reasons, a buffer region has been included in assessment case calculations involving STALLION, but the thickness of this region is made sufficiently small that it has not impact on the release rates of radionuclides from the ILW near field.

A7.5 The PICNIC model

Tab. A7.5.1 summarises phenomena that are either modelled explicitly by PICNIC, or their magnitude, timing, rate, spatial extent and performance (which may be evaluated by another model or code) directly determine one or more input parameters. The following model features or categories of phenomena are distinguished:

- Phenomena in a single leg; and
- network structure and properties.

Tab. A7.5.1: Phenomena explicitly included in the PICNIC model

Model features	**Phenomena explicitly included in the PICNIC model**
All	Radionuclide decay and ingrowth
Phenomena in a single leg: retardation processes	Stationary flow
	Advection / dispersion
	Aqueous diffusion (incl. matrix diffusion where the leg represents a fractured medium)
	Linear equilibrium sorption
Network structure and properties	Transport paths provided by: - the tunnels / ramp / shaft; - the Oplainus Clay and confining units; - by transmissive discontinuities, faults and repository-induced fractures in the clay; - the confining units and regional aquifers; as required by the assessment case under consideration

A7.6 The TAME model

Tab. A7.6.1 summarises phenomena that are either modelled explicitly by PICNIC, or their magnitude, timing, rate, spatial extent and performance (which may be evaluated by another model or code) directly determine one or more input parameters. The following model features or categories of phenomena are distinguished:

- Interface with geosphere model;
- conceptual model objects (CMOs);
- material flows;
- contaminant transport / accumulation;
- exposure modes; and
- receivers of dose / critical group.

Tab. A7.6.1: Phenomena explicitly included in the TAME model

Model features	**Phenomena explicitly included in the TAME model**
All	Radionuclide decay and ingrowth
Interface with geosphere model	Contaminated groundwater
Conceptual model objects (CMOs)	Soils
	Surface water bodies / water supplies
	Near-surface water bodies / water supplies / irrigation
	Atmosphere / airborne particulates
	Flora and fauna / foodstuffs
Material flows	Bulk water movement
	Deposition / erosion
Contaminant transport / accumulation	Partitioning (between solid, liquid and gas phases)
Exposure modes	Ingestion
	Inhalation
	External radiation
Receivers of dose / critical group	Exposed population / subsistence agriculture

A7.7 The FRAC3DVS model

Tab. A7.7.1 summarises phenomena that are either modelled explicitly by FRAC3DVS, or their magnitude, timing, rate, spatial extent and performance (which may be evaluated by another model or code) directly determine one or more input parameters. The following model features or categories of phenomena are distinguished:

- Geometric features;
- flow phenomena; and
- transport and retention phenomena.

Tab. A7.7.1: Phenomena explicitly included in the FRAC3DVS model

Model features	Phenomena explicitly included in the FRAC3DVS model
All	Radionuclide decay and ingrowth
Geometric features	Transmissive discontinuities, faults and repository induced fractures in the clay
	Path length
Flow phenomena	Stationary flow
	Transient flow
Transport and retention phenomena	Advection / dispersion
	Aqueous diffusion
	Linear equilibrium sorption

A7.8 The Gas Model

Tab. A7.8.1 summarises phenomena that are either modelled explicitly by the Gas Model, or their magnitude, timing, rate, spatial extent and performance (which may be evaluated by another model or code) directly determine one or more input parameters. The following model features or categories of phenomena are distinguished:

- Pressure evolution and gas migration; and
- dose due to volatile ^{14}C in the gas phase.

Tab. A7.8.1: Phenomena explicitly included in the Gas Model

Model features	**Phenomena explicitly included in the Gas Model**
General	Radionuclide decay
Pressure evolution and gas migration	Gas generation rate for SF / HLW
	Gas generation rates for ILW
	Gas dissolution and diffusion (SF / HLW near field; ILW near field; Opalinus Clay, incl. tunnel EDZs)
	Porewater displacement by gas (ILW near field)
	Capillary leakage into the Opalinus Clay
	Dilatant gas pathway formation in the Opalinus Clay
	Porewater displacement in the Wedelsandstein
	Gas dissolution and diffusion in the low-permeability upper confining units
Dose due to volatile ^{14}C in the gas phase	Organic ^{14}C in volatile form upon release
	Corrosion rate (cladding)
	Dissolution rate (fuel matrix)
	Time of occurrence of breaching (SF canisters)
	Dilution in the Quaternary aquifer
	Ingestion of drinking water from Quaternary aquifer

Appendix 8: Qualification of the assessment codes

A8.1 Introduction

The audit of the assessment codes against the Super-FEPs that have been identified in the course of the safety assessment is described in Section 5.1 of the main part of this report. The audit may be seen as an evaluation of the "qualification" of the assessment codes to represent the Super-FEPs, or at least their safety-relevant aspects that must be taken into account in selecting and applying the codes for assessment calculations. The results of the audit are summarised in Tab. 5.1-1. The purpose of this appendix is to explain in more details the allocation of symbols in Tab. 5.1-1. Each code is considered in turn, and the ways in which the various aspects of the Super-FEPs can (or cannot) be represented by the different features of the codes, as indicated by the symbols defined below, are explained via short comments.

The following symbols used in Tab. 5.1-1 and in the tables of this appendix:

✓ *A safety-relevant aspect of a Super-FEP is fully represented by a code*: either a process modelled explicitly, or the magnitude, timing, rate or spatial extent of a process, or the performance of a feature, directly determines one or more input parameters.

✓ *A safety-relevant aspect of a Super-FEP is only partially represented by a code*: either only some limited aspect of a feature is modelled explicitly, or assumptions regarding the (non-negligible) impact of a process on the properties of the system are be built into the code, but no parameters values are directly affected that can be used to vary these assumptions.

○ *A safety-relevant aspect of a Super-FEP is not represented by a code, but gives rise time-dependent system properties that can be treated indirectly*: parameter sets can be chosen that represent steady-state system properties corresponding, for example, to the end-state of the system once the process is complete or to one of a number of possible transient states.

Where a code of the Reference Model Chain cannot treat a safety-relevant aspect of a Super-FEP or incorporates an assumption of negligible impact, but an alternative code exists that can treat this aspect quantitatively, this is indicated using the symbol ► in the table. Where no qualified code exists, this is indicated using the symbol ●.

Note that the safety-relevant aspects of the Super-FEPs indicated by large bold ticks in the overview table Tab. 5.1-1 and the code-specific tables of this appendix in general are a subset of the phenomena explicitly included in the codes that are summarised in Appendix 7.

Key findings of the audit and conclusions regarding the qualification of the assessment codes are given in Seciton 5.1.3.

A8.2 Representation of the Super-FEPs and their safety-relevant aspects by the assessment codes

Tabs. A8.2.1 to A8.2.7 describe how each assessment code represents the different Super-FEPs that fall into their respective model domains.

Tab. A8.2.1: Super-FEPs, their safety-relevant aspects and the ways in which they are represented by the code SPENT

Symbols: see Section A8.1.

Super-FEPs	Safety-relevant aspects to be represented by models	Model features: Containment period and breaching modes	Model features: Fuel release mechanisms & the reservoir	Model features: Transport through the buffer	Model features: Interface with the host rock	Explanatory comments
SF						
B.1.1 Quantities and burnup of fuel and associated radionuclide inventories, including the instant release fraction (IRF)	**SF1** Waste inventory in a single package and number of packages	✓				Directly provides input parameters.
	SF2 Partitioning between fuel matrix, cladding and IRF		✓			Directly provides input parameters.
	SF3 ^{14}C in organic and inorganic form upon release		✓			Solubility limits and sorption coefficients for ^{14}C depend on whether it is in organic or inorganic form.
	SF4 Proportion of organic ^{14}C in volatile form upon release		►			Release of organic ^{14}C in volatile form not considered (see Gas Model).
B.1.2 Corrosion of cladding	**SF5** Corrosion rate		✓			Directly provides input parameter.
B.1.3 Breaching of cladding	**SF6** Timing	✓				Cladding is breached at or before the time of canister breaching. The possibility of a period of complete containment by cladding following canister breaching cannot be modelled with the existing version of SPENT, since release of cladding inventory is assumed to begin simultaneously with the release from the fuel matrix and release of IRF.
B.1.4 Dissolution of fuel matrix	**SF7** Dissolution rate		✓			Fuel matrix dissolution rate as a function of time is input as a list of parameter values.
B.1.5 Criticality	-	●	●	●	●	Ruled out by design and supporting calculations.

Tab. A8.2.1: (Cont.)

Super-FEPs	Safety-relevant aspects to be represented by models	Model features: Containment period and breaching modes	Model features: Fuel release mechanisms & the reservoir	Model features: Transport through the buffer	Model features: Interface with the host rock	Explanatory comments
SF canisters						
B.3.5 Breeching of steel canisters	**CN1** Distribution of breeching times	●				Not included, but canister breaching time can be selected such that results err on the side of pessimism.
	CN2 Time of occurrence of breaching	✓				Time of breaching (containment) time is input as a parameter value – see, however, "the long resaturation time of the repository and its surroundings", below.
B.3.6 Gas generation by steel canister corrosion	**CN3** Gas generation rate for SF / HLW			►	►	No transport of radionuclides in volatile form considered. Gas generation assumed to be irrelevant (see Gas Model).
B.3.7 Canister material	**CN4** Time of occurrence of breaching (time of occurrence affected by canister material)	✓				Canister material affects evaluation of breaching time, which must be input as parameter.
	CN5 Presence of initial defects (likelihood affected by canister material)	✓				Canister material affects the possibility of localised defects, with associated transport resistances, which are characterised by input parameters.
SF near field						
B.4.1 The long resaturation time of the repository and ist surroundings	**NF1** The rate of the resaturation process	✓				The resaturation process and its transient effects on the transport-relevant properties of the buffer are not modelled by SPENT. However, the period of complete containment can, if required, be extended beyond canister breaching time to account for a long resaturation time (this is not done in the present assessment).
B.4.2 Geochemical immobilisation and retardation in the near field	**NF2** Solubility limitation (reservoir)		✓			Solubility limits for the reservoir are input as parameter values.
	NF3 Solubility limitation (buffer)			✓		Solubility limits for the buffer are input as parameter values.
	NF4 Linear, equilibrium sorption			✓		Sorption coefficients for the buffer are input as parameter values.
	NF5 Colloid filtration by bentonite			✓		Precipitated solids are assumed to be immobile.
	NF6 The extent of co-precipitation with secondary minerals		✓	✓		Can be taken into account via the setting of the solubility limits.
	NF7 The extent of sorption on canister corrosion products		●			Sorption on canister corrosion products not included, but omission is conservative.
	NF8 The effects on solubility limitation of the natural concentrations of isotopes		●	●		Natural background concentrations not included, but omission is conservative.

Tab. A8.2.1: (Cont.)

Super-FEPs	Safety-relevant aspects to be represented by models	Model features: Containment period and breaching modes	Model features: Fuel release mechanisms & the reservoir	Model features: Transport through the buffer	Model features: Interface with the host rock	Explanatory comments
SF near field						
B.4.3 Migration of radiolytic oxidants generated at SF surfaces into bentonite buffer	**NF9** Proportion of the buffer affected and the magnitude of the effects on geochemical immobilisation			○		Penetration (if any) of oxidants into the buffer must be evaluated separately. Sorption coefficients and solubility appropriate to oxidising conditions can be input, if required, as parameter values for the reservoir and all or part of the buffer.
B.4.4 Thermal alteration of the bentonite buffer adjacent to the SF / HLW canisters	**NF10** Proportion of the buffer affected and the magnitude of the effects on buffer transport properties			○		Extent of thermal alteration must be evaluated separately. Diffusion coefficients appropriate to altered buffer can be input, if required, as parameter values for all or part of the buffer.
B.4.5 Transport resistances provided by internal spaces (fractures) within the waste forms, by the breached SF / HLW canisters and by corrosion products	**NF11** The magnitude of transport resistance of initial defects		✓			Transport resistance of breached canisters can be considered via the "pinhole model" built into SPENT – in practice, this is only used in cases that consider the alternative composite copper / steel canister.
	NF12 The magnitude and time-dependence of other transport resistances		●			Other transport resistances not included, but omission is conservative.
B.4.6 Tunnel liner	**NF13** Requirement for a liner				○	Requirement for a liner ruled out by supplementary studies.
B.4.7 Hydraulic transport characteristics of bentonite	**NF18** Effective flow rate at outer boundary				✓	Input parameter.
	NF17 Aqueous diffusion			✓		Aqueous diffusion is assumed to convey radionuclides across the bentonite buffer; element-specific diffusion coefficients are input as parameter values.
	NF19 Compaction of bentonite by tunnel convergence			○		Compaction during tunnel convergence can be taken into account in setting the tunnel radius and bentonite transport properties.

Tab. A8.2.1: (Cont.)

Super-FEPs	Safety-relevant aspects to be represented by models	Model features: Containment period and breaching modes	Model features: Fuel release mechanisms & the reservoir	Model features: Transport through the buffer	Model features: Interface with the host rock	Explanatory comments
SF near field						
B.4.7.1 Gas transport characteristics of bentonite	**NF20** Gas induced release of dissolved radionuclides			○		Expulsion of the IRF by repository gas can be simulated, if required, by neglecting the transport resistance of the bentonite for the IRF.
	NF21 Dilatant gas pathway formation (SF / HLW near field)			►		Not considered in SPENT (see Gas Model).
	NF22 Gas dissolution and diffusion			►		See above.
The barrier system (general)						
B.7.2 Future human actions	**BS7** Borehole penetration of the repository				○	The nature and timing of future human actions cannot be evaluated using SPENT. The consequences of hypothetical actions that may influence the near field can, however, be bounded in some cases (e.g. the possibility of future drilling of a borehole inadvertently affecting the barrier system can be modelled by interfacing SPENT directly with the biosphere model).

Tab. A8.2.2: Super-FEPs, their safety-relevant aspects and the ways in which they are represented by the code STRENG

Symbols: see Section A8.1.

Super-FEPs	**Safety-relevant aspects to be represented by models**	**Model features**				**Explanatory comments**
		Containment period and breaching modes	**Glass release mechanisms & the reservoir**	**Transport through the buffer**	**Interface with the host rock**	
HLW						
B.2.1 Quantities of glass and associated radionuclide inventories	**HL1** Waste inventory in a single package and number of packages	✓				Directly provides input parameters.
B.2.2 Dissolution rate of glass	**HL2** Dissolution rate		✓			Fractured glass is modelled as equivalent spheres. Glass dissolution rate and glass spherical radius must be input as parameter values.
HLW canisters						
B.3.5 Breaching of steel canisters	**CN1** Distribution of breaching times	●				Not included, but canister breaching time can be selected such that results err on the side of pessimism.
	CN2 Time of occurrence of breaching	✓				Time of breaching (containment) time is input as a parameter value – see, however, "the long resaturation time of the repository and its surroundings", below.
B.3.6 Gas generation by steel canister corrosion	**CN3** Gas generation rate for SF / HLW			►	►	No transport of radionuclides in volatile form considered; gas generation assumed to be irrelevant (see Gas Model).
B.3.7 Canister material	**CN4** Time of occurrence of breaching (time of occurrence affected by canister material)	✓				Canister material affects evaluation of breaching time, which must be input as parameter.
	CN5 Presence of initial defects (likelihood affected by canister material)	✓				Canister material affects the possibility of localised defects, with associated transport resistances, which are characterised by input parameters.

Tab. A8.2.2: (Cont.)

Super-FEPs	Safety-relevant aspects to be represented by models	Model features				Explanatory comments
		Containment period and breaching modes	Glass release mechanisms & the reservoir	Transport through the buffer	Interface with the host rock	
HLW near field						
B.4.1 The long resaturation time of the repository and its surroundings	**NF1** The rate of the resaturation process	✓				The resaturation process and its transient effects on the transport-relevant properties of the buffer are not modelled by STRENG. However, the period of complete containment can, if required, be extended beyond canister breaching time to account for a long resaturation time (this is not done in the present assessment).
B.4.2 Geochemical immobilisation and retardation in the near field	**NF2** Solubility limitation (reservoir)		✓			Solubility limits for the reservoir are input as parameter values.
	NF3 Solubility limitation (buffer)			✓		Solubility limits for the buffer are input as parameter values.
	NF4 Linear, equilibrium sorption			✓		Sorption coefficients for the buffer are input as parameter values.
	NF5 Colloid filtration by bentonite			✓		Precipitated solids are assumed to be immobile.
	NF6 The extent of co-precipitation with secondary minerals		✓	✓		Can be taken into account via the setting of the solubility limits.
	NF7 The extent of sorption on canister corrosion products		●			Sorption on canister corrosion products not included, but omission is conservative.
	NF8 The effects on solubility limitation of the natural concentrations of isotopes		●	●		Natural background concentrations not included, but omission is conservative.
B.4.4 Thermal alteration of the bentonite buffer adjacent to the SF / HLW canisters	**NF10** Proportion of the buffer affected and the magnitude of the effects on buffer transport properties			○		Extent of thermal alteration must be evaluated separately. Diffusion coefficients appropriate to altered buffer can be input, if required, as parameter values for all or part of the buffer.
B.4.5 Transport resistances provided by internal spaces (fractures) within the waste forms, by the breached SF / HLW canisters and by corrosion products	**NF11** The magnitude of transport resistance of initial defects		✓			Transport resistance of breached canisters can be considered via the "pinhole model" built into STRENG.
	NF12 The magnitude and time-dependence of other transport resistances		●			Other transport resistances not included, but omission is conservative.

Tab. A8.2.2: (Cont.)

Super-FEPs	Safety-relevant aspects to be represented by models	Model features				Explanatory comments
		Containment period and breaching modes	Glass release mechanisms & the reservoir	Transport through the buffer	Interface with the host rock	
HLW near field						
B.4.6 Tunnel liner	**NF13** Requirement for a liner				○	Requirement for a liner ruled out by supplementary studies.
B.4.7 Hydraulic transport characteristics of bentonite	**NF18** Effective flow rate at outer boundary				✓	Input parameter.
	NF17 Aqueous diffusion			✓		Aqueous diffusion is assumed to convey radionuclides across the bentonite buffer. Element-specific diffusion coefficients are input as parameter values.
	NF19 Compaction of bentonite by tunnel convergence			○		Compaction during tunnel convergence can be taken into account in setting the tunnel radius and bentonite transport properties.
B.4.7.1 Gas transport characteristics of bentonite	**NF20** Gas-induced release of dissolved radionuclides			○		Expulsion of the IRF by repository gas can be simulated, if required, by neglecting the transport resistance of the bentonite for the IRF.
	NF21 Dilatant gas pathway formation (SF / HLW near field)			►		Not considered in STRENG (see Gas Model).
	NF22 Gas dissolution and diffusion			►		See above.
The barrier system (general)						
B.7.2 Future human actions	**BS7** Borehole penetration of the repository				○	The nature and timing of future human actions cannot be evaluated using STRENG. The consequences of hypothetical actions that may influence the near field can, however, be bounded in some cases (e.g. the possibility of future drilling of a borehole inadvertently affecting the barrier system can be modelled by interfacing STRENG directly with the biosphere model).

Tab. A8.2.3: Super-FEPs, their safety-relevant aspects and the ways in which they are represented by the code STALLION

Symbols: see Section A8.1.

Super-FEPs	**Safety-relevant aspects to be represented by models**	**Model features**			**Explanatory comments**
		Containment period	**The behaviour of radionuclides in the cementitious region**	**Interface with the host rock**	
ILW					
B.3.1 Quantities of waste and associated radionuclide inventories	**IL1** Waste inventory in a single package and number of packages	✓			Directly provides input parameters.
B.3.2 Breaching of ILW steel drums and emplacement containers	**IL2** Time of occurrence of breaching	✓			Time of breaching (containment) time is input as a parameter value – see, however, "the long resaturation time of the repository and its surroundings", below.
B.3.3 Corrosion / dissolution of ILW	**IL3** Corrosion rate of metallic components		✓		Delayed release of radionuclides due to the slow corrosion rate of ILW metallic components can be modelled (although conservatively omitted in the present assessment).
	IL4 Corrosion / dissolution rate of remaining ILW components		●		Corrosion / dissolution of ILW conservatively assumed to be instantaneous.
B.3.3.2 Immobilisation and retardation in the ILW near field	**IL5** Linear, equilibrium sorption and solubility limitation		✓		Sorption coefficients and solubility limits are input as parameter values.
B.3.4 Gas generation	**IL6** Gas generation rates for ILW		►	►	No transport of radionuclides in volatile form considered; gas generation assumed to be irrelevant (see Gas Model).
B.4.8 Hydraulic and gas transport characteristics ILW near field	**IL7** Effective flow rate at outer boundary			✓	Input parameter.
	IL8 Gas dissolution and diffusion			►	Not considered in STALLION (see Gas Model).
	IL9 Porewater displacement by gas			► or ○	The displacement of water by gas can be simulated by selecting an appropriate effective flow rate at the interface with the geosphere model.

Tab. A8.2.3: (Cont.)

Super-FEPs	Safety-relevant aspects to be represented by models	Model features			Explanatory comments
		Containment period	The behaviour of radionuclides in the cementitious region	Interface with the host rock	
ILW					
B.3.3.1 Compaction of waste / mortar	**IL10** Timing if convergence arising from void reduction of breached, corroded canisters			○	Compaction of waste / mortar is not modelled explicitly by STALLION. Its transient effects in terms of the expulsion of water from the near field must be evaluated separately. The effects on radionuclide release can then be bounded by assuming an increased effective flow rate assumed at near-field / geosphere interface (as in Cases 1.7a-b).
B.3.3.3 The long resaturation time of the ILW tunnels	**IL11** The rate of the resaturation process	✓			The resaturation process and its transient effects on the transport-relevant properties of the ILW tunnels are not modelled by STALLION. However, the period of complete containment can, if required, be extended beyond the steel drum / emplacement container breaching time to account for a long resaturation time.
The barrier system (general)					
B.7.2 Future human actions	**BS7** Borehole penetration of the repository			○	The nature and timing of future human actions cannot be evaluated using STALLION. The consequences of hypothetical actions that may influence the near field can, however, be bounded in some cases (e.g. the possibility of future drilling of a borehole inadvertently affecting the barrier system can be modelled by interfacing STALLION directly with the biosphere model).

Tab. A8.2.4: Super-FEPs, their safety-relevant aspects and the ways in which they are represented by the code PICNIC

Symbols: see Section A8.1.

Super-FEPs	Safety-relevant aspects to be represented by models	Model features: Phenomena in a single leg	Model features: Network structure and properties	Explanatory comments
Tunnels / ramp / shaft and seals				
B.5.1 Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)	**TS1** Transport paths provided by the tunnels / ramp / shaft		✓	The situation of negligible flow through the tunnels / ramp / shaft can be modelled by using a single leg to represent transport through the intact Opalinus Clay only. Uncertainties (e.g. due to reduced performance of seals) can be handled by choosing an appropriate network of legs to represent transport paths through the tunnels / ramp / shaft / host rock, and selecting appropriate parameters for the transport / retention properties of backfilled tunnels / ramp / shaft / host rock, as well as flow.
	TS2 Stationary flow	✓		Darcy velocity provided as input parameter.
	TS3 Transient flow	○		Transient flow cannot be modelled using PICNIC, but the effects can be bounded by assuming an increased steady-state flow field.
	TS4 Advection / dispersion	✓		Modelled explicitly.
	TS5 Aqueous diffusion	✓		Modelled explicitly.
B.5.2 The seals and the surrounding rock	**TS7** Transport resistance of the seals and the surrounding rock	✓		The performance (effectiveness and longevity) of the seals affects the groundwater flow rate along the sealed tunnels / ramp / shaft / host rock, and through the surrounding excavation disturbed zones (EDZs) (see above).
Opalinus Clay and confining units				
B.6.1 Low groundwater flow rate through undisturbed Opalinus Clay	**OP1** Stationary flow	✓		Darcy velocity provided as input parameter.
	OP2 Transient flow	► or ○		Transient flow cannot be modelled using PICNIC, but the effects can be bounded by assuming an increased steady-state flow field. Explicit representation of transient flow in the Opalinus Clay requires the use of FRAC3DVS.
	OP3 Advection / dispersion	✓		Modelled explicitly.
	OP4 Aqueous diffusion	✓		Modelled explicitly.
	OP5 Long-term changes (e.g. due to erosion of overburden)	○		Long-term changes in physical and chemical properties of the transport paths are not modelled using PICNIC, but significant effects of, for example, uplift and erosion are ruled out within the one million year period of primary interest in the safety assessment.

Tab. A8.2.4: (Cont.)

Super-FEPs	Safety-relevant aspects to be represented by models	Model features: Phenomena in a single leg	Model features: Network structure and properties	Explanatory comments
		Opalinus Clay and confining units		
B.6.1.a Length of vertical transport path from emplacement tunnels to overlying and underlying formations	**OP6** Transport paths provided by the Opalinus Clay and confining units		✓	The situation of homogeneous Opalinus Clay can be modelled by using a single leg, with advective / dispersive / diffusive transport only.
B.6.2 Geochemical immobilisation and retardation in the Opalinus Clay and confining units	**OP7** Linear, equilibrium sorption	✓		Sorption constants input as parameter values.
	OP8 Immobilisation processes	●		Irreversible immobilisation processes not modelled, but omission is conservative.
B.6.3 Homogeneity	**OP9** Transport paths provided by transmissive discontinuities, faults and repository induced fractures in the clay		✓	The situation of a transmissive feature affecting a part of the near-field release can be modelled by introducing a second leg, with advective / dispersive / diffusive transport along the feature, and matrix diffusion into the adjoining undisturbed rock.
B.6.4 Migration of high-pH plume from ILW backfill into Opalinus Clay	**OP10** The depth of migration, and associated physical and chemical changes in the clay	○		The migration of high-pH plume from ILW backfill into Opalinus Clay must be evaluated separately. Transport properties appropriate to Opalinus Clay affected by such a plume could be input, if required, as parameter values for all or part of the Opalinus Clay.
B.6.5 Radionuclide transport through the confining units and regional aquifers	**OP11** Transport paths provided by the confining units and regional aquifers		✓	Radionuclide transport through the confining units and regional aquifers can either be conservatively neglected, or modelled by choosing an appropriate network of legs to represent transport paths through these features.
		The barrier system (general)		
B.7.1 The migration of repository induced gas	**BS1** Gas dissolution and diffusion in the Opalinus Clay (incl. tunnel EDZs)	►	►	No transport of radionuclides in volatile form considered (see Gas Model).
	BS2 Capillary leakage in the Opalinus Clay	►	►	See above.
	BS3 Pathway dilation in the Opalinus Clay	►	►	See above.

Tab. A8.2.4: (Cont.)

Super-FEPs	Safety-relevant aspects to be represented by models	Model features: Phenomena in a single leg	Model features: Network structure and properties	Explanatory comments
The barrier system (general)				
	BS4 Porewater displacement in the Wedelsandstein	►	►	See above.
	BS5 Gas dissolution and diffusion in the low-permeability upper confining units	►	►	See above.
	BS6 Capillary leakage through low-permeability upper confining units	►	►	See above.
B.7.2 Future human actions	**BS9** Abandonment of repository before backfilling / sealing	○	○	The nature and timing of future human actions cannot be evaluated using PICNIC. The consequences of hypothetical actions that may influence the repository system can, however, be bounded in some cases (e.g. the possibility of the repository being abandoned before it is backfilled and sealed can be modelled by choosing an appropriate network of legs to represent transport paths through the tunnels / ramp / shaft / host rock, and selecting appropriate parameters for the transport / retention properties of backfilled tunnels / ramp / shaft / host rock, as well as flow).

Tab. A8.2.5: Super-FEPs, their safety-relevant aspects and the ways in which they are represented by the code TAME

Symbols: see Section A8.1.

Super-FEPs	Safety-relevant aspects to be represented by models	Phenomena included in TAME						Explanatory comments
		Interface with geosphere model	Conceptual model objects (CMOs)	Material flows	Contaminant trans-port / accumulation	Exposure modes	Receivers of dose / critical group	
The barrier system (general)								
B.7.2 Future human actions	**BS7** Borehole penetration of the repository	○						The nature and timing of future human actions cannot be evaluated using TAME. The consequences of hypothetical actions that may influence the repository system can, however, be bounded in some cases (e.g. the possibility of future drilling of a borehole inadvertently affecting the barrier system can be modelled by interfacing TAME directly with the near-field model).
	BS8 Drinking water extraction from the Malm aquifer	►						A simple drinking water model is used, based on a hypothetical pumping rate and capture efficiency of the deep well.
The surface environment								
B.8 Climatic evolution	**SE1** The nature and timing of climate change		○					Climatic evolution is not modelled directly. Rather, alternative future climate states can be postulated and assumed to exist throughout the modelled period.
B.9 Geomorphological evolution	**SE2** Properties of the exfiltration area for groundwater conveying radionuclides		○					Geomorphological evolution is not modelled directly. Rather, alternative geomorphological situations can be postulated and assumed to exist throughout the modelled period.

Tab. A8.2.6: Super-FEPs, their safety-relevant aspects and the ways in which they are represented by the code FRAC3DVS

Symbols: see Section A8.1.

Super-FEPs	**Safety-relevant aspects to be represented by models**	**Model features: Geometric features**	**Model features: Flow phenomena**	**Model features: Transport and retention phenomena**	**Explanatory comments**
SF / HLW near field					
B.4.2 Geochemical immobilisation and retardation in the near field	**NF4** Linear, equilibrium sorption			✓	Sorption coefficients used to calculate retardation factors, which are input as FRAC3DVS parameters.
B.4.7 Hydraulic transport characteristics of bentonite	**NF14** Stationary flow		✓		Can be represented by FRAC3DVS; the hydraulic conductivity of the bentonite is, however, set to zero in all assessment cases.
	NF15 Transient flow		✓		See above.
	NF16 Advection / dispersion			✓	See above.
	NF17 Aqueous diffusion			✓	Aqueous diffusion is assumed to convey radionuclides across the bentonite buffer; element-specific diffusion coefficients are input as parameter values.
Opalinus Clay and confining units					
B.6.1 Low groundwater flow rate through undisturbed Opalinus Clay	**OP1** Stationary flow		✓		Determined by hydraulic conductivity and hydraulic head boundary conditions.
	OP2 Transient flow		✓		Time dependent hydraulic head boundary conditions can be imposed to model transient effects (e.g. due to gas pressure build-up in the near field, tunnel convergence and ice loads).
	OP3 Advection / dispersion			✓	Aqueous diffusion, together with some advection / dispersion, is assumed to convey radionuclides across the Opalinus Clay and confining units.
	OP4 Aqueous diffusion			✓	
	OP5 Long-term changes (e.g. due to erosion of overburden)			○	Long-term changes in physical and chemical properties of the transport paths are not modelled using PICNIC, but significant effects of, for example, uplift and erosion are ruled out within the one million year period of primary interest in the safety assessment.

Tab. A8.2.6: (Cont.)

Super-FEPs	Safety-relevant aspects to be represented by models	Model features			Explanatory comments
		Geometric features	Flow phenomena	Transport and retention phenomena	
Opalinus Clay and confining units					
B.6.1.a Length of vertical transport path from emplacement tunnels to overlying and underlying formations	**OP6** Transport paths provided by the Opalinus Clay and confining units	✓			Directly affects geometry of modelled domain.
B.6.2 Geochemical immobilisation and retardation in the Opalinus Clay and confining units	**OP7** Linear, equilibrium sorption			✓	Sorption coefficients used to calculate retardation factors, which are input as FRAC3DVS parameters.
	OP8 Immobilisation processes			●	Irreversible immobilisation processes not modelled, but omission is conservative.
B.6.3 Homogeneity	**OP9** Transport paths provided by transmissive discontinuities, faults and repository induced fractures in the clay	✓			Homogeneity of the Opalinus Clay is assumed in modelling this as a single matrix zone with no transmissive discontinuities. Transmissive discontinuities and multiple matrix zones with different properties can be included as necessary.

Tab. A8.2.7: Super-FEPs, their safety-relevant aspects and the ways in which they are represented by the Gas Model

Symbols: see Section A8.1.

Super-FEPs	Safety-relevant aspects to be represented by models	Model features: Pressure evolution and gas migration	Model features: Release of volatile ^{14}C in the gas phase	Explanatory comments
SF				
B.1.1 Quantities and burnup of fuel and associated radionuclide inventories, including the instant release fraction (IRF)	**SF1** Waste inventory in a single package and number of packages	✓	✓	Inventory partially represented by model (^{14}C only); number of SF packages affects gas generation rate.
	SF2 Partitioning between fuel matrix, cladding and IRF		✓	See above.
	SF3 ^{14}C in organic and inorganic form upon release		✓	See above.
	SF4 Proportion of organic ^{14}C in volatile form upon release		✔	All organic ^{14}C assumed to be released in volatile form.
B.1.2 Corrosion of cladding	**SF5** Corrosion rate		✔	Directly provides input parameter.
B.1.4 Dissolution of fuel matrix	**SF7** Dissolution rate		✔	Directly provides input parameter.
HLW glass				
B.2.1 Quantities of glass and associated radionuclide inventories	**HL1** Waste inventory in a single package and number of packages	✓		It is assumed that radionuclides originating from the HLW near field are not released and transported in the gas phase. Gas generation in the HLW near field does, however, contribute to overall gas generation in the repository and thus provides input to the Gas Model.
SF / HLW canisters				
B.3.5 Breaching of steel canisters	**CN2** Time of occurrence of breaching		✔	Time of breaching (containment) time is input as a parameter value.
B.3.6 Gas generation by steel canister corrosion	**CN3** Gas generation rate for SF / HLW	✔		Directly provides input parameter.

Tab. A8.2.7: (Cont.)

Super-FEPs	**Safety-relevant aspects to be represented by models**	**Model features** **Pressure evolution and gas migration**	**Model features** **Release of volatile ^{14}C in the gas phase**	**Explanatory comments**
SF / HLW near field				
B.4.1 The long resaturation time of the repository and its surroundings	**NF1** The rate of the resaturation process	✓		While gas pressure in the repository is below the formation pore pressure of 6.5 MPa, slow inflow of water from the Opalinus Clay occurs and water saturation in the emplacement tunnels gradually increases.
B.4.7.1 Gas transport characteristics of bentonite	**NF21** Dilatant gas pathway formation (SF / HLW near field)	✓		Assumption underlying calculation of gas pressure buildup.
	NF22 Gas dissolution and diffusion	✔		Directly provides input parameters.
ILW				
B.3.1 Quantities of waste and associated radionuclide inventories	**IL1** Waste inventory in a single package and number of packages	✓	✓	Directly provides input parameters (ILW inventory affects gas generation rate and provides inventories of radionuclides that form volatile species).
B.3.4 Gas generation rates for ILW	**IL6** Gas generation rates for ILW	✔		Directly provides input parameter.
B.4.8 Hydraulic and gas transport characteristics ILW near field	**IL8** Gas dissolution and diffusion	✔		Explicitly included process.
	IL9 Porewater displacement by gas	✔		Explicitly included process.
Tunnels / ramp / shaft and seals				
B.5.2 The seals and the surrounding rock	**TS6** Formation of dilatant gas pathways through the sealing zone	✓		Process implicitly considered in a separate calculational case by increasing the total length of the ILW emplacement tunnels from 180 m to 360 m with the purpose to include the additional gas storage volume available in the Operations Tunnel following gas escape through the ILW tunnel plugs (incl. EDZ).
Opalinus Clay and confining units				
B.6.1.a Length of vertical transport path from emplacement tunnels to overlying and underlying formations	**OP6** Transport paths provided by the Opalinus Clay and confining units	✓		Path length affects capillary leakage of gas (and hence radionuclides as volatile species) through Opalinus Clay via the parameter "distance over which hydraulic gradient is maintained". It also affects the amount of gas that can be stored in the Opalinus Clay.

Tab. A8.2.7: (Cont.)

Super-FEPs	Safety-relevant aspects to be represented by models	Model features		Explanatory comments
		Pressure evolution and gas migration	Release of volatile ^{14}C in the gas phase	
The barrier system (general)				
B.7.1 The migration of repository induced gas	**BS1** Gas dissolution and diffusion in the Opalinus Clay (incl. tunnel EDZs)	✓		Explicitly included process.
	BS2 Capillary leakage in the Opalinus Clay	✓		Explicitly included process.
	BS3 Pathway dilation in the Opalinus Clay	✓		Explicitly included process.
	BS4 Porewater displacement in the Wedelsandstein	✓		Explicitly included process.
	BS5 Gas dissolution and diffusion in the low-permeability upper confining units	✓		Explicitly included process.
	BS6 Capillary leakage through low-permeability upper confining units	✓		Explicitly included process, although this process does not contribute to gas transport in practice because the threshold pressure for capillary leakage through low-permeability upper confining units is not reached.

Appendix 9: Representation of Super-FEPs in the assessment cases and codes

A9.1 Introduction

The purpose of this appendix is to combine information from Appendix 5 on the significance and treatment in assessment cases of uncertainties and design / system options associated with specific Super-FEPs (Tab. A5.2.1) and information from Appendix 8 on the qualification of codes to represent safety-relevant aspects of the Super-FEPs that can be affected by these uncertainties and design / system options. This result is the overview of the repesentaton of Super-FEPs and their safety-relevant aspects in the assessment cases and codes given in Tab. A9.1.1.

The first two columns in Tab. A9.1.1 correspond to those in Tab. 5.1-1. The next two columns are based on information from Tab. A5.2.1. The third column shows the realistaions of the safety-relevant aspects of the Super-FEPs that arise as a result of the uncertainties and design / system options. For conciseness, the identifiers used in Tab. A5.2.1 rather than full text descriptions are used. An (R) following the identifier denotes the Reference Case realisation of an uncertainty or design / system options. (A) indicates an alternative realisation. The fourth column shows the assessment cases that include these realisations. In this column, the term "Other similar cases" means cases that treat this particular safety-relevant aspect in the same way as the Reference Case.

The next seven columns are equivalent to the right-most seven columns in Tab. 5.1-1 and show how the safety-relevant aspects are represented in the safety assessment computer codes. The following symbols are used in these.

✓ *A safety-relevant aspect of a Super-FEP is fully represented by a code*: either a process modelled explicitly, or the magnitude, timing, rate or spatial extent of a process, or the performance of a feature, directly determines one or more input parameters.

✓ *A safety-relevant aspect of a Super-FEP is only partially represented by a code*: either only some limited aspect of a feature is modelled explicitly, or assumptions regarding the (non-negligible) impact of a process on the properties of the system are be built into the code, but no parameters values are directly affected that can be used to vary these assumptions.

○ *A safety-relevant aspect of a Super-FEP is not represented by a code, but gives rise time-dependent system properties that can be treated indirectly*: parameter sets can be chosen that represent steady-state system properties corresponding, for example, to the end-state of the system once the process is complete or to one of a number of possible transient states.

Where a code of the Reference Model Chain cannot treat a safety-relevant aspect of a Super-FEP, or incorporates an assumption of negligible impact, this is indicated using the symbol ► in the table. Brackets around a tick or open circle indicate that this was not the code used in practice to model the assessment cases indicated in the fourth column.

Finally, in the right-most two columns, the following symbols are used.

A *Arguments exist for omission*: either (i), significant effects can be ruled out by complementary studies, (ii), effects are intrinsically favourable to safety and the aspect can be conservatively omitted, or (iii) if the aspect is omitted, parameters can be chosen to ensure that calculations err on the side of pessimism.

R One of the codes is **r**eplaced by a simple analytical calculation.

Tab. A9.1.1: Overview of the representation of Super-FEPs and their safety-relevant aspects in the assessment cases and codes

Super-FEPs	Safety-relevant aspects represented by models	Realisations of safety-relevant aspects (R) = Reference (A) = Alternative	Assessment cases incorporating reference and alternative realisations	Reference Chain					Alternative codes		Analytical calculations	Arguments for omission
				STMAN codes								
				SPENT	STRENG	STALLION	PICNIC	TAME	FRAC3DVS	Gas Model		
SF												
B.1.1 Quantities and burnup of fuel and associated radionuclide inventories, including the instant release fraction (IRF)	**SF1** Waste inventory in a single package and number of packages	B.1.1.1(R), B.1.1.2(R), B.1.1.3(R)	RC (1.1a) and other similar cases	✓						(✓)		
		B.1.1.1(A)	5.1a									
		B.1.1.2(A), B.1.1.3(A)	1.1b									
	SF2 Partitioning between fuel matrix, cladding and IRF	B.1.1.2(R)	RC (1.1a) and other similar cases	✓						(✓)		
		B.1.1.2(A)	1.1b									
	SF3 ^{14}C in organic and inorganic form upon release	B.1.1.2a(R)	RC (1.1a) and other similar cases	✓						(✓)		
		B.1.1.2a(A)	1.1k									
	SF4 Proportion of organic ^{14}C in volatile form upon release	See "The migration of repository induced gas", B.7.1		►						✓		
B.1.2 Corrosion of cladding	**SF5** Corrosion rate	B.1.2(R)	RC (1.1a) and other similar cases	✓						(✓)		
		B.1.2(A)	4.9a									
B.1.3 Breaching of cladding	**SF6** Timing	B.1.3(R)	Does not affect containment in any assessment cases	(✓)						(✓)		A
B.1.4 Dissolution of fuel matrix	**SF7** Dissolution rate	B.1.4.1(R), B.1.4.2(R)	RC (1.1a) and other similar cases	✓								
		B.1.4.1(A)	1.2a									
		B.1.4.2(A)	4.3a-b									
B.1.5 Criticality	**SF8** None – ruled out by design and supporting calculations	None	Not considered in any assessment cases									A

Tab. A9.1.1: (Cont.)

Super-FEPs	Safety-relevant aspects represented by models	Realisations of safety-relevant aspects (R) = Reference (A) = Alternative	Assessment cases incorporating reference and alternative realisations	Reference Chain – STMAN codes – SPENT	Reference Chain – STMAN codes – STRENG	Reference Chain – STMAN codes – STALLION	Reference Chain – PICNIC	Reference Chain – TAME	Alternative codes – FRAC3DVS	Alternative codes – Gas Model	Analytical calculations	Arguments for omission
HLW glass												
B.2.1 Quantities of glass and associated radionuclide inventories	**HL1** Waste inventory in a single package and number of packages	B.2.1(R)	RC (1.1a) and other similar cases		✓					(✓)		
B.2.2 Dissolution rate of glass	**HL2** Dissolution rate	B.2.2(R)	RC (1.1a) and other similar cases		✓							
		B.2.2(A)	1.1e									
SF / HLW canisters												
B.3.5 Breaching of steel canisters	**CN1** Distribution of breaching times	B.3.5.3(R)	Not included any assessment cases									A
	CN2 Time of occurrence of breaching	B.3.5.1(R), B.3.5.2(R)	RC (1.1a) and other similar cases	✓	✓					(✓)		
		B.3.5.1(A)	1.1c									
B.3.6 Gas generation by steel canister corrosion	**CN3** Gas generation rate for SF / HLW	See "The migration of repository induced gas", B.7.1		►	►					✓		
B.3.7 Canister material	**CN4** Time of occurrence of breaching (time of occurrence affected by canister material)	B.3.7(R)	RC (1.1a) and other similar cases	✓	(✓)							
		B.3.7(A)	5.3a									
	CN5 Presence of initial defects (likelihood affected by canister material)	B.3.7(A)	5.3b-c	✓	(✓)							

Tab. A9.1.1: (Cont.)

Super-FEPs	Safety-relevant aspects represented by models	Realisations of safety-relevant aspects (R) = Reference (A) = Alternative	Assessment cases incorporating reference and alternative realisations	Reference Chain: STMAN codes: SPENT	STRENG	STALLION	PICNIC	TAME	Alternative codes: FRAC3DVS	Gas Model	Analytical calculations	Arguments for omission
SF / HLW near field												
B.4.1 The long resaturation time of the repository and its surroundings	**NF1** The rate of the resaturation process	B.4.1(R)	Not relevant in any assessment cases	(✓)	(✓)					(✓)		A
B.4.2 Geochemical immobilisation and retardation in the near field	**NF2** Solubility limitation (reservoir)	B.4.2.1(R)	RC (1.1a) and other similar cases	✓	✓							
		B.4.2.1(A)	1.1d, 1.1i									
	NF3 Solubility limitation (buffer)	B.4.2.1(R)	RC (1.1a) and other similar cases	✓	✓							
		B.4.2.1(A)	1.1d, 1.1i									
	NF4 Linear, equilibrium sorption	B.4.2.1(R)	RC (1.1a) and other similar cases	✓	✓					(✓)		
		B.4.2.1(A)	1.1d, 1.1i									
	NF5 Colloid filtration by bentonite	B.4.2.1a(R)	RC (1.1a) and other similar cases	✓	✓							
	NF6 The extent of co-precipitation with secondary minerals	B.4.2.2(R)	Co-precipitation of Ra taken into account in all relevant cases	✓	✓							
	NF7 The extent of sorption on canister corrosion products	B.4.2.3(R)	Process conservatively omitted in all cases									A
	NF8 The effects on solubility limitation of the natural concentrations of isotopes	B.4.2.4(R)	Effects conservatively omitted in all cases									A

Tab. A9.1.1: (Cont.)

Super-FEPs	Safety-relevant aspects represented by models	Realisations of safety-relevant aspects (R) = Reference (A) = Alternative	Assessment cases incorporating reference and alternative realisations	Reference Chain: STMAN codes: SPENT	Reference Chain: STMAN codes: STRENG	Reference Chain: STMAN codes: STALLION	Reference Chain: PICNIC	Reference Chain: TAME	Alternative codes: FRAC3DVS	Alternative codes: Gas Model	Analytical calculations	Arguments for omission
SF / HLW near field												
B.4.3 Migration of radio-lytic oxidants generated at SF surfaces into bentonite buffer	**NF9** Proportion of the buffer affected and the magnitude of the effects on geochemical immobilisation	B.4.3(R)	RC (1.1a) and other similar cases	○								
		B.4.3(A)	4.4a									
B.4.4 Thermal alteration of the bentonite buffer adjacent to the SF / HLW canisters	**NF10** Proportion of the buffer affected and the magnitude of the effects on buffer transport properties	B.4.4(R)	RC (1.1a) and other similar cases	○	○							
		B.4.4(A)	1.3a									
B.4.5 Transport resistances provided by internal spaces (fractures) within the waste forms, by the breached SF / HLW canisters and by corrosion products	**NF11** The magnitude of transport resistance of initial defects	B.4.5(R)	See "Canister material", B.3.7	✓	(✓)							
	NF12 The magnitude and time-dependence of other transport resistances	B.4.5(R)	Conservatively omitted in all cases									A
B.4.6 Tunnel liner	**NF13** Requirement for a liner	B4.6(R)	Feature omitted in all cases									A
B.4.7 Hydraulic transport characteristics of bentonite	**NF14** Stationary flow	Assumed to be negligible	Process omitted in all assessment cases						(✓)			
	NF15 Transient flow	As above	As above						(✓)			
	NF16 Advection / dispersion	As above	As above						(✓)			

Tab. A9.1.1: (Cont.)

Super-FEPs	Safety-relevant aspects represented by models	Realisations of safety-relevant aspects (R) = Reference (A) = Alternative	Assessment cases incorporating reference and alternative realisations	Reference Chain					Alternative codes		Analytical calculations	Arguments for omission
				STMAN codes			PICNIC	TAME	FRAC3DVS	Gas Model		
				SPENT	STRENG	STALLION						
SF / HLW near field												
B.4.7 Hydraulic transport characteristics of bentonite	**NF17** Aqueous diffusion	Assumed to be the dominant transport process	RC (1.1a) and other similar cases	✓	✓				(✓)			
	NF18 Effective flow rate at outer boundary	Concept used in modelling the transport of radionuclides away from the bentonite	RC (1.1a) and other similar cases	✓	✓							
	NF19 Compaction of bentonite by tunnel convergence	B.4.7(R)	RC (1.1a) and other similar cases	○	○							
B.4.7.1 Gas transport characteristics of bentonite	**NF20** Gas-induced release of dissolved radionuclides	B.4.7.1(R)	RC (1.1a) and other similar cases	○								
		B.4.7.1(R)	1.8a									
	NF21 Dilatant gas pathway formation (SF / HLW near field)	See "The migration of repository induced gas", B.7.1		►	►					✓		
	NF22 Gas dissolution and diffusion	See "The migration of repository induced gas", B.7.1		►	►					✓		
ILW												
B.3.1 Quantities of waste and associated radionuclide inventories	**IL1** Waste inventory in a single package and number of packages	B.3.1(R)	RC (1.1a) and other similar cases			✓				(✓)		
		B.3.1(A)	5.2a									
B.3.2 Breaching of ILW steel drums and emplacement containers	**IL2** Time of occurrence of breaching	B.3.2(R)	RC (1.1a) and other similar cases			✓						

Tab. A9.1.1: (Cont.)

Super-FEPs	Safety-relevant aspects represented by models	Realisations of safety-relevant aspects (R) = Reference (A) = Alternative	Assessment cases incorporating reference and alternative realisations	Reference Chain: STMAN codes: SPENT	Reference Chain: STMAN codes: STRENG	Reference Chain: STMAN codes: STALLION	Reference Chain: PICNIC	Reference Chain: TAME	Alternative codes: FRAC3DVS	Alternative codes: Gas Model	Analytical calculations	Arguments for omission
ILW												
B.3.3 Corrosion / dissolution of ILW	**IL3** Corrosion rate of metallic components	B.3.3(R)	Delayed release conservatively neglected			(✓)						A
	IL4 Corrosion / dissolution rate of remaining ILW components	B.3.3(R)	As above			(✓)						A
B.3.3.2 Immobilisation and retardation in the ILW near field	**IL5** Linear, equilibrium sorption and solubility limitation	B.3.3.2(R)	RC (1.1a) and other similar cases			✓						
		B.3.3.2(A)	1.1d									
			1.1i									
			4.4a									
B.3.4 Gas generation	**IL6** Gas generation rates for ILW	See "The migration of repository induced gas", B.7.1				▶				✓		
B.4.8 Hydraulic and gas transport characteristics of the ILW near field	**IL7** Effective flow rate at outer boundary	Concept used in modelling the transport of radionuclides away from the bentonite	RC (1.1a) and other similar cases			✓						
	IL8 Gas dissolution and diffusion	See "The migration of repository induced gas", B.7.1				▶				✓		
	IL9 Porewater displacement by gas	B.4.8(R)	RC (1.1a) and other similar cases			▶ or ○				✓		
		B.4.8(A)	1.8b									
B.3.3.1 Compaction of waste / mortar (see B.4.7)	**IL10** Timing if convergence arising from void reduction of breached, corroded canisters	B.3.3.1(A)	1.7a-b			○						

Tab. A9.1.1: (Cont.)

Super-FEPs	Safety-relevant aspects represented by models	Realisations of safety-relevant aspects (R) = Reference (A) = Alternative	Assessment cases incorporating reference and alternative realisations	Reference Chain					Alternative codes		Analytical calculations	Arguments for omission
				STMAN codes								
				SPENT	STRENG	STALLION	PICNIC	TAME	FRAC3DVS	Gas Model		
ILW												
B.3.3.3 The long resaturation time of the ILW tunnels	**IL11** The rate of the resaturation process	B.3.3.3(R)	RC (1.1a) and other similar cases			✓						
Tunnels / ramp / shaft and seals												
B.5.1 Low groundwater flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones (EDZs)	**TS1** Transport paths provided by the tunnels / ramp / shaft	B.5.1.1(R)	RC (1.1a) and other similar cases				✓					
		B.5.1.1(A)	1.6a-b									
	TS2 Stationary flow	As above	As above				✓					
	TS3 Transient flow	B.5.1.2(R), B.5.1.3(R)	RC (1.1a) and other similar cases				○					
		B.5.1.2(A), B.5.1.3(A)	1.7b									
			1.8a-b									
	TS4 Advection / dispersion	Transport processes along tunnels / ramp / shaft	All cases involving transport along tunnels / ramp / shaft				✓					
	TS5 Aqueous diffusion	As above	As above				✓					
B.5.2 The seals and the surrounding rock (see also "The creation of gas pathways", B.7.1.1)	**TS6** Formation of dilatant gas pathways through the sealing zone	See "The migration of repository induced gas", B.7.1								(✓)		
	TS7 Transport resistance of the seals and the surrounding rock	B.5.2(R)	RC (1.1a) and other similar cases				✓					
		B.5.2(A)	4.5a-b									

Tab. A9.1.1: (Cont.)

Super-FEPs	Safety-relevant aspects represented by models	Realisations of safety-relevant aspects (R) = Reference (A) = Alternative	Assessment cases incorporating reference and alternative realisations	Reference Chain: STMAN codes: SPENT	Reference Chain: STMAN codes: STRENG	Reference Chain: STMAN codes: STALLION	Reference Chain: PICNIC	Reference Chain: TAME	Alternative codes: FRAC3DVS	Alternative codes: Gas Model	Analytical calculations	Arguments for omission
Opalinus Clay and confining units												
B.6.1 Low groundwater flow rate through undisturbed Opalinus Clay (see also "Low ground-water flow rate along the sealed tunnels / ramp / shaft, and through the surrounding excavation disturbed zones", B.5.1)	**OP1** Stationary flow	B.6.1.1(R)	RC (1.1a) and other similar cases				✓		(✓)			
		B.6.1.1(A)	1.1f-g									
			4.1a									
			4.7a-c									
			4.8a									
	OP2 Transient flow	B.5.1.2(R), B.5.1.3(R), B.6.1.2(R)	RC (1.1a) and other similar cases				▶ or ○		✓			
		B.5.1.2(A), B.5.1.3(A), B.6.1.2(A)	1.4a									
			1.7a-b									
			1.8a-b									
	OP3 Advection / dispersion	Transport processes	RC (1.1a) and other similar cases				✓		✓			
	OP4 Aqueous diffusion	As above	RC (1.1a) and other similar cases				✓		✓			
	OP5 Long-term changes (e.g. due to erosion of overburden)	B.6.1.3	Not included in evaluation of assessment cases				✓		✓			A
B.6.1a Length of vertical transport path from emplacement tunnels to overlying and underlying formations	**OP6** Transport paths provided by the Opalinus Clay and confining units	B.6.1a(R)	RC (1.1a) and other similar cases				✓		✓	(✓)		
		B.6.1a(A)	4.11a									

Tab. A9.1.1: (Cont.)

Super-FEPs	Safety-relevant aspects represented by models	Realisations of safety-relevant aspects (R) = Reference (A) = Alternative	Assessment cases incorporating reference and alternative realisations	Reference Chain					Alternative codes		Analytical calculations	Arguments for omission
				STMAN codes								
				SPENT	STRENG	STALLION	PICNIC	TAME	FRAC3DVS	Gas Model		
Opalinus Clay and confining units												
B.6.2 Geochemical immobilisation and retardation in the Opalinus Clay and confining units	**OP7** Linear, equilibrium sorption	B.6.2.1(R)	RC (1.1a) and other similar cases				✓		(✓)			
		B.6.2.1(A)	1.1h-j									
			4.10a									
	OP8 Immobilisation processes	B.6.2.2(R)	Conservatively omitted in all cases									A
B.6.3 Homogeneity	**OP9** Transport paths provided by transmissive discontinuities, faults and repository induced fractures in the clay	B.6.3.1(R), B.6.3.2(R)	Discontinuities absent in RC (1.1a) and other similar cases				✓		(✓)			
		B.6.3.1(A), B.6.3.2(A)	4.2a-f									
B.6.4 Migration of high pH plume from ILW backfill into Opalinus Clay	**OP10** The depth of migration, and associated physical and chemical changes in the clay	Not considered	None				(○)					A
B.6.5 Radionuclide transport through the confining units and regional aquifers	**OP11** Transport paths provided by the confining units and regional aquifers	B.6.5(R)	RC (1.1a) and other similar cases				✓					
		B.6.5(A)	1.5a-b									

Tab. A9.1.1: (Cont.)

Super-FEPs	Safety-relevant aspects represented by models	Realisations of safety-relevant aspects (R) = Reference (A) = Alternative	Assessment cases incorporating reference and alternative realisations	Reference Chain					Alternative codes		Analytical calculations	Arguments for omission
				STMAN codes			PICNIC	TAME	FRAC3DVS	Gas Model		
				SPENT	STRENG	STALLION						
The barrier system (general)												
B.7.1 The migration of repository induced gas	**SF2, SF4, CN3, NF21, NF22, IL6, IL8, TS6**	B.7.1.1(R), B.7.1.2(R), B.7.1.3(R), B.7.1.4(R), B.7.1.5(R), B.7.1.6(R)	Aspects not included in RC (1.1a) and other similar cases				▶			✓		
		B.7.1.1(A), B.7.1.6(A)	2.1a-c									
		B.7.1.2(A), B.7.1.6(A)	2.2a-c									
		B.7.1.4(A), B.7.1.6(A)	4.6a-c									
	BS1 Gas dissolution and diffusion in the Opalinus Clay (incl. tunnel EDZs)	As above	As above				▶			✓		
	BS2 Capillary leakage in the Opalinus Clay	As above	As above				▶			✓		
	BS3 Pathway dilation in the Opalinus Clay	As above	As above				▶			✓		
	BS4 Porewater displacement in the Wedelsandstein	As above	As above				▶			✓		
	BS5 Gas dissolution and diffusion in the low-permeability upper confining units	As above	As above				▶			✓		
	BS6 Capillary leakage through low-permeability upper confining units	As above	As above				▶			✓		

Tab. A9.1.1: (Cont.)

Super-FEPs	Safety-relevant aspects represented by models	Realisations of safety-relevant aspects (R) = Reference (A) = Alternative	Assessment cases incorporating reference and alternative realisations	Reference Chain					Alternative codes		Analytical calculations	Arguments for omission
				STMAN codes								
				SPENT	STRENG	STALLION	PICNIC	TAME	FRAC3DVS	Gas Model		
The barrier system (general)												
B.7.2 Future human actions	**BS7** Borehole penetration of the repository	B.7.2.1(R)	Event not included in RC (1.1a) and other similar cases	○	○	○		○				
		B.7.2.1(A)	3.1a-g									
	BS8 Drinking water extraction from the Malm aquifer	B.7.2.2(R)	Process not included in RC (1.1a) and other similar cases					▶			R	
		B.7.2.2(A)										
	BS9 Abandonment of repository before backfilling / sealing	B.7.2.3(R)	Event not included RC (1.1a) and other similar cases				○					
			3.3a									
The surface environment												
B.8 Climatic evolution	**SE1** The nature and timing of climate change	B.8(R)	The process not included in RC (1.1a and 6.2a) and other similar cases					○				
		B.8(A)	6.2b-d									
B.9 Geomorphological evolution	**SE2** Properties of the exfiltration area for groundwater conveying radionuclides	B.9(R)	RC (1.1a and 6.1a) and other similar cases					○				
		B.9(A)	6.1b-d									

The table shows that:

- Codes are available that are qualified to treat almost all of the safety-relevant aspects of the Super-FEPs that are listed in Table A5.2.1 of Appendix 5.
- Where the codes of the Reference Model Chain are not qualified to handle a Super-FEP (indicated by a right arrow), alternative codes (FRAC3DVS and the Gas Model) are available that are in most cases qualified to do so.
- Where no qualified code exists (e.g. in the case of criticality), significant effects are ruled out by supplementary studies, or the safety-relevant aspects of the Super-FEP can be omitted on the grounds of conservatism (as in the case of sorption on canister corrosion products).

In addition:

- Where a safety-relevant aspect of a Super-FEP is modelled explicitly, or the magnitude, timing, rate or spatial extent of a process, or the performance of a feature, directly determines one or more input parameters (as indicated by a bold tick), different realisations can be achieved by changing the affected parameters.
- Where assumptions regarding the (non-negligible) impact of a Super-FEP on the properties of the system are built into the code, but no parameters values are directly affected (as indicated by a non-bold tick), these assumptions (or at least their conservatism) are generally well supported, and different realisations need not be considered.
- In some cases (indicated by open circles), the time-dependence of system properties associated with a Super-FEP cannot be directly represented by the code. Parameter sets can, however, be chosen for realisations that represent steady-state system properties corresponding, for example, to the end-state of the system once the process is complete or to one of a number of possible transient states.