EUROPEAN COMMISSION
Community research

PAMINA
Performance Assessment Methodologies in Application to Guide the Development of the Safety Case

(**Contract Number: FP6-036404**)

Specifications for an Integrated Radionuclide Release Code (IRRC) in Support of a Probabilistic Safety Assessment for Swiss Nuclear Waste Repositories: FEP–Screening Report

MILESTONE (N°: M2.2.E.2)

[Nagra NAB 07-38]

Author(s): **Peter Gribi (*S+R Consult GmbH, Baden)***

Gerhard Mayer, Joachim Poppei and Georg Resele (*Colenco Power Engineering AG, Baden)*

Jürg Schneider (*NAGRA*), Christian Sprecher (*Sprecher Consulting GmbH, Wettingen)*

Date of issue of this report : **31/12/2007**

Start date of project : **01/10/2006** Duration : 36 Months

Project co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	X
RE	Restricted to a group specified by the partners of the [PAMINA] project	
CO	Confidential, only for partners of the [PAMINA] project	

Foreword

The work presented in this report was developed within the Integrated Project PAMINA: **P**erformance **A**ssessment **M**ethodologies **IN** **A**pplication to Guide the Development of the Safety Case. This project is part of the Sixth Framework Programme of the European Commission. It brings together 25 organisations from ten European countries and one EC Joint Research Centre in order to improve and harmonise methodologies and tools for demonstrating the safety of deep geological disposal of long-lived radioactive waste for different waste types, repository designs and geological environments. The results will be of interest to national waste management organisations, regulators and lay stakeholders.

The work is organised in four Research and Technology Development Components (RTDCs) and one additional component dealing with knowledge management and dissemination of knowledge:

- In RTDC 1 the aim is to evaluate the state of the art of methodologies and approaches needed for assessing the safety of deep geological disposal, on the basis of comprehensive review of international practice. This work includes the identification of any deficiencies in methods and tools.

- In RTDC 2 the aim is to establish a framework and methodology for the treatment of uncertainty during PA and safety case development. Guidance on, and examples of, good practice will be provided on the communication and treatment of different types of uncertainty, spatial variability, the development of probabilistic safety assessment tools, and techniques for sensitivity and uncertainty analysis.

- In RTDC 3 the aim is to develop methodologies and tools for integrated PA for various geological disposal concepts. This work includes the development of PA scenarios, of the PA approach to gas migration processes, of the PA approach to radionuclide source term modelling, and of safety and performance indicators.

- In RTDC 4 the aim is to conduct several benchmark exercises on specific processes, in which quantitative comparisons are made between approaches that rely on simplifying assumptions and models, and those that rely on complex models that take into account a more complete process conceptualization in space and time.

The work presented in this report was performed in the scope of RTDC 2.

All PAMINA reports can be downloaded from http://www.ip-pamina.eu.

Arbeitsbericht NAB 07-38

PAMINA RTDC-2 Milestone M2.2.E.2

Specifications for an Integrated Radionuclide Release Code (IRRC) in Support of a Probabilistic Safety Assessment for Swiss Nuclear Waste Repositories:

FEP-Screening Report

December 2007

Nationale Genossenschaft
für die Lagerung
radioaktiver Abfälle

Hardstrasse 73
CH-5430 Wettingen
Telefon 056-437 11 11

www.nagra.ch

Arbeitsbericht NAB 07-38

PAMINA RTDC-2
Milestone M2.2.E.2

Specifications for an Integrated Radionuclide Release Code (IRRC) in Support of a Probabilistic Safety Assessment for Swiss Nuclear Waste Repositories:

FEP-Screening Report

December 2007

KEYWORDS
FEP-screening, safety-relevant phenomena, probabilistic safety analysis, Probabilistische Sicherheitsanalyse, PSA, PSA project, PSA Projekt, ergänzende Prozessmodellierung.

Nationale Genossenschaft
für die Lagerung
radioaktiver Abfälle

Hardstrasse 73
CH-5430 Wettingen
Telefon 056-437 11 11

www.nagra.ch

This report was prepared by a working group consisting of (in alphabetical order): Peter Gribi (S+R Consult GmbH, Baden), Gerhard Mayer, Joachim Poppei and Georg Resele (Colenco Power Engineering AG, Baden), Jürg Schneider (Nagra) and Christian Sprecher (Sprecher Consulting GmbH, Wettingen).

Table of Contents

List of Tables

1 Introduction

This report summarises the results of the FEP screening conducted by the working group "Ergänzende Prozessmodellierung"[1]. The objective of the working group was to identify and evaluate all potentially safety-relevant phenomena and their interdependencies as a preliminary step to the development of the components of an Integrated Radionuclide Release Code (IRRC) in the framework of the project "Probabilistische Sicherheitsanalyse für geologische Tiefenlager".

The objective of the project "Probabilistische Sicherheitsanalyse für geologische Tiefenlager" is to develop a system of tools for the probabilistic safety analysis which takes the interactions between different parts of the repository system and between different phenomena into account. It is not the objective to improve the system understanding with respect to the impact of single phenomena and / or to develop the quantitative simulation of physical processes beyond the current state of the art.

The first activity of the working group was to generate a list of all phenomena considered to be worth of evaluation, based on the experience of the members of the working group from earlier long-term safety assessments for nuclear waste repositories, but clearly focussed on a deep geological repository for SF, vitrified HLW, and ILW (and L/ILW) in Opalinus Clay. This starting list is referred to as "list of candidate FEPs". It is given in Table 1. The subsequent evaluation of the candidate FEPs by the working group has finally led to a "list of accepted FEPs", i.e. a list of phenomena which are recommended to be modelled in the component codes of the IRRC. The "accepted FEPs" are listed in Table 2 (environmental processes) and Table 3 (radionuclide processes).

The list of accepted FEPs, resulting from the FEP-screening process, does not include any specifications of models or conceptual representations of the phenomena. Also, no criteria related to the feasibility or difficulty of implementing a phenomenon in a simulation model was applied in the evaluation. The sole criterion for screening-in a phenomenon in the "accepted" list was a possibly non-negligible impact on the long-term safety of the repositories at potential sites in Switzerland. The terms "safety relevant" or "potentially safety relevant", as used in this report, indicate that a FEP may have a significant impact on safety or repository performance, meaning that its relevance cannot a priory be excluded. While this was considered to be sufficient reason to include the phenomenon in the list of FEPs to be modelled, it does not mean that all accepted FEPs are in fact safety relevant. A better-founded judgment of the impact can only be expected after the safety analyses have been carried out. The main information sources for the assessment were the findings of the Project Opalinus Clay of Nagra (Nagra (2002a), and related published and unpublished reports).

The evaluation of the phenomena by the working group started – as mentioned above – from an **unbiased list of phenomena** and included a discussion of each phenomenon with respect to its potential quantitative impact on long-term safety. Basis of the discussion were the results and findings from earlier investigations and model calculations, mainly related to the Project Opalinus Clay. Where reported results and findings could directly be used for the judgement, the reference is given without citing the information itself. Where the working group judged the potential relevance of a phenomenon based on a specific assessment, this is either given in the text or in a separate memorandum. Where the working group considered a phenomenon to be

---

[1] The working group was initiated by Nagra on August 11, 2006 as a result of the pilot study "Probabilistische Sicherheitsanalyse" (see inside cover page). From October 2006 to February 2007, they have held 10 project meetings.

potentially relevant but judged the quantitative impact not to be sufficiently known to allow a definitive decision whether it should be included in the list of “accepted FEPs” or not, the group proposed complementary model calculations (process modelling) to improve the decision basis. Processes in the biosphere are not included in the evaluation.

The evaluation of the phenomena encompassed the following steps:

1. Identification of potentialy safety relevant phenomena for the “candidate FEP-list”[2]
2. Discussion of the phenomena with respect to
   - process understanding, evolution and possible consequences
   - relevance with regard to the Swiss repository types and host rock options (see below)
   - the possibility to rate (or exclude) the phenomenon based on fundamental principles
3. Judgement on the impact on long-term safty and the inclusion in the list of accepted FEPs

The evaluation was conducted for the following repository options:

- SF/HLW repository in Opalinus Clay,
- ILW and L/ILW repositories in Opalinus Clay,
- L/ILW repository in marls with limestone interbeds and
- L/ILW repository in Molasse.

The focus was on the first two options, i.e. on repositories in Opalinus Clay. The relevance for L/ILW- type repositories in other potential host rocks was also evaluated but this supplementary information will not be considered any further in the context of the IRRC model conceptu-alisation or the PSA-project.

This report is structured on the basis of Nagra (2002b) “FEP management for the Opalinus Clay safety assessment”. It is, however, not intended to supplement or expand the FEP management report (Nagra 2002b).

[2] without copying the phenomena directly from an existing FEP-list, e.g., from Nagra (2002b)

2 Discussion of potentially safety relevant phenomena

This chapter provides a description and discussion of all phenomena and processes, listed as candidate FEPs in Table 1 (see Chapter 3). Paragraphs are numbered according to the candidate FEP numbers in Table 1 and bear no relation to the hierarchy of chapters, subchapters or paragraphs of the report. A summary description, reflecting the present process understanding, is given for each phenomenon, together with an assessment of its potential impact on long-term safety. If this impact is considered to be negligible, the most important arguments for the judgement are given, incl. references to relevant reports (if applicable). The phenomena- and process descriptions are formulated with the objectives to 1) prevent ambiguities and avoid misunderstandings in the communication between the members of the project team, and 2) to provide keywords for the later conceptualisation of the phenomena in a numerical code. They are not intended to serve as comprehensive or exhaustive definitions of the listed phenomena.

The list of candidate FEPs in Table 1 includes all phenomena deemed worthy of discussion. Each is assigned to one of the three following groups (by analogy with Opalinus Clay FEP report, Nagra 2002b):

- phenomena related to **environmental processes**, i.e. to processes acting to change the characteristics of the repository over time (without consideration of the release and migration of radionuclides);
- phenomena related to **radionuclide processes**, i.e. to processes related to the release and migration of radionuclides within the repository system; and
- **special issues** related to alternative scenario classes[3], e.g. safety-relevant effects of human actions on the performance of the engineered and geological barriers.

The following sub-categories are considered for the phenomena related to environmental processes (coupled processes are allocated to the category considered most suitable):

- radiation-related processes;
- thermal processes;
- hydraulic and gas processes;
- mechanical processes;
- chemical and microbial processes; and
- flow influenced by Onsager processes.

For the radionuclide processes, the sub-categories are:

- radioactive inventory and decay;
- containment failure mechanisms;
- radionuclide mobilisation;
- transport of dissolved (non-volatile) radionuclides;
- transport of volatile radionuclides (^{14}C);
- radionuclide pathways through host rock and confining units;
- radionuclide pathways through access tunnel system; and
- radionuclide transport influenced by Onsager processes.

[3] These phenomena will not be included in the present phase of code development.

1. Environmental processes

1.1 Radiation related processes

1.1.1 Radiogenic heat generation

The radiogenic heat generation is independent of any influence from the repository and can be calculated externally (see Nagra (2002a), Figure 5.3-1 and Figure 5.4-1). It is limited to a relatively short time period (see phenomenon 1.2.1). The radiogenic heat generation of ILW and from L/ILW is very low and negligible.

The potential impact of radiogenic heat generation is covered by the following coupled processes which will be discussed below:

- thermo-hydraulic impacts: see 1.2.1 and 1.3.8
- impact on long-term properties of bentonite: see 1.2.2
- thermo-mechanical impacts: see 1.4.8.

1.1.2 Radiolysis

Radiolysis is the dissociation of molecules by radiation. In the context of nuclear waste disposal in deep geological repositories, radiolysis mainly affects water molecules and produces hydrogen and oxygen. The impact of the phenomenon on redox conditions is included in 1.5.1. Radiolytically generated oxidants may play an important role in SF dissolution (reference model for SF dissolution in Project Opalinus Clay, see Johnson & Smith 2000) and are considered in deriving SF dissolution rates (see 2.3.4). The impact on gas generation is included in 1.3.11.

No additional effort to assess the safety relevance of the phenomenon is considered to be necessary.

1.2 Thermal processes

1.2.1 Temperature evolution

The temperature evolution in a repository is the result of a number of different thermal processes including heat generation (e.g. radiogenic heat generation, see 1.1.1), heat conduction, heat convection and heat radiation. Thermal calculations are reported in Johnson et al. (2002). The conclusion from this study is that the temperature close to SF canisters exceeds 100°C for times up to 1'000 years. This could lead to isolated zones of thermally altered bentonite, but this effect is not considered to be safety-relevant (see 1.2.2). Moreover, it has been shown that the elevated temperatures in the Opalinus Clay have no significant effects on hydraulic properties or the barrier function of the host rock.

Non-isothermal hydraulic effects are discussed in Poppei et al. (2002) (see also 1.3.8). The study shows that there will be temperature and (thermally induced) pressure peaks which cause an accelerated resaturation of SF/HLW emplacement tunnels (see 1.3.9). The total pore pressure due to heat generation is, however, at all times well below the lithostatic pressure.

These thermal processes (including the effect on pressure evolution) induced by SF and HLW are significant only well before a canister may breach. Heat generation by ILW and – even more – by L/ILW is too low to induce safety-relevant effects (possible thermal convection inside of emplacement tunnels would not be safety-relevant).

All chemical processes are temperature-dependent, but due to the evolution of the temperature in relation to the canister lifetime this impact is not judged to be safety-relevant.

For these reasons, thermal processes are judged to be not safety-relevant.

1.2.2 Thermal alteration of bentonite

Bentonite may be altered by high temperatures. However, no safety-relevant impact on hydraulic properties and radionuclide transport properties of the bentonite buffer is expected because the altered zones around each canister will remain isolated from one another and will not reach the tunnel wall. (see Nagra 2002a, p. 138). It is important to note that the outer part of the bentonite maintains its swelling properties with their favourable effect on hydraulic flow and transport. The diffusion / sorption characteristics of altered bentonite remain favourable.

The phenomenon is judged to be not safety-relevant.

1.2.3 Evaporation / condensation of water

This phenomenon refers to the transfer of water from the liquid phase to the gas phase (water vapour) and vice versa due to temperature and pressure changes. These processes are expected to be relevant only during the operational phase. No significant long-term impact on flow is expected (see Poppei et al. 2002).

The phenomenon is judged to be negligible with respect to long-term safety.

1.3 Hydraulic and gas processes

1.3.1 Water flow through the rock matrix (including fissures)

Water flow through the rock matrix is considered to be one of the dominant potential transport mechanisms for dissolved radionuclides. By definition, fissures of a size up to the metre-scale are included here as part of the bulk rock matrix. While being heterogeneous on small scales, the water flow through the rock matrix can be considered to be homogeneous on the scale of a few metres (equivalent porous medium flow).

The phenomenon is judged to be safety-relevant for all potential host rocks.

1.3.2 Water flow through transmissive discontinuities in host rock (including channelling)

The term “transmissive discontinuity” includes here all transmissive features in the host rock (e.g. fractures, fracture zones), except for those described in 1.3.1 (fissures) and 1.3.3 (macroscopic inclusions). Transmissive discontinuities are considered to have a relatively small thickness and an extension in the order of 10 m (or more). Water flow along transmissive discontinuities is not equally distributed in space but will be concentrated to preferred flow channels (channelling). Channelling effects are included in the phenomenon.

In the Opalinus Clay, fractures might become hydraulically active only for special conditions, e.g. if the overburden is reduced to less than about 200 m due to uplift / erosion (phenomenon 1.4.7).

The phenomenon is judged to be safety-relevant for all potential host rocks, for Opalinus Clay, however, only if special conditions prevail.

1.3.3 Water flow through macroscopic rock inclusions

Macroscopic rock inclusions are inclusions with lithological properties that are significantly different from those of the host rock. Examples for macroscopic rock inclusions are

- Opalinus Clay: sand lenses, sandy layers
- Marls: interbedded layers of limestone (Kalkbankabfolgen)
- Molasse: Rinnengürtel, Durchbruchfächer

Macroscopic rock inclusions in Opalinus Clay (i.e. sand lenses and sandy layers) are not relevant for water flow. They do, however, affect the gas transport from the emplacement tunnels through the Opalinus Clay (see 1.3.18).

The phenomenon is judged to be negligible in Opalinus Clay and safety-relevant only in the marl and Molasse host rocks.

1.3.4 Gas / water flow through EDZ

The flow of gas and water in the EDZ interacts strongly due to two-phase-effects, particularly during periods of resaturation and gas generation. At small scales the EDZ is a highly heterogeneous medium. For single-phase water flow the hydraulic properties of the EDZ can be represented by spatially averaged values. For two-phase flow, however, the determination of effective parameters and their justification require special attention. The formation of distinct gas flow channels with small cross sections ("gas piping") will have a considerable impact on the pore water flow along the EDZ.

In Opalinus Clay, a partial self-sealing of the EDZ occurs due to the combined effects of rock creep, mineral precipitation, and bentonite swelling (the latter in the SF/HLW emplacement tunnels only). These processes will alter the two-phase flow properties of the EDZ with time.

The phenomenon (including the interaction between the flow of gas and the flow of water) is judged to be safety-relevant for all potential host rocks.

1.3.5 Gas / water flow through sealing zones

This phenomenon describes the mutually interacting flow of gas and of water from one side of a sealing zone to the other side. It includes pathways through the bentonite, along the EDZ around the bentonite and – in principle – along the contact zone between the bentonite and the host rock (EDZ). When constructing the seal, the existing EDZ will to a large extent be excavated. Yet, due to rock mechanical effects an EDZ will form again after the construction of the seal, but its dimension and hydraulic properties will be different from the first one. Swelling of the bentonite will prevent a significantly enhanced permeability of the contact zone between the bentonite and the host rock (EDZ). As in phenomenon 1.3.4 partial self-sealing of the EDZ will occur due to the combined effect of rock creep, mineral precipitation and bentonite swelling. In analogy to 1.3.4 the present phenomenon includes gas piping.

The phenomenon is judged to be safety-relevant for all potential host rocks.

1.3.6 Gas / water flow through the concrete backfill between emplacement tunnel and operations tunnel

This phenomenon describes the mutually interacting flow of gas and of water between ILW or L/ILW emplacement tunnels on one side, and the operations tunnel on the other side. The two tunnels are separated from one another by concrete backfill. The phenomenon includes pathways through the concrete backfill (plugs), along the EDZ and along the contact zone between the backfill and the host rock (EDZ). Note that no significant hydraulic resistance is assigned to the concrete backfill (see 1.5.3). Note also that fluid flow from the ILW or L/ILW emplacement tunnels to the operations tunnel may be inhibited (or reduced) by phenomenon 1.5.11.

This phenomenon is judged to be potentially safety-relevant for ILW and L/ILW emplacement tunnels in all potential host rocks.

1.3.7 Water flow in confining units

The confining units are the geological / hydrogeological units between the host rock and the "nearest" regional aquifers above and below the repository. Confining units are thought to contain local aquifers (the Wedelsandstein formation in the upper confining unit and the Sandsteinkeuper below the Opalinus Clay). By definition the regional aquifers (Malm and Muschelkalk) do not belong to the confining units (see Figure 7.4-4 in Nagra 2002a).

Water flow in the confining units has an impact on the water flow in the host rock (phenomena 1.3.1 through 1.3.3).

The phenomenon is judged to be safety-relevant for all host rock options except the Molasse.

1.3.8 Density-driven water flow (thermal, saline)

Density-driven water flow may be induced by gradients of temperature or salinity in the pore water.

In the Opalinus Clay, salinity is considered to be too low to cause any significant density effects.

Non-isothermal hydraulic effects have been studied with TOUGH2 model calculations to investigate the impact on the resaturation of the SF/HLW and ILW emplacement tunnels (Poppei et al. 2002). No indications of density-driven water flow were found.

The phenomenon is judged to be negligible.

1.3.9 Resaturation of bentonite

Resaturation of the bentonite buffer in SF/HLW emplacement tunnels has been analysed by TOUGH2 model calculations under inclusion of non-isothermal effects (see Poppei et al. 2002). The main findings were as follows: the resaturation time is significantly reduced due to higher hydraulic gradients caused by thermal expansion of the pore water in the host rock and thermally reduced pore water viscosity leading to increased hydraulic conductivity.

According to the model calculations, the resaturation of the bentonite buffer will occur within decades or hundreds of years; i.e. within timeframes that are much shorter than the expected canister lifetime (10'000 a).

The thermal conductivity of unsaturated bentonite is low, leading to high temperatures near the canister surface (for thermal alteration effects, see 1.2.2) and to delayed bentonite resaturation.

These effects, however, have been shown to have no significant impact on long-term safety (see Section 5.3.3 in Nagra 2002a).

The phenomenon, i.e. the evolution of bentonite saturation during the early times of the post-operational phase, is judged to be not safety-relevant for times after canister failure.

1.3.10 Resaturation of cementitious backfill

Cementitious backfill has an initial water saturation at the beginning of the post-operational phase, and part of the fluid accessible voids in ILW and L/ILW emplacement tunnels are filled with air. The resaturation of the cementitious backfill in the emplacement tunnels depends on the inflow of pore water from the host rock. Inflow of water from the host rock leads to a reduction of the volume accessible for gas (incl. the initial air) and may lead to degradation of concrete (phenomenon 1.5.3).

The evolution of the gas pressure significantly depends on the gas generation rate and on the evolution of the gas storage volume. The inflow of water from the host rock, on the other hand, depends on the gas pressure (and the capillary pressure) in the emplacement tunnel. The relative rates of resaturation and gas generation are important for the system evolution. In addition, it is conceivable that phenomenon 1.3.13 may have an influence on the resaturation of the cementitious backfill in the emplacement tunnels.

The phenomenon (incl. the initial water saturation of the backfill) is judged to be safety-relevant for the ILW and L/ILW repositories.

1.3.11 Gas generation by anaerobic corrosion of metals, microbial degradation, radiolysis and decay

Gas is generated by anaerobic corrosion of metals, microbial degradation of organic material, radiolysis (mainly of water), and by radioactive decay leading to volatile decay products or conversion of α-particles to helium. Gas generation generally leads to the formation of a gas phase (if a gas phase does not exist already at the beginning of the post-operational phase) and to gas pressure build-up (see 1.3.15). Through the linkage between gas pressure and water pressure gas generation may lead to a displacement of water.

The main components of the generated gas are hydrogen (corrosion, hydrolysis), methane and carbon-dioxide (both from microbial degradation of organic matter). Oxygen from the radiolysis will not be transferred to the gas phase (see also 1.5.1). Hydrogen and carbon-dioxide can react to form methane (methanogenesis).

Gas generation phenomena are judged to be safety-relevant for all potential host rocks.

1.3.12 Limitation of gas generation by the availability of water

Gas generation depends on the availability of water, either as educt for the reaction or as transport medium. The issue has been analysed in Senger et al. (2006). It was found, that the availability of water had no significant effect on the gas generation.

The phenomenon is judged to be negligible with respect to long-term safety[4].

1.3.13 Effective water consumption by gas generation

Water consumption by gas generation (predominantly by anaerobic corrosion of metals) leads to a pressure reduction in the emplacement tunnel, which in turn influences the recovery of hydrostatic pressure conditions in the emplacement tunnel and – in a later stage – leads to a reduction of water expulsion from the emplacement tunnel into the operations tunnel and the host rock, if compared to the situation with neglected phenomenon 1.3.13. The lower the permeability of the host rock, the stronger is the effect. Therefore, the relevance of the phenomenon is restricted to repositories in Opalinus Clay. Even for Opalinus Clay, it has been shown that the effect leads to a minor reduction of the maximal gas pressure only (Senger et al. 2006).

[4] A reduction of gas generation due to water shortage as a consequence of phenomenon 1.3.13 can be excluded for all potential host rocks.

The phenomenon "corrosion products – volume expansion effects" (1.4.6) compensates the above mentioned effect to some extent. In order to describe the net effect, phenomenon 1.3.13 is defined to be the water consumption by gas generation minus the related reduction of pore space by conversion of metals to corrosion products ("*effective* water consumption by gas generation").

This *effective* water consumption is judged to be safety-relevant for Opalinus Clay.

1.3.14 Gas dissolution / degassing

The gas in a repository mainly consists of the following gas fractions: hydrogen, methane, and carbon-dioxide (see 1.3.11). The relative abundance of the gas fractions may change with time. The partitioning of the gas fractions to the gas phase and the liquid phase depends on the fluid pressure according to Henry's law: The concentration of a gas fraction in the liquid phase and the partial pressure of the gas fraction in the gas phase are approximately proportional, the ratio is called Henry's constant. Henry's constant is different for hydrogen, methane, and carbon-dioxide. Any change of the ratio of dissolved concentration and partial pressure at the gas / water interface, either by a selective process in one of the fluid phases (e.g. methanogenesis, cf. 1.3.11) or a change of total gas pressure, will lead to equilibrating processes. These are gas dissolution (transfer from the gas phase to the liquid phase) and degassing (transfer from the liquid phase to the gas phase). Under fully water saturated conditions, degassing occurs, if the solubility limit of one of the species is exceeded.

Dissolution of gas in the liquid phase contributes to the gas storage capacity of the repository and leads to diffusion and advection of dissolved gas away from the gas source (phenomenon 1.3.17). Degassing is an important process for the onset of gas phase formation away from gas sources.

The phenomenon is judged to be safety-relevant for all potential host rocks.

1.3.15 Formation of a gas phase and gas pressure build-up

The formation of a gas phase at a gas source takes place if the rate of gas generation (1.3.11) exceeds the rate of gas transport away from the gas source (1.3.17 through 1.3.20) (Nagra 2002a, Figure 5.5-2). At locations away from gas sources, a gas phase is formed if the inflow of gas (dissolved or in gas phase) to the location exceeds the sum of outflow from the location and the change of dissolved gas at the location.

The formation of a gas phase requires the displacement of pore water (phenomenon 1.3.16). The hydraulic resistance to this pore water displacement determines the level of gas pressure. The level of gas pressure with respect to the pressure in the liquid phase determines the gas saturation in the domain taken up by the gas phase, depending on the capillary pressure function of the medium in the domain.

Gas pressure build-up may occur in all parts of the repository system, but mainly acts as a driving force at the repository-, tunnel- and waste package-scale. There the gas pressure build-up mainly depends on the gas generation rate, the absolute fluid pressure and the hydraulic resistance to water displacement from the location of gas phase formation.

The phenomenon is judged to be safety-relevant for all potential host rocks.

1.3.16 Gas-induced pore water displacement

The formation of a gas phase requires the displacement of pore water (see phenomenon 1.3.15).

In the case of SF/HLW, water can be displaced from the interior of a defective canister through bentonite, if the defect is located at the underside of the canister (see Nagra 2002a, Figure 7.4-7).

There is experimental evidence that very little pore water is displaced when a mobile gas phase is formed in initially water saturated bentonite which allows for sufficient gas transport in the gas phase through the bentonite (Nagra 2002a, p. 132).

In the case of L/ILW, pore-water in the cementitious backfill is highly mobile and is likely to be displaced if gas is trapped within the emplacement tunnels. Gas-induced pore-water displacement through the Opalinus Clay takes place if the gas pressure in the emplacement tunnel exceeds the pore water pressure in the Opalinus Clay (Nagra 2002a, Section 5.5.2).

The phenomenon is judged to be safety-relevant for all potential host rocks.

1.3.17 Gas transport by advection and diffusion of dissolved gas

Advection / dispersion and diffusion of dissolved gas in the aqueous phase contribute to the gas transport capacity of all engineered and natural barriers (bentonite, mortar, EDZ, Opalinus Clay, confining units). Advection / dispersion and diffusion are, however, not capable of transporting dissolved gas away from emplacement tunnels fast enough to prevent a gas phase from being formed (Nagra 2002a, Section 5.5.2.1). For an illustration of advection / dispersion and diffusion of dissolved gas in Opalinus Clay, see Figure 3.1-1 in Nagra (2004), illustration 1.

The phenomenon is judged to be safety-relevant for all potential host rocks.

1.3.18 Gas transport by two-phase flow (capillary flow)

Two-phase flow contributes to the gas transport capacity of all engineered and natural barriers (bentonite, mortar, EDZ, Opalinus Clay, confining units). There are different theories and models to describe two phase flow gas transport in porous media, incl. matrix-fluid interaction (see e.g. Rodwell et al. 1999).

Two phase-flow gas transport through the bentonite is thought to have no significant retardation or gas storage effect, due to the short transport path length.

In the case of the Opalinus Clay the spatial variability of its properties has to be considered. Opalinus Clay is layered and heterogeneous on a small scale. On medium to large scales, field data do not show any systematic depth-dependency of spatially averaged parameters over the whole of the Opalinus Clay layer, i.e. the most complicated model supported by field data is the homogeneous, anisotropic model. For an illustration of two-phase flow in Opalinus Clay, see Figure 3.1-1 in Nagra (2004), illustration 2. The two-phase parameters for the homogeneous, anisotropic model cannot be directly derived from small scale field data by simply taking spatial averages. Therefore it has been decided to investigate the impact of spatial variability by a dedicated study (see below). The phenomenon is judged to be safety-relevant for all potential host rocks.

1.3.19 Gas transport by dilatant gas pathway formation (reversible)

The dilatant formation of gas pathways involves plastic mechanical deformation of the solid phase of the medium and the creation of additional pore space at relatively high gas pressures which are somewhat lower than the geomechanical stress in the medium. A consequence of the deformation is a significant increase of the permeability[5].

[5] In this report, the pathways generated by phenomenon 3.1.19 are named “dilatant pathways”.

Dilatant gas pathway formation contributes to the gas transport capacity of clay rich barriers (bentonite, EDZ, Opalinus Clay, some confining units). The deformations are partially reversible by virtue of the self-sealing capacity of the barriers (Nagra 2002a, Nagra 2002c, Nagra (2004)).

As far as bentonite is concerned, the remarks made under 1.3.18 apply. If gas transport occurs by dilatant pathway formation, self-sealing takes place after the gas breakthrough and the barrier function of the buffer material is not expected to be downgraded in any way.

Opalinus Clay is layered and heterogeneous, i.e. the gas-relevant parameters vary more strongly in the direction perpendicular to the bedding planes than along the bedding planes. Pathway dilation will preferentially occur along bedding planes, although over longer distances, dilatant formation of pathways perpendicular to the bedding planes cannot be excluded. For an illustration of pathway dilation in Opalinus Clay, see Figure 3.1-1 in Nagra (2004), illustration 3.

The phenomenon is judged to be safety-relevant in Opalinus Clay. Gas pressure build-up (1.3.15) in the marls with limestone interbeds and the Molasse is expected to be too low to induce dilatant formation of gas pathways.

1.3.20 Gas transport in tensile fractures (gasfracs)

Gasfracs involve tensile plastic deformations of the medium with disruptive effects at the metre-scale (or more). Gasfracs can only form at high gas pressures (above the sum of the mechanical stress in the solid phase of the medium and the minimum tensile strength of the medium) and at much higher gas generation rates than those expected for repository conditions (Nagra 2002a, Nagra (2004)). Gasfracs are, therefore, not assumed to occur in any of the engineered or natural barriers of the repository system (and specifically not in the Opalinus Clay). The validity of this assumption needs to be monitored during the model calculations (non-exceedance of critical gas pressure). For an illustration of the phenomenon, see Figure 3.1-1 in Nagra (2004), illustration 4.

The phenomenon is judged to be not safety-relevant for all potential host rocks.

1.3.21 Gas accumulation in confining units

Whether or not gas accumulations will occur in the confining units depends on the geological situation at the repository site, particularly on the existence of embedded layers with a low capillary pressure curve. Such gas accumulations may influence the hydraulic conditions and the release of volatile ^{14}C along gas pathways.

In the case of a SF/HLW/ILW repository in the Zürcher Weinland, substantial gas accumulation in the Wedelsandstein, is expected based on simplified model calculations (km-scale, see Nagra 2002c, Figure 4.3-8).

The phenomenon is judged to be safety-relevant for Opalinus Clay. No judgement is made for the marls with limestone interbeds and the Molasse.

1.3.22 Glacially-induced flow

Glacial overburden causes enhanced geomechanical stress and altered hydrogeological conditions. In Nagra 2002a, Section 7.4.5, it is demonstrated that future compaction and drainage of Opalinus Clay during glaciations will only have a slight impact on safety. It is suggested to handle glacial loads in model calculations through appropriate hydraulic boundary conditions. A conceptualisation of the phenomenon is given in Nagra 2002c (Chapter 3.4).

The phenomenon is judged not to be safety-relevant for Opalinus Clay. No judgement is made for the marls with limestone interbeds and the Molasse.

1.4 Mechanical processes

1.4.1 Rock mechanical evolution of EDZ

The phenomenon includes the formation of the EDZ around tunnels, caverns and shafts during construction and operation of the repository and its evolution in the post-operational phase. The formation of the EDZ depends on the tunnel construction technique, the rock mechanical properties of the host rock and the prevailing geomechanical stress. The evolution in the post-operational phase includes self-sealing and temporal changes in the properties of the EDZ. Relevant consequences may be a decreasing hydraulic conductivity and gas permeability with its corresponding effects on flow and gas transport.

The formation of an EDZ is judged to be safety-relevant for all potential host rocks. The temporal evolution of the EDZ in the post-operational phase is judged to be safety-relevant for Opalinus Clay, and to be negligible for the marls with limestone interbeds and the Molasse due to their lower clay content.

1.4.2 Formation of fracture zones

The formation of hydraulically significant new fracture zones in Opalinus Clay is considered to be very unlikely, because if neotectonic movements happen, they are expected to take place along pre-existing structures. A respect distance will be kept between the repository and existing larger-scale fracture zones. Smaller-scale fracture zones are not hydraulically active and will not be affected by neo-tectonic events (Nagra 2002a, Section 5.2.2.4).

The phenomenon is judged to be not safety-relevant for all potential host rocks, although no formal argument is made for the marls with limestone interbeds and the Molasse.

1.4.3 Tunnel convergence

Tunnel convergence is the decrease of the bulk tunnel volume as a consequence of a compaction of the engineered structures by creep of the host rock. This causes an increase of the mechanical stress on the engineered structures. Tunnel convergence leads to a reduction of the fluid-accessible volume in the emplacement tunnel and may lead to displacement of pore water.

Tunnel convergence will take place, during the resaturation of SF/HLW emplacement tunnels in Opalinus Clay and lead to a compaction of bentonite until its increased density – together with the stress increase from bentonite swelling (phenomenon 1.4.4) – is sufficient to counteract the stress imposed by the Opalinus Clay. This has no safety-relevant impact, because tunnel convergence is expected to be completed by the time of canister failure (Nagra 2002a, Section 5.3.3.1).

In the case of ILW & L/ILW in Opalinus Clay, tunnel convergence may lead to the compaction of voids inside waste drums and to displacement of contaminated pore water (NTB 02-05, Section 5.4.3).

The phenomenon is judged to be safety-relevant for ILW and L/ILW emplacement tunnels in Opalinus Clay, and to be negligible for SF/HLW emplacement tunnels in Opalinus Clay. Also, the phenomenon is judged to be negligible for the marls with limestone interbeds and the Molasse although this latter judgement will have to be verified if model calculations for any of these host rocks are to be carried out.

1.4.4 Bentonite swelling

The swelling of bentonite is driven by its resaturation (phenomenon 1.3.9). It counteracts tunnel convergence (mechanical equilibrium) (phenomenon 1.4.3), reduces the hydraulic conductivity of the bentonite and increases its filter efficiency with respect to colloids (phenomenon 1.5.10). It is assumed that swelling is complete before canister failure (Nagra 2002a, Section 5.3.3.1).

Due to the swelling of the bentonite being completed before canister failure, the phenomenon, i.e. the evolution of bentonite swelling during the early times of the post-operational phase, is judged to be not safety-relevant for SF/HLW emplacement tunnels and for bentonite seals in any of the host rocks.

1.4.5 Bentonite piping / erosion and mass redistribution

Highly localized water inflow into emplacement tunnels (e.g. in granitic host rocks) may lead to significant bentonite mass redistribution and density changes (piping and bentonite erosion). However, since localised inflows of water are not expected to occur in the Opalinus Clay the phenomenon is judged to be negligible in the case of this host rock.

The phenomenon is judged to be negligible for SF/HLW emplacement tunnels and bentonite seals in Opalinus Clay.

1.4.6 Corrosion products – volume expansion effects

By metal corrosion, solid phase metal is converted into another solid phase, the corrosion products, with the latter having a greater volume than the initial solid phase. This increase of the solid phase volume may result in 1) an increase of the bulk volume and / or 2) a reduction of the pore volume. An increase of the bulk volume may be counteracted by stress increase, leading to compaction and, again, pore space reduction or possibly, to the formation of fracs. A reduction of pore volume without stress increase will lead to an expulsion of pore-water and a reduced volume available for gas storage.

Corrosion of SF/HLW canisters is a very slow process (about 1 cm in 10’000 a), causing a slow volume expansion and compaction of bentonite and creep of the Opalinus Clay. The effect on pore water flow, gas storage and gas flow is judged to be negligible. The impact of the volume expansion and stress increase on the formation of fractures in Opalinus Clay is also considered to be negligible. The impact on pore water displacement is included in phenomenon 1.3.13. The reduction of volume available for gas storage is judged to be negligible, since it is estimated to amount to less than 10 % and since another counteracting effect, the creation of pore volume by microbial degradation of organic matter, is also ignored. The possible cracking of concrete is also believed to have a negligible impact on safety.

1.4.7 Increase of hydraulic conductivity by uplift / erosion

Uplift and erosion lead to a reduction of the overburden, and, hence, to a decompaction of the host rock and the confining units. Consequences may include an increased permeability and increased flow in the host rock and the confining units.

The phenomenon is judged to be safety-relevant in all potential host rocks, even though a significant effect is not expected earlier than 1 million years after closure of a repository in Opalinus Clay (“period of primary interest”; Chapter 5.2.2.3, Nagra 2002a). At times much greater than about 1 million years the phenomenon may lead to transient flow fields in Opalinus Clay.

The phenomenon is judged to be potentially safety-relevant in all host rocks considered.

1.4.8 Thermo-mechanical effects

Thermal expansion leads to uplift of geological strata above the repository (metre-scale) and to differential thermo-mechanical stresses. This uplift is reversible and occurs only at relatively early times after closure. The differential thermo-mechanical stresses are considered to be too small to cause significant alterations in the repository system. Rock spalling (high-stress induced brittle rock disintegration) at the tunnel walls is not thought to be relevant in Opalinus Clay.

The phenomenon is therefore judged to be negligible for all potential host rocks.

1.5 Chemical and microbial processes

1.5.1 Redox front penetration in bentonite and mortar (radiolytic oxidants)

Radiolysis of water generates oxydants and may lead to oxidizing conditions (see 1.1.2). Such a change of the chemical conditions would alter the sorption of redox-sensitive species. The strongest effect of this phenomenon is expected for SF after canister breaching.

Experiments show that significant changes of the redox-conditions by radiolytic oxidants are unlikely, since the iron inventory of the waste is large enough to react with the oxidants. Even if the phenomenon occurred, its impact would be small (see Nagra 2002c, Chapter 6.4.1).

Therefore, the phenomenon is judged to be negligible.

1.5.2 Chemical / mineralogical alteration of bentonite

Structural and stray materials may lead to chemical / mineralogical alteration of bentonite. For example, interactions of iron and bentonite and interactions of cement and bentonite may lead to a reduction in swelling pressure and to an increase in hydraulic conductivity. An increase in hydraulic conductivity is also thought to be possible as a consequence of a high-pH plume (e.g. pore water from cementitious liner or backfill) coming into contact with bentonite

The phenomenon is judged to be safety-relevant for SF/HLW repositories.

1.5.3 Cement degradation

Cementitious material may not be stable in contact with water intruding into the nearfield from the host rock. Cement degradation by water from the host rock may occur by dissolution, carbonation, etc. The consequences are a change of porosity and sorption capacity of the cementitious material. Degradation products lead to the formation of a high-pH pore water plume which, in turn, has an impact on the host rock, the bentonite buffer and the sand / bentonite backfill. These effects are addressed under 1.5.4 (host rock), 1.5.2 (bentonite) and 1.5.11 (sand / bentonite backfill).

The changes of porosity and sorption capacity due to cement degradation in the nearfield of the ILW and L/ILW repositories are not thought to be of consequence for a repository in the Opalinus Clay. Under Opalinus Clay conditions, these processes are very slow due to the low inflow of water from the host rock into the emplacement tunnels. Furthermore, the concrete plugs are not expected to act as seals of ILW and L/ILW emplacement tunnels in the post-operational phase according to the present concept.

As a consequence, the possible degradation of concrete in an Opalinus Clay repository is judged to be not safety-relevant. For repositories in other host rocks, this phenomenon may be safety relevant.

1.5.4 High-pH plume: sealing effect in host rock

High-pH plumes cause changes in the pore water composition which may lead to mineralogical alterations in the host rock. These may have an impact on material properties (hydraulic conductivity, porosity, self-sealing capacity) of the host rock. In the Opalinus Clay, around the ILW and L/ILW tunnels, the pH plume may cause the formation of a “skin” on the surface of the host rock (host rock / cement interface) with locally reduced permeability and porosity (clogging). The “skin” will grow as long as pH-determining species (mainly OH^--ions) migrate from the tunnel towards the host rock by advection or diffusion.

The phenomenon is judged to be safety-relevant for repositories with cementitious liners, and / or cementitious backfill, such as the ILW and L/ILW repositories.

1.5.5 Anion exclusion

Due to the small pore size of clay and the electric surface charges of clay minerals the transport-relevant porosity and the diffusion constant are smaller for anions than for non-anions. This can be taken into account by assigning different diffusion coefficients and porosities for anions and non-anions.

The phenomenon is considered to be relevant for Opalinus Clay but negligible for the marls with limestone interbeds and the Molasse.

1.5.6 Pyrite oxidation

Pyrite in the host rock may be oxidized in the operations phase and at the beginning of the post-operational phase by oxygen penetrating from open tunnels into the host rock. This process enhances the sulphate concentration in the pore water. However, this alteration of the pore water chemistry is small and has no significant impact on the transport of relevant radionuclides.

The phenomenon is judged to be negligible for all potential host rocks.

1.5.7 Intrusion of oxygenated water

The pore water in the Opalinus Clay is reducing. The intrusion of oxygenated and, therefore, oxidising water to the repository and the area of radionuclide transport in the host rock would alter the chemical conditions with a potential impact on radionuclide transport (enhanced solubility and reduced sorption for redox-sensitive nuclides, see Nagra 2002b). For Opalinus Clay, however, no evidence for hydraulically active fracture zones, acting as fast pathways for surface water, has been found.

The phenomenon is, therefore, judged to be not safety-relevant for Opalinus Clay. No judgement is made for the marls with limestone interbeds and the Molasse.

1.5.8 Saltwater up-coning

Up-coning of saltwater (brine) from greater depth into the host rock can be a consequence of freshwater pumping (possibly also thermohaline convection, see phenomenon 1.3.8), if there are highly permeable, sub-vertical features cutting through the host rock. The effect of saltwater up-coning would lead to an alteration of the chemical conditions in the host rock with a potential impact on radionuclide transport. Opalinus Clay, however, has a very low permeability, and the existence of hydraulically active, highly permeable features can be excluded.

The phenomenon is, therefore, judged to be not safety-relevant for Opalinus Clay. No judgement is made for the marls with limestone interbeds and the Molasse.

1.5.9 Microbial effects

Metabolites of microbes may form complexes with radionuclides, thereby reducing the effective sorption and increasing the effective solubility of radionuclides. These effects are taken into account by using adjusted values for the sorption coefficients in the host rock (Nagra 2002b, page B-41). Microbes are not viable in bentonite, therefore no such effects are expected in bentonite seals and bentonite buffer.

The phenomenon is judged to be not safety-relevant in Opalinus Clay (apart from its impact on sorption which is included in the sorption coefficients, see phenomenon 2.4.4). No judgement is made for the marls with limestone interbeds and the Molasse.

1.5.10 Radionuclide transport by colloids

Radionuclides may be bound to colloids and transported with colloids. When radionuclides are transported by colloids, sorption on the solid phase of the backfill or host rock is much less effective. Although colloids may be formed in the nearfield, e.g. by dissolution of SF and HLW, from bentonite etc., they are expected to be filtered out by the fine pore structure of bentonite and Opalinus Clay (see Nagra 2002a).

The phenomenon is judged to be negligible for Opalinus Clay. No judgement is made for the marls with limestone interbeds and the Molasse.

1.5.11 High-pH plume: tunnel backfill sealing effect

Similar to its impact on the host rock (phenomenon 1.5.4), a high-pH plume may also have a sealing effect on the sand / bentonite backfill of the operations tunnel This phenomenon may coexist with the possible alteration of the bentonite component leading to an increase of hydraulic conductivity as described in FEP 1.5.2.

The phenomenon is judged to be safety-relevant for the operations tunnel near ILW and L/ILW emplacement tunnels.

1.6 Flow induced by Onsager processes

1.6.1 Onsager processes

Fluid, heat and solute fluxes and electric currents are driven by hydraulic, thermal or chemical gradients and electrical fields. The primary dependences are fluid flow – hydraulic gradient, heat flow – thermal gradient, solute migration – chemical gradient and electric current – electric field. “Off-diagonal” processes, e.g. fluid flow driven by chemical gradient, are collectively termed coupled processes or Onsager processes (see Soler 1999). Coupled fluid fluxes may also convey dissolved radionuclides.

All Onsager processes have been shown to be negligible in the Opalinus Clay (Soler 1999). The potential relevance of these processes in the marls with limestone interbeds and the Molasse has not been evaluated.

2. Radionuclide processes

2.1 Radioactive inventory and decay

2.1.1 Partitioning of inventory

Based on the scientific understanding of SF (Figure 4.5-2 in Nagra 2002a), for modelling purposes, the radionuclide inventory in a SF canister is often partitioned into three parts: (i) Instant Release Fraction (IRF), (ii) congruent release from cladding, (iii) congruent release from matrix. Some ILW (compacted hulls and ends from reprocessing of SF) are sometimes also partitioned.

The phenomenon is judged to be safety-relevant.

2.1.2 Speciation of radionuclides

The transport behaviour of a radionuclide (specifically solubility and sorption, but also diffusion) is determined by the chemical species to which it is converted depending on the physical and chemical characteristics of the element (of which it is an isotope) and the prevailing chemical conditions in its environment. The chemical conditions are expected to remain stable for a long time period in Opalinus Clay (at least up to 1 million years).

By definition, the phenomenon does not include the speciation of ^{14}C which is treated under 2.1.3.

The phenomenon is judged to be safety-relevant for all potential host rocks.

2.1.3 Speciation of ^{14}C

^{14}C can be released from the waste as organic or inorganic species, the latter being mainly carbonate. The organic species can either be dissolved or become dissolved in the liquid phase or exist as a volatile species in the gas phase. The following distinction between ^{14}C fractions is usually made in the context of a for long-term safety analysis: inorganic-dissolved, organic-dissolved and organic in the gas phase.

The phenomenon is judged to be safety-relevant for all potential host rocks.

2.1.4 Chain decay (branching, in-growth)

Radionuclides decay and generate decay products which are either radioactive or stable. In the first case the decay of the precursor radionuclide contributes to the inventory of the decay product (in-growth). Some radionuclides decay with different decay modes (branching). The ratio of the decay rates (branching ratio) is a physical constant and independent of the repository conditions or any other FEP.

The phenomenon is judged to be safety-relevant for all potential host rocks.

2.2 Containment failure mechanisms

2.2.1 Breaching of canisters

This phenomenon describes the loss of the physical retention capability of SF and HLW canisters as a result of corrosion and mechanical loads, exposing the waste to groundwater.

The phenomenon is judged to be safety-relevant.

2.2.2 Pinhole defect of canisters (and resistance)

Localised corrosion (pitting corrosion) may lead to pinhole defects of the SF and HLW canisters. In this case, the pathway between waste and bentonite backfill will exhibit a hydraulic resistance due to the small cross section of the pinhole defect.

The phenomenon is judged to be safety-relevant.

2.2.3 Breaching of waste containers

This phenomenon describes the loss of the physical retention capability of ILW and L/ILW containers as a result of degradation of concrete, corrosion and mechanical loads, exposing the waste to groundwater.

The phenomenon is judged to be safety-relevant.

2.3 Radionuclide mobilisation

2.3.1 Glass dissolution

After canister breaching (phenomenon 2.2.1), the glass matrix of HLW will get in contact with water. The glass matrix is thermodynamically unstable in contact with water, and therefore begins to alter and dissolve. As a consequence, radionuclides will be released from the waste.

The phenomenon is judged to be safety relevant.

2.3.2 Cladding corrosion

Radionuclides embedded in the cladding (generated by activation) are released concurrent with cladding corrosion. Cladding is present in SF and some ILW (compacted hulls and ends from reprocessing of SF).

The phenomenon is judged to be safety-relevant.

2.3.3 Leaching of IRF

The Instant Release Fraction (IRF) is a fraction of the radionuclide inventory of SF and specific ILW which is released within a short time after canister breaching (see phenomena 2.1.1 and 2.2.1)

The phenomenon is judged to be safety-relevant.

2.3.4 Fuel matrix dissolution

Radionuclides are contained in the matrix of SF and are released at the rate at which the fuel matrix dissolves.

The phenomenon is judged to be safety relevant.

2.3.5 Radionuclide release from cemented and / or metallic wastes

Radionuclides are released from the waste when water enters the ILW and L/ILW waste containers and the conditioning material (cement) begins to degrade. For modelling purposes, this process is often assumed to be instantaneous. On the other hand, for slowly corroding metallic wastes, congruent release of the embedded radionuclides is sometimes assumed as a more realistic alternative conceptual model for this type of waste.

The phenomenon is judged to be safety relevant.

2.3.6 Precipitation of radionuclides (incl. isotopic dilution)

Element solubility limits may lead to the precipitation of the corresponding radionuclides. Due to the ongoing continuous exchange processes between the dissolved and the precipitated phase, the isotope ratio will equilibrate in the two phases after some time. If the ratio of radionuclide and stable isotope in the dissolved phase is initially higher than in the precipitated phase, then the radionuclide concentration in solution decreases with time due to these exchange processes (isotopic dilution).

The phenomenon is judged to be safety-relevant for all types of waste in Opalinus Clay, but only in the nearfield. In the geophere the phenomenon is judged to be negligible because the radionuclide concentrations will be much lower due to dilution with non-contaminated water.

2.3.7 Sorption on corrosion products

Radionuclides may be sorbed on metal corrosion products. This effect is beneficial. Since it is difficult to quantify, it is conservatively neglected ("reserve FEP").

The phenomenon is classified as not safety-relevant.

2.3.8 Corrosion products – redox effects

The products of metal corrosion contribute to the reducing conditions in the nearfield with influence on the solubility (2.3.6) and sorption (2.4.4) of radionuclides.

The phenomenon is judged to be safety-relevant for all potential host rocks (considered in the solubility and sorption databases).

2.4 Transport of dissolved (non-volatile) radionuclides

2.4.1 Advection / dispersion

Advection and (macroscopic) dispersion are fundamental transport processes for dissolved radionuclides. Macroscopic dispersion leads to a mixing of contaminated and non-contaminated water, and, therefore, to dilution which is included in the phenomenon. Another consequence of macroscopic dispersion is the spreading out of radionuclide transport fronts and a reduction of concentration gradients. The rate of macroscopic dispersion is related to the rate of mean advection.

Advection and dispersion may be the dominant radionuclide transport processes, they are safety-relevant.

2.4.2 Diffusion

Diffusion of dissolved radionuclides in the liquid phase is driven by concentration gradients and depends on the pore structure of the rock, in clay on the surface charges of the solid phase and on the diffusing species.

Diffusion may be the dominant radionuclide transport process in low permeable rock, it is safety-relevant.

2.4.3 Matrix diffusion

Matrix diffusion is the diffusive transport of radionuclides between the flowing groundwater in a transmissive feature and the stagnant pore water of the adjacent rock matrix. The process may significantly delay the advective transport along transmissive features.

The phenomenon is judged to be safety-relevant in connection with transport along transmissive features in all potential host rocks.

2.4.4 Sorption

Sorption of radionuclides on the solid phase of the medium (backfill, rock) leads to significant retardation with respect to the transport of non-sorbing species. Sorption depends on the geochemical conditions, radionuclide speciation (2.1.2, 2.1.3), the presence of complexing agents (1.5.9, 2.4.5) and colloids (1.5.10), and the characteristics of the solid phase.

The phenomenon is judged to be safety-relevant for all potential host rocks.

2.4.5 Facilitated transport by complexing agents

Complexing agents may form stable chemical complexes with radionuclides. These complexes hardly interact any more with the solid phase of the medium (backfill, rock). The consequence is a reduction of the effective Kd values of the radionuclides and thus a reduction of sorption and an acceleration of the radionuclide transport.

The phenomenon is judged to be safety-relevant for all potential host rocks (considered in the sorption databases).

2.4.6 Facilitated transport by colloids / microbes

This phenomenon is covered by 1.5.9 and 1.5.10.

2.5 Transport of volatile radionuclides (^{14}C)

For the Swiss waste inventories, organic ^{14}C has been identified as the only potentially relevant volatile species. Organic ^{14}C is present in SF, ILW and L/ILW, but not in vitrified HLW.

2.5.1 Advection / dispersion in the gas phase

Advection and (macroscopic) dispersion of volatile radionuclides in the gas phase are fundamental transport processes, though spatially limited to the spread of the gas phase. Macroscopic dispersion leads to an equilibration of the radionuclide concentration in the gas phase in addition to the effect of diffusion (2.5.4). The rate of advection is determined by the rate at which the gas phase spreads out. The rate of macroscopic dispersion is related to the rate of mean advection.

Advection / dispersion may be the main transport processes of volatile radionuclides in the gas phase, they are safety-relevant.

2.5.2 Advection / dispersion of dissolved volatile radionuclides in the liquid phase

The comments and the judgement on phenomenon 2.4.1 apply unchanged to the advection and macroscopic dispersion of dissolved volatile radionuclides.

2.5.3 Diffusion of dissolved volatile radionuclides in the liquid phase

The comments and the judgement on phenomenon 2.4.2 apply unchanged to the diffusion of dissolved volatile radionuclides.

2.5.4 Diffusion of volatile radionuclides in the gas phase

The process leads to an equilibration of the concentration of volatile radionuclides in the gas phase. The rate depends on the diffusion constant in the gas phase which, in turn, depends on the gas pressure and the temperature. The process may lead to a transport of volatile radionuclides over long distances in a short time, if a continuous gas phase exists.

This fundamental transport process is judged to be safety-relevant.

2.5.5 Dissolution / degassing

The partitioning of volatile species into a gas phase and a liquid phase depends on the fluid pressure according to Henry's law: The concentration of the volatile species in the liquid phase and the partial pressure of the volatile species in the gas phase are approximately proportional, the ratio is called Henry's constant. Henry's constant is specific to the volatile species. Any change of the ratio of dissolved concentration and partial pressure at the gas / water interface, either by a transport of the volatile species in one of the fluid phases or a change of total gas pressure, will lead to equilibrating processes. These are dissolution of the volatile species (transfer from the gas phase to the liquid phase) and degassing (transfer from the liquid phase to the gas phase).

On fully water saturated conditions degassing occurs if the gas solubility is exceeded by the radioactive species (here: predominantly $^{14}CH_4$) and its non-radioactive equivalent (methane).

These fundamental processes are judged to be safety-relevant.

2.6 Radionuclide pathways through host rock and confining units

2.6.1 Transport through dilatant pathways (of type 1.3.19)

According to phenomenon 1.3.19 high gas pressures may lead to the formation of dilatant pathways and additional pore space. The formation of such pathways is restricted to Opalinus Clay. Gas pressure in a repository in the marls with limestone interbeds or in the Molasse is not expected to raise to a high enough level for the formation of new pathways.

The dilatant pathways will act as pathways for gas flow and, therefore, also for the transport of volatile radionuclides in the gas phase. However, the pathways may also contain a liquid phase, depending on the gas and liquid phase pressure and the capillary pressure in the dilatant pathways. If this liquid phase is mobile, it will transport dissolved radionuclides along the dilatant pathways. In this case matrix diffusion from the dilatant pathways into the undisturbed rock matrix will attenuate the transport.

For Opalinus Clay the phenomenon is judged to be safety-relevant with respect to both gas-phase and liquid-phase transport.

2.6.2 Transport through transmissive discontinuities

The phenomenon refers to the advective / dispersive transport along single transmissive discontinuities with an extension of 10 m or more (type 1.3.2), excluding type 1.3.19, i.e. dilatant pathways formed by high gas pressure. It includes matrix diffusion from the transmissive discontinuities into the rock matrix.

The phenomenon is judged to be safety-relevant for all host rocks with such transmissive discontinuities. In the case of the Opalinus Clay, such transmissive discontinuities are expected to occur only under special conditions.

2.6.3 Transport through rock matrix

According to the definition of phenomenon 1.3.1 the rock matrix includes fissures (here: discontinuities up to the 1m-scale). On small scales (smaller than 1m) transport through the matrix is a coupled process of advection, dispersion and diffusion with large spatial heterogeneities. On larger scales, however, the transport process can be treated as transport through an equivalent porous medium with corresponding, spatially averaged properties.

In the absence of transmissive discontinuities and dilatant pathways, radionuclide transport through the rock matrix is the main transport process from the repository nearfield to regional aquifers and to the biosphere. The phenomenon is safety-relevant.

2.6.4 Transport through boreholes

Open boreholes represent a potentially significant pathway for fluid flow and, therefore, also for radionuclide transport. Backfilled boreholes may form pathways, depending on the permeability contrast between the backfill, the EDZ of the borehole and the host rock. Generally, backfilled boreholes may act as relatively fast transport pathways for very small portions of the total flux from the repository, if any.

This phenomenon has only to be considered as part of scenarios related to human intrusion. It is included in phenomenon 3.4.

2.7 Radionuclide pathways through access tunnel system

2.7.1 Transport through / around sealing zones

This phenomenon includes radionuclide transport in the gas- and liquid phase from one side of a bentonite seal to the other side. It is related to phenomenon 1.3.5. The transport can occur along pathways through the bentonite and along pathways through the EDZ that surrounds the seal. A gap between the bentonite and the host rock (EDZ), which would represent a preferred and fast pathway, can be excluded due to bentonite swelling.

The phenomenon is safety-relevant for all types of host rock.

2.7.2 Transport within backfill and EDZ

This phenomenon refers to radionuclide transport (in gas or liquid phase) along tunnels with a concrete liner and a sand / bentonite backfill, and is related to phenomenon 1.3.4. Tunnels with these attributes are the operations tunnels, the ventilation tunnel, and the access tunnel. The transport can occur along pathways through the sand / bentonite backfill, along pathways in the concrete liner (particularly after degradation of the concrete liner) and along pathways through the EDZ of the tunnel. Depending on the swelling potential of the sand / bentonite backfill and on the achievable degree of tunnel backfill, a gap may develop between the backfill and the liner at the top of the tunnel after the inflow of water. Such a gap represents a preferred fast pathway. In the Opalinus Clay no gap between the liner and host rock EDZ has to be anticipated in the long term because of self-sealing phenomena and creeping of the host rock.

Radionuclide transport along tunnels in the liquid phase includes matrix diffusion from preferred advective pathways (incl. gaps) into areas of stagnant water in the backfill or the undisturbed host rock adjacent to the EDZ.

The phenomenon is considered to be safety-relevant for all types of host rock.

2.8 Radionuclide transport influenced by Onsager processes

2.8.1 Onsager processes

The Onsager processes have been discussed under 1.6.1 in relation to fluid flow as well as to radionuclide transport phenomena.

As for the Onsager processes related to fluid flow, the Onsager processes related to radionuclide transport have been shown to be negligible in the Opalinus Clay (Soler 1999).

3. Special issues

The third group of phenomena includes phenomena which are specific to special scenarios and which do not belong to group 1 (environmental processes) or group 2 (radionuclide processes).

3.1 Interactions between SF/HLW, ILW and L/ILW repositories

Interactions between SF/HLW repositories, ILW repositories and L/ILW repositories may include:

1. the spread of high-pH plumes from cement based backfill (ILW and L/ILW emplacement tunnels), cement liner (ILW and L/ILW emplacement tunnels, infrastructural tunnels), or cemented waste (ILW and L/ILW) into the bentonite buffer and the bentonite seals of the SF/HLW emplacement tunnels.
2. the fluid pressure increase in any of the repositories as a result of gas generation in another repository

The phenomenon is not judged to be safety-relevant since such interactions will be avoided by the repository design.

3.2 Network of transmissive discontinuities (excl. dilatant pathways)

In this report, transmissive discontinuities are features with a small thickness, an extension in the order of 10 m or more, and a significantly higher transmissibility than that of a corresponding slice of rock matrix (defined in 1.3.1). Dilatant pathways (generated by gas pressure increase, phenomenon 1.3.19) are not included in this definition.

In Opalinus Clay, the existence of networks of transmissive features is hypothetical or, at most, very unlikely. In the absence of any positive evidence, they are not considered to be part of the base scenario that is to be covered by the standard version of the IRRC (Integrated Radionuclide Release Code).

An existing network of transmissive features in the Opalinus Clay would define an alternative scenario and be safety-relevant within this scenario. The related fluid flow processes are subject of phenomenon 1.3.2, the related radionuclide transport processes subject of phenomenon 2.6.2. The phenomenon is also considered to be safety relevant in the case of the marls with limestone interbeds and the Molasse.

3.3 *Repository abandoned without backfilling*

This phenomenon is not considered to be part of the base scenario that is to be covered by the standard version of the IRRC. As part of an alternative scenario it has been analysed for Opalinus Clay (see Nagra 2002a, Chapter 7.6.4) and is considered to be safety-relevant.

3.4 *Inadvertent borehole penetration of repository*

The same remark as under 3.3 above (with reference to Nagra 2002a, Chapter 7.6.2) applies here.

3.5 *Deep groundwater extraction*

This phenomenon is not considered to be part of the base scenario that is to be covered by the standard version of the IRRC. As part of an alternative scenario groundwater extraction from the regional Malm aquifer above the Opalinus Clay has been evaluated (see Nagra 2002a, Chapter 7.6.3). The main consequence is the reduced dilution of radionuclide concentrations. The phenomenon is judged to be safety-relevant.

3.6 *Criticality*

Transport of fissile material in the repository may lead to a local accumulation of such material up to the point where it exceeds the critical mass. Additional prerequisites for criticality are a favourable geometry of the material accumulation and the moderation of the fast neutrons from the radioactive decay.

The phenomenon relates to the emplacement of SF only. It will be avoided by an appropriate design of the repository and by a certain minimum level of SF-burnup that will be asked for as part of the acceptance criteria (see Nagra 2002a, Ch. 4.5.2.4). Therefore, the phenomenon is judged to be not safety-relevant.

3 Summary list of candidate FEPs and final judgements

For each of the candidate FEPs the summary provides:

- the identification number and title,
- a short description or explanation and
- the final judgement on safety relevance for each of the repository type- and host rock options on the basis of the arguments presented in Chapter 2.

This judgement on safety relevance is indicated with the following symbols:

x phenomenon judged to be safety-relevant for the considered repository and host rock option, under the conditions of the base- or standard scenario.

(x) phenomenon judged to be safety-relevant but is not part of the base- or standard scenario.

- phenomenon judged to have a negligible impact on long term safety for the considered repository and host rock option under all conceivable conditions of the base- or standard scenario.

blank no judgement made in the case of alternative host rock options, either because the phenomenon is not applicable (e.g. bentonite barrier effects for ILW and L/ILW) or because a judgement would require dedicated studies and / or supplementary process modelling which are not considered to be within the scope of the PSA code development programme.

Table 1: Summary list of candidate FEPs and final judgements

Phenomenon / process		**Description / explanation**	**Opalinus Clay SF / HLW**	**Opalinus Clay ILW & L/ ILW**	marls with limestone interbeds L/ILW	Molasse L/ILW
1.	**Environmental processes**					
1.1	**Radiation-related processes**					
1.1.1	Radiogenic heat generation	impacts are discussed separately for THMC-phenomena (1.2.1, 1.2.2, 1.3.8, 1.4.8)				
1.1.2	Radiolysis	dissociation of molecules by radiation; impact on redox conditions included in 1.5.1; impact on gas generation included in 1.3.11; no other potentially safety-relevant impacts have been identified.				
1.2	**Thermal processes**					

Phenomenon / process		Description / explanation	Opalinus Clay SF / HLW	Opalinus Clay ILW & L/ ILW	marls with limestone interbeds L/ILW	Molasse L/ILW
1.2.1	Temperature evolution	due to heat generation (1.1.1) and heat transport by conduction / convection / radiation; non-isothermal hydraulic effects are included in 1.3.8, thermo-mechanical effects in 1.4.8	-	-	-	-
1.2.2	Thermal alteration of bentonite	altered zone due to enhanced temperature close to canister surface around SF and HLW waste packages; impact on bentonite swelling included in 1.4.4	-	-	-	-
1.2.3	Evaporation / condensation of water	no significant impact on flow in post-closure phase, relevant during operation phase only	-	-	-	-
1.3	**Hydraulic and gas processes**					
1.3.1	Water flow through rock matrix (including fissures)	fissures are small discontinuities in the rock matrix up to the metre scale	×	×	×	×
1.3.2	Water flow through transmissive discontinuities in host rock (including channelling)	“transmissive discontinuities” include all transmissive elements in the host rock, except for fissures (see 1.3.1) and macroscopic rock inclusions (see 1.3.3). Examples are fractures and fracture zones. In Opalinus Clay, fractures are only hydraulically active under special conditions (less than about 200 m of overburden).	×	×	×	×
1.3.3	Water flow through macroscopic rock inclusions	Opalinus Clay: sand lenses and sandy layers; Marls: layers of limestone; Molasse: Rinnengürtel and Durchbruchfächer	-	-	×	×
1.3.4	Gas / water flow through EDZ	flow pathways through the EDZ, including relevant gas-water interactions, particularly during resaturation and gas generation periods	×	×	×	×
1.3.5	Gas / water flow through sealing zones (bentonite and sealing zone EDZ)	flow pathways through bentonite, EDZ and contact zone; including gas piping	×	×	×	×
1.3.6	Gas / water flow through concrete backfill between emplacement tunnel and operations tunnel	flow pathways through concrete plugs, EDZ and contact zone	-	×	×	×

Phenomenon / process		Description / explanation	Opalinus Clay SF / HLW	Opalinus Clay ILW & L/ ILW	marls with limestone interbeds L/ILW	Molasse L/ILW
1.3.7	Water flow in confining units	water flow in the layers between host rock and regional aquifers (Malm & Muschelkalk aquifers in the case of the Zürcher Weinland site considered in Project Opalinus Clay.	×	×	×	-
1.3.8	Density-driven water flow (thermal, saline)	free or natural convection driven by thermal and / or salinity gradients in water (density effects)	-	-	-	-
1.3.9	Resaturation of bentonite	SF/HLW emplacement tunnels only, affects heat conduction through bentonite backfill (1.2.1), onset of gas generation (1.3.11) and swelling of bentonite (1.4.4)	-			
1.3.10	Resaturation of cementitious backfill	ILW and L/ILW emplacement tunnels only; includes initial saturation at onset of gas generation; impact on cement degradation (1.5.3), on gas storage volume and, hence, on gas pressure		×	×	×
1.3.11	Gas generation by anaerobic corrosion of metals, microbial degradation, radiolysis, decay	leads to gas pressure build-up (1.3.15) and generation of volatile radionuclide species (particularly ^{14}C, see 2.1.3); dependent on the availability of water (1.3.12)	×	×	×	×
1.3.12	Limitation of gas generation by availability of water	availability of water (or vapour) can in principle control gas generation (esp. by corrosion) (1.3.11)	-	-	-	-
1.3.13	Effective water consumption by gas generation	defined as water consumption by gas generation (predominantly anaerobic corrosion of metals) minus reduction of pore volume by conversion of metals to corrosion products (1.4.6); can influence the recovery of hydro-static pressure conditions if the perme-ability of the host rock is very low	×	×	-	-
1.3.14	Gas dissolution / degassing	contributes to gas storage capacity (1.3.15), leads to dissolved gas transport by diffusion and advection (1.3.17); degassing occurs if the solubility limit of gases is exceeded by changes in pressure and temperature	×	×	×	×
1.3.15	Formation of a gas phase and gas pressure build-up	takes place if the gas generation rate (1.3.11) exceeds the rate of gas transport (1.3.17-1.3.20) away from the gas source, it causes pore water displacement (1.3.16)	×	×	×	×

Phenomenon / process		Description / explanation	Opalinus Clay SF / HLW	Opalinus Clay ILW & L/ ILW	marls with limestone interbeds L/ILW	Molasse L/ILW
1.3.16	Gas-induced pore water displacement	related to the formation of a gas phase (1.3.15)	×	×	×	×
1.3.17	Gas transport by advection and diffusion of dissolved gas	occurs in all engineered and natural barriers, controlled by gas dissolution (1.3.14)	×	×	×	×
1.3.18	Gas transport by two-phase flow (capillary flow)	gas transport in the gas phase; gas flow and water flow mutually interact: the saturations of the two phases reflect the pressure difference between the gas and the water phase (capillary pressure) and determine the relative permea-bilities for the two phases.	×	×	×	×
1.3.19	Gas transport by dilatant gas pathway formation (reversible)	dilatant gas pathway formation contri-butes to the gas transport capacity of clay rich barriers (bentonite, EDZ, Opalinus Clay, some confining units). It involves plastic mechanical deforma-tion of the solid phase of the medium and the creation of additional pore space. It occurs at relatively high gas pressure (somewhat below the stress in the medium). The deformations are partially reversible and approximated to be fully reversible.	×	×	-	-
1.3.20	Gas transport in tensile fractures (gasfracs)	Macroscopic gas fracs (tensile mode) expected for rapid pressure build-up only, if gas pressure exceeds the geo-mechanical stress by the minimum tensile strength of the medium	-	-	-	-
1.3.21	Gas accumulation in confining units	depending on the geological setting: in Zürcher Weinland expected in Wedel-sandstein; important for hydraulic conditions and transport of volatile ^{14}C along gas pathways	×	×		
1.3.22	Glacially-induced flow	compaction of host rock / confining units and drainage by glacial overburden	-	-		
1.4	**Mechanical processes**					
1.4.1	Rock mechanical evolution of EDZ	incl. formation and self-sealing; evolu-tion after formation leads to decreasing hydraulic conductivity and gas permea-bility, has impact on gas release	×	×	-	-
1.4.2	Formation of fracture zones	neo-tectonic shear deformations intersecting emplacement tunnels	-	-	-	-

Phenomenon / process		Description / explanation	Opalinus Clay SF / HLW	Opalinus Clay ILW & L/ ILW	marls with limestone interbeds L/ILW	Molasse L/ILW
1.4.3	Tunnel convergence	compaction of bentonite or mortar by creep of host rock; can lead to displacement of pore water	-	×	-	-
1.4.4	Bentonite swelling	Swelling of bentonite counteracts tunnel convergence (1.4.3), provides low hydraulic conductivity and filter efficiency wrt. colloids (1.5.10)	-			
1.4.5	Bentonite piping / erosion and mass redistribution	bentonite mass redistribution and density changes due to localised water inflows, corresponds to erosion of bentonite	-			
1.4.6	Corrosion products – volume expansion effects	increase of solid phase volume by corrosive conversion of metals to corrosion products; very slow process, causing compaction of bentonite and Opalinus Clay; wrt. Opalinus Clay SF/HLW: possible impact on formation of fractures; wrt. ILW & L/ILW: closure of pore space and pore water expulsion, possible cracking of concrete; reduction of pore volume included in 1.3.13	-	-		
1.4.7	Increase of hydraulic conductivity by uplift / erosion	long-term changes due to continuous uplift and erosion of overburden cause decompaction and, therefore, increased hydraulic conductivity; this may lead to increased flow in the vicinity of the repository at very late times	×	×	×	×
1.4.8	Thermo-mechanical effects	thermal dilation leads to uplift of geological strata and to differential thermo-mechanical stresses; incl. rock spalling (high-stress induced brittle rock disintegration) at tunnel walls	-	-	-	-
1.5	**Chemical & microbial processes**					
1.5.1	Redox front penetration in bentonite and mortar (radiolytic oxidants)	alteration of chemical conditions due to a change of the redox potential; here: radiolytic oxidants from failed canisters may affect redox conditions in bentonite buffer (or cementitious backfill) and change sorption of redox-sensitive radionuclides	-	-	-	-

Phenomenon / process	Description / explanation	Opalinus Clay SF / HLW	Opalinus Clay ILW & L/ ILW	marls with limestone interbeds L/ILW	Molasse L/ILW
1.5.2 Chemical / mineralogical alteration of bentonite	bentonite alteration by structural and stray materials, here: iron-bentonite and cement-bentonite interactions may lead to a reduction of swelling pressure and to a change in hydraulic conductivity.	×			
1.5.3 Cement degradation	cementitious material may not be stable in contact with host-rock water: dissolution, carbonatisation, etc.; relevant through linkage to porosity changes and sorption (impact on nearfield only, impact on host rock is considered by 1.5.4)	-	-		
1.5.4 High-pH plume: sealing effect in host rock	a high-pH plume originating from cementitious material in the repository may influence the hydraulic conductivity and porosity of host rock: formation of a “skin” in the host rock adjacent to the cavern walls with locally reduced permeability and porosity		×	×	×
1.5.5 Anion exclusion	reduced accessibility of pore space (effective porosity) for anions due to their size and electric charge; retards diffusion rates of anionic radionuclides (diffusion coefficient)	×	×	-	-
1.5.6 Pyrite oxidation	may lead to enhanced sulphate concentration in pore water with possible impact on radionuclide transport	-	-	-	-
1.5.7 Intrusion of oxygenated water	oxidising pore water may have an adverse effect by enhancing the transport of some radionuclides (enhanced solubility and lower sorption); in Opalinus Clay theoretically conceivable only in relation with hydraulically active transmissive discontinuities, which have never been observed in Opalinus Clay underneath an overburden of more than 200 m.	-	-		
1.5.8 Saltwater up-coning	up-coning of saltwater, or brine, originally underlying freshwater by pumping of freshwater (possibly induced also by thermohaline convection 1.3.8), alters the chemical conditions in the host rock	-	-		

Phenomenon / process	Description / explanation	Opalinus Clay SF / HLW	Opalinus Clay ILW & L/ ILW	marls with limestone interbeds L/ILW	Molasse L/ILW
1.5.9 Microbial effects	metabolites of microbes may form complexes with radionuclides, thereby reducing the radionuclide sorption and increasing the radionuclide solubility, effect included in 2.4.4	-	-		
1.5.10 Radionuclide transport by colloids	bentonite may be a source of colloids; radionuclides may sorb on colloids, if the colloids are mobile and radionuclide transport may be affected; transport of colloids is suppressed by small pore size, charged surfaces of bentonite and clay minerals in the host rock	-	-		
1.5.11 High-pH plume: tunnel backfill sealing effect	a high-pH plume originating from cementitious material in the repository may influence the hydraulic conductivity of tunnel backfill material (sand / bentonite mixture); may locally reduce permeability and porosity (in analogy to 1.5.4)		×	×	×
1.6 Flow induced by Onsager processes					
1.6.1 Onsager processes	fluid, heat, current or solute fluxes are driven by hydraulic, thermal, electrical and chemical gradients; the off-diagonal processes are collectively termed coupled processes or Onsager processes; coupled fluid fluxes may enhance dissolved radionuclide transport	-	-		
2. Radionuclide processes					
2.1 Radioactive inventory and decay					
2.1.1 Partitioning of inventory	for modelling purposes, the radionuclide inventory in a SF canister is often partitioned into three parts: (i) Instant Release Fraction (IRF), (ii) congruent release from cladding and (iii) congruent release from matrix; some ILW (compacted hulls and ends from reprocessing of SF) are sometimes also partitioned.	× (SF)	× (ILW)	-	-
2.1.2 Speciation of radionuclides	the transport behaviour of a radionuclide is influenced by the chemical species to which it is converted according to the chemical characteristics of the element (of which it is an isotope) and the prevailing chemical conditions	×	×	×	×

Phenomenon / process	Description / explanation	Opalinus Clay SF / HLW	Opalinus Clay ILW & L/ ILW	marls with limestone interbeds L/ILW	Molasse L/ILW
2.1.3 Speciation of ^{14}C	the transport behaviour of ^{14}C depends on its speciation; for modelling purposes the following groups of species are distinguished: (i) inorganic-dissolved, (ii) organic-dissolved, (iii) organic in the gas phase	×	×	×	×
2.1.4 Chain decay (branching, in-growth)	radionuclides decay and generate decay products which are stable or radio-active (in-growth of decay product) at characteristic rates (decay rates); some radionuclides decay with different decay modes to different decay products (branching)	×	×	×	×
2.2 Containment failure mechanisms					
2.2.1 Breaching of canisters	SF or HLW canisters are assumed to be breached after a certain lifetime	×	-	-	-
2.2.2 Pinhole defect of canisters (and resistance)	localised corrosion (pitting corrosion) may lead to pinhole defects of SF or HLW canisters; the pathway between waste and bentonite backfill exhibits a hydraulic resistance due to the small cross section of the pinhole defect	×	-	-	-
2.2.3 Breaching of waste containers	ILW and L/ILW containers are assumed to be breached after a certain lifetime	-	×	×	×
2.3 Radionuclide mobilisation					
2.3.1 Glass dissolution	after canister breaching, bentonite pore-water may enter the canister and get in contact with the HLW glass matrix , whereupon the matrix may slowly start to dissolve	× (HLW)	-	-	-
2.3.2 Cladding corrosion	radionuclides present in the cladding (SF and ILW) are released congruently with cladding corrosion (see 2.1.1)	× (SF)	× (ILW)	-	-
2.3.3 Leaching of IRF	some radionuclides in SF or in specific ILW (compacted hulls and ends from reprocessing of SF) may be released rapidly after canister breaching; for modelling purposes these are often treated as being instantly released after canister breaching (instant release fraction, see 2.1.1)	× (SF)	× (ILW)	-	-
2.3.4 Fuel matrix dissolution	the SF matrix starts to slowly dissolve in contact with water due to a number of processes (see 2.1.1)	× (SF)	-	-	-

Phenomenon / process		Description / explanation	Opalinus Clay SF / HLW	Opalinus Clay ILW & L/ ILW	marls with limestone interbeds L/ILW	Molasse L/ILW
2.3.5	Radionuclide release from cemented and / or metallic wastes	after breaching of waste containers groundwater inflow will lead to radionuclide release from cemented and / or metallic wastes; radionuclide release from cemented waste is assumed to be fast; possibly congruent mobilisation of radionuclides from corroding metals	-	×	×	×
2.3.6	Precipitation of radionuclides (incl. isotopic dilution)	element solubility limits may lead to the precipitation of the corresponding radionuclides and to isotopic dilution (equal isotope ratio in solution and in precipitated phase); potentially relevant in nearfield only	×	×	-	-
2.3.7	Sorption on corrosion products	radionuclides may sorb on corrosion products (reserve FEP)	-	-	-	-
2.3.8	Corrosion products – redox effects	corrosion products contribute to reducing conditions, influence on solubility (2.3.6) and sorption (2.4.4) of radionuclides	×	×	×	×
2.4	**Transport of dissolved (non-volatile) radionuclides**					
2.4.1	Advection / dispersion	fundamental transport processes	×	×	×	×
2.4.2	Diffusion	fundamental transport process	×	×	×	×
2.4.3	Matrix diffusion	diffusive transport of radionuclides between the water flowing along narrow flow paths and the stagnant pore water of the rock matrix; only in connection with transmissive features; slows down the advective transport of radionuclides	×	×	×	×
2.4.4	Sorption	leads to retardation with respect to the transport of non-sorbing species, conservatively considered to be reversible	×	×	×	×
2.4.5	Facilitated transport by complexing agents	complexing agents may enhance solubility and reduce sorption of radionuclides by formation of radionuclide-complexes; effect included in 2.4.4	×	×	×	×
2.4.6	Facilitated transport by colloids / microbes	see 1.5.10 and 1.5.9	-	-		
2.5	**Transport of volatile radionuclides (^{14}C)**					
2.5.1	Advection / dispersion in the gas phase	fundamental transport processes	× (SF)	×	×	×

Phenomenon / process		Description / explanation	Opalinus Clay SF / HLW	Opalinus Clay ILW & L/ ILW	marls with limestone interbeds L/ILW	Molasse L/ILW
2.5.2	Advection / dispersion of dissolved volatile radionuclides in the liquid phase	fundamental transport processes	× (SF)	×	×	×
2.5.3	Diffusion of dissolved volatile radionuclides in the liquid phase	fundamental transport process	× (SF)	×	×	×
2.5.4	Diffusion of volatile radionuclides in the gas phase	fundamental transport process	× (SF)	×	×	×
2.5.5	Dissolution / degassing	the partition of volatile species to the gas phase and the liquid phase depends on the fluid pressure according to Henry's law; dissolution (degassing) occurs in case of an increase (decrease) of the partial pressure of the volatile species in the gas phase; on fully water saturated conditions degassing occurs if the gas solubility is exceeded	× (SF)	×	×	×
2.6	**Radionuclide pathways through host rock and confining units**					
2.6.1	Transport through dilatant pathways (of type 1.3.19)	dilatant formation of pathways and microscopic pore space by enhanced gas pressure (see 1.3.19) forms also potential pathways for the transport of dissolved and volatile radionuclides; incl. matrix diffusion from the dilatant pathways into the adjacent undisturbed rock matrix	×	×		
2.6.2	Transport through transmissive discontinuities	related to 1.3.2, including 2.4.3, not including dilatant pathways of type 1.3.19; for Opalinus Clay, relevant under special conditions only	×	×	×	×
2.6.3	Transport through rock matrix	radionuclide transport through the rock matrix (incl. fissures, see 1.3.1) is treated as transport through an equivalent porous media	×	×	×	×
2.6.4	Transport through boreholes	radionuclide transport along open or backfilled boreholes; covered by 3.4	-	-	-	-
2.7	**Radionuclide pathways through access tunnel system**					
2.7.1	Transport through / around sealing zones	radionuclide transport through the seals and through the EDZ around the seals; a gap at the interface between bentonite seal and host rock can be excluded because of bentonite swelling	×	×	×	×

Phenomenon / process		Description / explanation	**Opalinus Clay SF / HLW**	**Opalinus Clay ILW & L/ ILW**	marls with limestone interbeds L/ILW	Molasse L/ILW
2.7.2	Transport within backfill and EDZ	radionuclide transport along tunnels with concrete liner and sand / bentonite backfill (operations tunnel, access tunnel, etc.), includes matrix diffusion from the EDZ into the undisturbed host rock; a permanent gap outside the concrete liner is excluded because of creep of host rock (self sealing of EDZ)	×	×	×	×
2.8	**Radionuclide transport influenced by Onsager processes**					
2.8.1	Onsager processes	see 1.6.1	-	-		
3.	**Special issues (alternative scenario classes)**					
3.1	Interactions between SF/HLW, ILW and L/ILW repositories	potential interactions between ILW and SF/HLW may arise due to spread of a high-pH plume originated from cement based backfill, cement liner and cemented wastes (ILW); other interactions may arise due to gas induced pressure increase (ILW to SF/HLW)	-	-	-	-
3.2	Network of transmissive discontinuities (excl. dilatant pathways)	transmissive discontinuities are potential pathways for radionuclide transport	(×)	(×)	(×)	(×)
3.3	Repository abandoned without backfilling	if the repository is abandoned without backfilling, radionuclide transport from the emplacement tunnels through the access tunnels into the biosphere may be enhanced	(×)	(×)	(×)	(×)
3.4	Inadvertent borehole penetration of repository	in the future, a borehole may be drilled which penetrates an emplacement tunnel, or, in the extreme case, a SF canister. The borehole would then form a direct pathway from the repository to the biosphere	(×)	(×)	(×)	(×)
3.5	Deep groundwater extraction	drinking water may be extracted from a deep aquifer instead of from a shallow aquifer (Quaternary)	(×)	(×)	(×)	(×)
3.6	Criticality	transport of fissile material in the repository may lead to the accumulation of a critical mass; depends (among others) on inventory (burnup) and geometry	-	-	-	-

4 Summary of accepted FEPs

The following summary tables (Tables 2 and 3) include all phenomena judged to be safety-relevant for the considered repository types and the Opalinus Clay host rock option, under the conditions of the base scenario. These accepted FEPs together with their interdependencies will have to be taken into account by the standard- or base version of the IRRC (Integrated Radionuclide Release Code).

In order to facilitate later references, the accepted FEPs have been assigned with new numbers (Nr). Upon publication of NAB 07-38, the new numbering system will replace the reference numbers (Ref. Nr.) that have been used throughout this report and earlier FEP-screening publications within the PSA project.

Table 2: Summary of environmental processes

Category (Nagra 2002b)	**Nr**	**Process (FEP)**	Ref. Nr.	**OPA SF/ HLW**	**OPA ILW & L/ILW**	**Remarks**
Hydraulic & Gas	**1**	Water flow through rock matrix	1.3.1	×	×	incl. fissures
	2	Water flow through transmissive discontinuities in host rock	1.3.2	×	×	incl. channelling
	3	Gas / water flow through EDZ	1.3.4	×	×	
	4	Gas / water flow through sealing zones	1.3.5	×	×	bentonite & sealing zone EDZ
	5	Gas / water flow through concrete backfill	1.3.6		×	between emplacement tunnel and operations tunnel
	6	Water flow in confining units	1.3.7	×	×	excluding regional aquifers
	7	Resaturation of cementitious backfill	1.3.10		×	evolution of gas pressure depends on initial saturation
	8	Gas generation by anaerobic corrosion of metals, microbial degradation, radiolysis, and decay	1.3.11	×	×	
	9	Effective water consumption by gas generation	1.3.13	×	×	
	10	Gas dissolution / degassing	1.3.14	×	×	
	11	Formation of gas phase and gas pressure build-up	1.3.15	×	×	
	12	Gas-induced pore water displacement	1.3.16	×	×	little pore water displacement in bentonite; Figure7.4-7 in Nagra (2002a)

Category (Nagra 2002b)	Nr	Process (FEP)	Ref. Nr.	OPA SF/ HLW	OPA ILW & L/ILW	Remarks
	13	Gas transport by advection / diffusion of dissolved gas	1.3.17	×	×	
	14	Gas transport.by two-phase flow	1.3.18	×	×	capillary flow; Figure 3.1-1 in Nagra (2004), Picture 2
	15	Gas transport by dilatant gas pathway formation	1.3.19	×	×	reversible; Figure 3.1-1 in Nagra (2004), Picture 3
	16	Gas accumulation in confining units	1.3.21	×	×	hydraulics / release of volatile ^{14}C along gas pathway
Mechanical	**17**	Rock mechanical evolution of EDZ	1.4.1	×	×	decreasing hydraulic conductivity and gas permeability
	18	Tunnel convergence	1.4.3		×	displacement of pore-water
	19	Increase of hydraulic con-ductivity by uplift / erosion	1.4.7	×	×	decompaction, transient flow field
Chemical & Microbial	**20**	Chemical / mineralogical alteration of bentonite	1.5.2	×		by iron, cement, high-pH plume etc., increase of hydraulic conductiv-ity
	21	High-pH plume: sealing effect in host rock	1.5.4		×	by iron, cement, high-pH plume etc., increase of hydraulic conductiv-ity
	22	Anion exclusion	1.5.5	×	×	
	23	High-pH plume: tunnel backfill sealing effect	1.5.11		×	

Table 3: Summary of radionuclide processes

Category (Nagra 2002b)	**Nr**	**Process**	Ref. Nr.	**OPA SF/ HLW**	**OPA ILW & L/ILW**	**Remarks**
Radioactive inventory and decay	**24**	Partitioning of inventory	2.1.1	×	×	IRF, cladding, matrix: for SF and part of ILW; STMAN
	25	Speciation of radionuclides	2.1.2	×	×	considered in solubility and sorption databases
	26	Speciation of ^{14}C	2.1.3	×	×	three fractions of ^{14}C: 1) inorganic dissolved 2) organic dissolved 3) organic in the gas phase
	27	Chain decay	2.1.4	×	×	branching, in-growth
Containment failure mechanisms	**28**	Breaching of canisters	2.2.1	×		STMAN
	29	Pinhole defects of canisters	2.2.2	×		and resistance; STMAN
	30	Breaching of waste containers	2.2.3		×	STMAN (ILW)
Radionuclide mobilisation	**31**	Glass dissolution	2.3.1	×		STMAN (HLW)
	32	Cladding corrosion	2.3.2	×	×	STMAN (SF/ILW/cladding)
	33	Leaching of IFR	2.3.3	×	×	STMAN (SF/ILW/IRF)
	34	Fuel matrix dissolution	2.3.4	×		STMAN (SF)
	35	Radionuclide release from cemented and / or metallic wastes	2.3.5		×	STMAN (ILW)
	36	Precipitation of radionuclides	2.3.6	×	×	incl. isotopic dilution, relevant for nearfield transport only; STMAN
	37	Corrosion products – redox effects	2.3.8	×	×	considered in solubility and sorption databases
	38	Advection / dispersion	2.4.1	×	×	
	39	Diffusion	2.4.2	×	×	
	40	Matrix diffusion	2.4.3	×	×	only in connection with transmissive features (fractures)
	41	Sorption	2.4.4	×	×	
	42	Facilitated transport by complexing agents	2.4.5	×	×	considered by sorption database
Transport of volatile radio-nuclides (^{14}C)	**43**	Advection / dispersion in gas phase	2.5.1	×	×	for SF, ILW and L/ILW
	44	Advection / dispersion of dissolved volatile radio-nuclides in the liquid phase	2.5.2	×	×	for SF, ILW and L/ILW

Category (Nagra 2002b)	**Nr**	**Process**	Ref. Nr.	**OPA SF/ HLW**	**OPA ILW & L/ILW**	**Remarks**
	45	Diffusion of dissolved volatile radionuclides in the liquid phase	2.5.3	×	×	for SF, ILW and L/ILW
	46	Diffusion of volatile radio-nuclides in the gas phase	2.5.4	×	×	for SF, ILW and L/ILW
	47	Dissolution / degassing	2.5.5	×	×	for SF, ILW and L/ILW
Radionuclide pathways through host rock and confining units	**48**	Transport through dilatant pathways	2.6.1	×	×	refers to 15; includes matrix diffusion into the adjacent rock matrix
	49	Transport through trans-missive discontinuities	2.6.2	×	×	refers to 2, incl. matrix diffusion into HR, not including 48.
	50	Transport through rock matrix	2.6.3	×	×	refers to 1; rock matrix treated as equivalent porous medium
Radionuclide pathways through access tunnel system	**51**	Transport through / around sealing zones	2.7.1	×	×	transport through seals and EDZ around sealing zones; incl. matrix diffusion into HR
	52	Transport within backfill and EDZ	2.7.2	×	×	transport along tunnels with sand / bentonite backfill and EDZ; incl. matrix diffusion into HR

5 References

Johnson, L.H. & Smith, P.A. (2000): The interaction of radiolysis products and canister corrosion products and the implications for radionuclide transport in the near field of a repository for spent fuel. Nagra Technical Report NTB 00-04. Nagra, Wettingen, Switzerland.

Johnson, L.H., Niemeyer, M., Klubertanz, G., Siegel, P. & Gribi, P. (2002): Calculations of the temperature evolution of a repository for spent fuel, vitrified high-level waste and long-lived intermediate level waste in Opalinus Clay. Nagra Technical Report NTB 01-04. Nagra, Wettingen, Switzerland.

Nagra (2002a): Project Opalinus Clay – Safety Report – Demonstration of disposal feasibility for spent fuel vitrified high-level waste and long-lived intermediate level waste (Entsorgungsnachweis). Nagra Technical Report NTB 02-05. Nagra, Wettingen, Switzerland.

Nagra (2002b): FEP management for the Opalinus Clay safety assessment. Nagra Technical Report NTB 02-23. Nagra, Wettingen, Switzerland.

Nagra (2002c): Project Opalinus Clay: Models, codes and data for safety assessment. Demonstration of disposal feasibility for spent fuel vitrified high-level waste and long-lived intermediate level waste (Entsorgungsnachweis). Nagra Technical Report NTB 02-06. Nagra, Wettingen, Switzerland.

Nagra (2004): Effects of Post-disposal Gas Generation in a Repository for Spent Fuel, High-level Waste and Long-lived Intermediate Level Waste Sited in Opalinus Clay. Nagra Technical Report NTB 04-06. Nagra, Wettingen, Switzerland

Poppei, J., Mayer, G. & Croisé, J. (2002): Scoping calculations on gas transport processes in the vicinity of a HLW/SF/ILW repository in Opalinus Clay. Nagra unpublished report. Nagra, Wettingen, Switzerland

Rodwell et al. (1999): Gas migration and two-phase flow through engineered and geological barriers for deep repository for radioactive waste; A joint EC/NEA Status Report. W.R. Rodwell et al., European Commission & Nuclear Energy Agency, EUR 19122 EN, 1999

Senger, R., Johnson, L.H. & Marschall, P. (2006): Investigation of two-phase flow phenomena associated with corrosion in a SF/HLW repository in Opalinus Clay. Nagra unpublished report. Nagra, Wettingen, Switzerland

Soler, J.M. (1999): Coupled transport phenomena in the Opalinus Clay: implication for radionuclide transport. Nagra Technical Report NTB 99-09. Nagra, Wettingen, Switzerland.