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# FEP Analysis for Disposal of Depleted Uranium at the Clive Facility

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# 1.0 Introduction

The safe storage and disposal of depleted uranium (DU) waste is essential for mitigating releases of radioactive materials and reducing exposures to humans and the environment. Currently, a radioactive waste facility located in Clive, Utah (the "Clive facility") operated by Energy*Solutions* is proposed to receive and store DU waste that has been declared surplus from radiological facilities across the nation. The Clive facility has been tasked with disposing of the DU waste in an economically feasible manner that protects humans from radiological releases.

To assess whether that the proposed Clive facility DU disposal location and containment technologies are suitable for protection of human health, specific performance objectives for land disposal of radioactive waste set forth in Title 10 Code of Federal Regulations Part 61 (10 CFR 61) Subpart C, promulgated by the U.S. Nuclear Regulatory Commission (NRC), must be met. In order to support the required radiological performance assessment (PA), a detailed computer model is being developed to evaluate the potential detrimental effects on human health that would result from the disposal of DU and its associated radioactive contaminants.

A key activity in developing a PA for a radiological waste repository is the comprehensive identification of relevant external factors that should be included in quantitative analyses. These factors, termed "features, events, and processes" (FEPs), form the basis for scenarios that are evaluated to assess site performance.

Although it is not a governing regulation for the disposal of LLW and DU at Clive, Title 40 CFR Part 191, promulgated by the U.S. Environmental Protection Agency (EPA), provides a useful and general definition for the scope of a PA analysis of a radiological disposal facility. The PA 1) identifies the processes and events that might affect the disposal system, 2) examines the effects of these processes and events on the performance of the disposal system, and 3) estimates the cumulative releases of radionuclides considering the associated uncertainties caused by all significant processes and events (40 CFR 191). The identification of FEPs is essential to the development of the conceptual site model (CSM) and model scenario development process (see *Conceptual Site Model* white paper).

This report serves to document and examine the universe of FEPs that may apply to the disposal of depleted uranium (DU) waste at the Clive Facility. FEPs that are screened and identified as relevant for the Clive facility PA are identified in this white paper and are further elaborated in the CSM white paper.

This document is considered to be a living document that is synchronized with current conceptual models, analysis, and modeling of the PA. As concepts and modeling evolve, so too will this document.

# 2.0 Identification of Features, Events, and Processes

The identification of FEPs for use in the Clive DU PA Model was an iterative process that began with compiling an exhaustive list of candidate FEPs that could affect the long-term performance of the radiological waste repository. As an initial step, all potentially relevant FEPs from a variety of reference sources were collected. The initial list from external sources was modified as additional FEPs were identified that are specific to the Clive facility.

This exhaustive initial compilation of FEPs led to significant redundancy across the original sources. Redundancy was addressed by the modification of the candidate list of FEPs through normalization (removal of redundant FEPs) and assignment of FEPs categories (grouping of common FEPs). This section describes the FEP identification process, including implementation of the normalization, categorization and screening processes.

## 2.1 Compilation of FEPs

The initial list of FEPs pertaining to the efficacy of disposal of radioactive wastes in general was compiled from several scenario development documents published for other nuclear waste disposal facilities, including those for Yucca Mountain Project, the Waste Isolation Pilot Plant, and several foreign radioactive waste projects. The primary literature source for FEP analysis is Guzowski and Newman (1993). They compiled over 700 potentially disruptive FEPs from a review of scenario documentation from other waste repositories around the world.

The facilities considered in Guzowski and Newman have substantially different geological, environmental and regulatory settings from those of the Clive facility. Consequently, the collection of FEPs in Guzowski and Newman provides a substantial list that should be considered for any PA, but they are also missing FEPs that pertain more particularly to the waste disposal facility at Clive. Site-specific understanding of the environmental and engineered attributes of the Clive facility, and the potentially affected region and population, was used to augment the initial compilation of FEPs.

Additional FEPs were also identified from the Nuclear Energy Agency database (NEA, 2000). In this initial compilation step, nearly 1,000 FEPs were identified from the literature and site-specific considerations. Initial FEPs compiled from all sources are listed in Table 1 in the Appendix.

## 2.2 Normalization and Consolidation of FEPs

Subsequent to the initial compilation of FEPs, steps were taken to reduce redundancy. Initially, FEPs were sorted alphabetically and duplicates were deleted. Recorded FEP values that were different only in vernacular/diction (e.g., “climate change” versus “change in climate”) were normalized to capture a single primary FEP value for a series of identical or closely-related concepts.

To address duplication of FEPs where similar terminology was stated dissimilarly, initial FEPs were grouped by keyword content (e.g., “climate,” “waste,” “groundwater,” etc.) and evaluated for possible normalization or consolidation. Where possible, FEPs were normalized to a standard terminology.

Similar but not identical FEPs were maintained, to be evaluated as part of the consolidation step. At this point, each FEP was considered for its similarity to other FEPs, so that they could be grouped into fewer classes, making the list more manageable. For example, all geochemical processes were grouped together. These would be easier to address as a group for inclusion in the CSM. Likewise, all coastal processes could be considered for exclusion as a group. For each FEP, the rationale behind its grouping was noted. No FEPs were excluded at this step, but nearly all were consolidated with others. This consolidation process reduced the total number to 135 unique FEP groupings.

# 3.0 Classifying Features, Events, and Processes

Following the normalization and consolidation steps, the 135 unique FEP groups were carried forward to the classification step and were considered for inclusion in the conceptual model scenarios. The classification is principally an organizational tool for the FEP analysis, although the categories identified also relate to components of the CSM. The 135 unique FEP groups were classified into the following 18 categories:

- Celestial
- Climate change
- Containerization
- Contaminant Migration
- Engineered Features
- Exposure
- Hydrology
- Geochemical
- Geological
- Human Processes
- Hydrogeological
- Marine
- Meteorology
- Model Settings
- Other Natural Processes
- Source Release
- Tectonic/Seismic/Volcanic
- Waste

These categories are relevant to the development of scenarios and are integral to the CSM for the Clive Facility. Occasionally, a FEP could have been classified into more than one category. However, the overall goal of the FEP analysis is to identify those processes that should be carried forward into the CSM, and subsequently into the modeling. Provided each FEP is identified in one of the categories, it was carried forward to the CSM. Ultimately, each FEP was given due consideration, and the implementation of relevant FEPs in the final modeling was rather independent of the classification.

# 4.0 Screening of FEPs

The long list of FEPs was screened in consideration of regulatory concern and professional judgment based on physical reasonableness, probability of occurrence, severity of consequence, and assessment scope.

The most basic screening criterion is regulatory concern. Regulatory requirements for performance of EnergySolutions' Clive facility are published in 10 CFR 61 and Utah Administrative Code R313. While the mention of something that can be construed as a feature, event, or process in the text of a regulation triggers its consideration in this FEP analysis, it does not mean that the FEP must become part of the PA analysis or modeling.

A subjective element of the FEP screening process is consideration of assessment scope and physical reasonableness. Physical reasonableness is a professional judgment based on logical arguments using available data and information to support a conclusion of whether or not conditions can exist within the period of regulatory concern that will result in the occurrence of a particular event or process that affects disposal system performance. In addition to meeting screening criteria, some FEPs were retained as model parameters specifically because they pertain to scenario development itself (e.g., exposure terms).

The inclusion or dismissal of FEPs and associated rationale is documented in support of constructing the conceptual model and scenarios. The product of this screening procedure is the identification of those FEPs that, either alone or in conjunction with others, could affect the performance of the disposal system.

## 4.1 Regulatory Considerations, Guidance, and Supporting Information

This section discusses the regulatory language, guidance, and other supporting information to be considered in developing scenarios and conceptual models for the Clive DU PA Model. Specific considerations of NRC's land disposal performance requirements (10 CFR 61 Subpart C) are required for the scenario development and are important to document as part of the FEP compilation and screening activity. In addition, observations and recommendations previously published by radioactive waste disposal facility working groups and technical advisers are also considered, although most of these are focused on geologic disposal of radioactive wastes.

Specific provisions of regulations for the operation and closure of a land-disposal LLW facility were specifically considered if they were mentioned in a regulatory document.

Based on these provisions, 55 of 135 FEPs were identified as relevant for evaluation in the conceptual model or exposure scenarios. The remaining FEPs were dismissed from further consideration for various reasons. Some, like a direct impact from a large meteorite, are simply beyond the scope of the analysis. Tsunami and other marine phenomena obviously do not apply at the Clive facility. Several FEPs from the original sources were dismissed because they apply only to geologic repositories, or to specific types of containment, like copper canisters for used nuclear fuel.

### 4.1.1 Nuclear Regulatory Commission: 10 CFR 61

This regulation contains Federal procedural requirements and performance objectives applicable to land disposal of radioactive waste. Specific considerations of 10 CFR 61 include attributes of facility siting, facility engineering (including post-closure stability and control), site monitoring, record-keeping, protection of health and safety, and a minimum time frame for which an assessment must be conducted to ensure long-term stability of the disposal site. The types of objectives mentioned in 10 CFR 61 include:

- long-term effectiveness based on physical siting of the disposal unit (including site geology and hydrology),
- protection of the general population (in terms of radiological dose),
- protection of inadvertent intruders (dose),
- protection of individuals during operations (dose),
- isolation and segregation of wastes,
- limitation of releases of radionuclides via pathways in air, water, surface water, plant uptake, or exhumation by burrowing animals,
- long-term stability of the disposal site,
- evaluation of engineering failures, including erosion, mass wasting, slope failure, settlement of wastes and backfill, infiltration through covers, and surface drainage,
- site monitoring requirements,
- identification of natural resources whose exploitation could result in inadvertent exposure, and
- efficacy of institutional controls.

### 4.1.2 Utah Administrative Code R313: Radiation Control

The Utah Administrative Code (UAC) Rules 313-15 (*Standards for Protection Against Radiation*) and 313-25 (*License Requirements for Land Disposal of Radioactive Waste*) mirror the provisions for land disposal of radioactive waste provided in 10 CFR 61. Notable performance objectives of near-surface disposal sites established of UAC Rule R313-25 include:

- protection of the general population,
- protection of inadvertent intruders,
- consideration of releases of radionuclides through pathways via air, water, surface water, plant update, and exhumation of burrowing animals,
- protection of individuals during operations,
- long-term stability of the disposal site,

- prevention of erosion, mass wasting, slope failure, settlement of wastes and backfill, infiltration through covers, and surface drainage,
- site monitoring requirements, and
- identification of natural resources whose exploitation could result in inadvertent exposure.

The majority of the FEPs identified as relevant under 10 CFR 61 are also applicable under UAC Rule R313-25 and are retained for analysis.

### 4.1.3 Additional Guidance

The NRC's PA working group has identified additional considerations in NRC's *Performance Assessment Methodology* (NRC 2000). The working group identifies two specific areas of interest in conducting a PA: pathway analysis and dose assessment.

Pathway analysis involves the mechanisms of radionuclide transfer through the biosphere to humans. These mechanisms, or transport and exposure pathways, must be identified and modeled. Pathway analysis should result in the determination of the total intake of radionuclides by the average member of the critical group. The critical group is defined as the "...group of individuals reasonably expected to receive the greatest dose from radioactive releases from the disposal facility over time, given the circumstances under which the analysis would be carried out" (NRC 2000).

Various considerations should be taken into account when analyzing the transport of radionuclides through the biosphere (to humans). These considerations should include

- modeling the movement of radionuclides through the environment and the food chain, adequately reflecting complex symbiotic systems and relationships,
- considering mechanisms of (biotic and) human uptake of radionuclides, and
- identifying usage, production, and consumption parameters, for various food products and related systems, that may vary widely, depending on regional climate conditions, local or ethnic diet, and habits.

The dose assessment requires that the dosimetry of the exposed individual be modeled. The objective of dose modeling in a LLW PA is to provide estimates of potential doses to humans, in terms of the average member of the critical group, from radioactive releases from a LLW disposal facility, after closure.

A "current conditions" philosophy is initially applied to determine which pathways are to be evaluated. That is to say that current regional land use and other local conditions in place at the time of the analysis will strongly influence pathways that are considered to be significant. The conceptual model and scenarios must consider each of the general pathways discussed in 10 CFR 61.13. Additional pathways for consideration are published in NUREG/CR-5453 (Shipers, 1989) and NUREG-1200 (NRC, 1994). NUREG-1200 discusses example potential "scenarios by which radioactivity may be released from the disposal facility and cause the potential for radiological impacts on individuals." Shipers (1989) identifies exposure pathways, and scenarios regarding transport mechanisms that could contribute to the release of radioactive materials from the disposal facility leading to human exposure, in the context of near-surface LLW disposal.

## 4.2 Scope of Assessment and Physical Reasonableness

The final phase of FEP screening is the application of professional judgment in terms of the scope of the PA and the physical reasonableness of evaluating those FEPs in the CSM and scenarios. Performance objectives include protection of the general population from releases of radioactivity (10 CFR 61.41), protection of individuals from inadvertent intrusion (§61.42), and stability of the site after closure (§61.44). Assumptions of the scope of the PA include:

- Performance assessment reflects post-closure conditions. Because PA considers the site only after closure, consideration of the protection of individuals during operations (§61.43) is not within the scope of the evaluation and FEPs related to operations are not considered relevant to the CSM or scenarios.
- Land-use assumptions relative to human exposures post-closure are based on current conditions and likely future conditions. Therefore urban settlement, residential use, farming, and aquaculture and FEPs pertaining to these incongruous uses are not included in the CSM or scenarios because of the high concentrations of salt in the soil and groundwater of this site. However, hunting, ranching, and recreational use are considered viable scenarios.
- Intentional human intruders are not protected.

# 5.0 Screening Results

**Using the identification and screening processes described in Sections 1 through 3, FEPs were consolidated from an exhaustive list of over 900 to 135 FEPs or FEP categories. Of this consolidation, 90 FEPs are retained for further consideration and 45 FEPs were dismissed from inclusion in the PA model. All FEPs considered and retained for inclusion in the CSM and scenarios are reported in**

Table 2 in the Appendix. FEPs that were considered and dismissed from evaluation in the CSM and scenarios are listed in Table 3, along with a brief rationale for their exclusion.

In summary, FEPs retained for consideration in the PA, CSM, and scenarios pertain to regulatory aspects of post-closure protection of human health and long-term stability of the disposal facility for the duration and spatial scope of the assessment period. FEPs that were dismissed from consideration in the PA include those that do not fall within the scope of the PA, were characterized as extremely unlikely to occur or having a low magnitude of consequence of affecting the performance of the repository, or were dismissed based on site-specific considerations.

# 6.0 Use of FEPs for Conceptual Model and Scenario Development

The CSM provides detailed descriptions of the physical environment, the engineered disposal facility, the sources and chemical forms of disposed wastes, potentially affected media, potential release pathways and exposure routes, and potential receptors. The CSM considers broad categories of FEPs that are relevant to these attributes, but individual FEPs may or may not be addressed in the CSM based on the scope of the assessment and the scenarios developed. This section identifies the FEPs that are considered for inclusion in the CSM and are addressed in the development of scenarios for the PA model. These are grouped into several categories, and listed in tabulated form in Appendix B. Those FEPs that were dismissed from consideration in the modeling are listed in Appendix C. Some FEPs may overlap or repeat between categories.

**Meteorology**

Frost weathering and other meteorological events (e.g., precipitation, atmospheric dispersion, resuspension) are considered in the conceptual model. Weathering may occur from frost cycles. Resuspension of particulates from surface soils allows them to be redistributed by atmospheric dispersion, which is a meteorological phenomenon. Dust devils are also possible at the site and a tornado occurred in Salt Lake City in 1999, which was the first tornado in Utah in over 100 years.

**Climate change**

Features, events, and processes of climate change considered in the conceptual model include effects on hydrology (including lake effects), hydrogeology, biota, and human behaviors. Lake effects include appearance/disappearance of large lakes and associated phenomena (sedimentation, wave action, erosion/inundation). Wave action, including seiches, is included in the CSM.

**Hydrology**

Hydrology is addressed in the conceptual model since it influences many processes in contaminant transport. Examples of FEPs considered for the conceptual model include groundwater transport, inundation, and water table changes.

**Hydrogeological**

Several hydrogeological FEPs were identified for consideration in the conceptual model. Groundwater transport, in both the unsaturated and saturated zones, is potentially a significant transport pathway. For some model endpoints, such as groundwater concentrations that are compared to groundwater protection levels (GWPLs), it is the only pathway of concern.

Groundwater flow and transport processes include advection-dispersion, diffusion, fluid migration, waterborne contaminant transport, changes in the flow system, recharge, water table movements, and brine interactions. Inundation of the site may occur due to changes in lakes or reservoirs, which is included in lake effects of climate change.

**Geochemical**

Geochemical effects include chemical sorption and partitioning between phases, aqueous solubility, precipitation, chemical stability, complexation, changes in water chemistry (redox potential, pH, Eh), fluid interactions, speciation, interactions with clays and other host materials, and leaching of radionuclides from the waste form. These processes are addressed in the model.

**Other Natural Processes**

The broad category of other natural processes considered for the conceptual model include ecological changes and pedogenesis (soil formation). Ecological changes are associated with catastrophic events (e.g., inundation), evolution, or climate change. Pedogenesis is expected on the cap, giving rise to vegetation growth or habitation by wildlife.

Denudation (cap erosion) may be sufficient to expose waste. Erosion of the repository resulting from pluvial, fluvial or aeolian processes can result from extreme precipitation, changes in surface water channels, and weathering. Sediment transport is an inherent aspect of erosion. Sedimentation/deposition onto the repository would also affect disposal at the site.

Faults are not present within the vicinity of Clive, although effects of isostatic rebound are still possible in the Lake Bonneville area.

**Engineered Features**

Engineered features are intended to promote containment and inhibit migration of contaminants. Conditions potentially affecting site performance include failure of general engineered features, repository design, repository seals, material properties, and subsidence of the repository.

### Containerization

Two key components of containerization were identified as FEPs: containment degradation and corrosion. Canister degradation, including fractures, fissures, and corrosion (pitting, rusting) could result in containment failure. These processes are evaluated in the conceptual model (*Conceptual Site Model* white paper, Section 8.1).

### Waste

Attributes of waste that could influence the performance of the Clive facility include the inventory of radionuclides, physical and chemical waste forms, container performance, matrix performance, leaching, radon emanation, and other waste release mechanisms.

### Source Release

Source release can result from many mechanisms, including containment failure, leaching, radon emanation, plant uptake, and translocation by burrowing animals. FEPs that fit in the category of source release include gas generation, radioactive decay and in-growth, and radon emanation.

### Contaminant Migration

Contaminant migration for the CSM includes the mechanisms and processes by which radionuclides may come to be located outside of the containment unit. The following contaminant migration processes were identified for consideration in the conceptual model: resuspension, atmospheric dispersion, biotically-induced transport, contaminant transport, diffusion, dilution, advection-dispersion, dissolution, dust devils, tornados, infiltration, and preferential pathways.

Animal ingestion is part of the human exposure model, both as ingestion of fodder and feed by livestock, and ingestion of livestock by humans. Transport by atmospheric dispersion is modeled and is associated with limited resuspension, dust devils, and tornados. Modeling of biotic (plant- and animal-mediated) processes leading to contaminant transport, and the evolution of these processes in response to climate change and other influences, including bioturbation, burrowing, root development, and contaminant uptake and translocation are considered. Contaminant transport includes transport media (water, air, soil), transport processes (advection-dispersion, diffusion, plant uptake, soil translocation), and partitioning between phases. Diffusion occurs in gas and water phases. Dilution occurs when mixing with less concentrated water. Hydrodynamic dispersion is associated with water advection. Dissolution in water is limited by aqueous solubility. Transport in the gas phase includes gas generation in the waste, partitioning between air and water phases, diffusion in air and water, and radioactive decay and ingrowth. Infiltration of water through the cap, into wastes, and potentially to the groundwater is another contaminant migration concern. Preferential pathways for contaminant transport are also addressed.

### Human Processes

The FEPs identified as human processes encompass human behaviors and activities, resource use, and unintentional intrusion into the repository. Human process FEPs identified for assessment are related to the human exposure model and include anthropogenic climate change, human behavior, human-induced processes related to engineered features at the site, human-induced transport, inadvertent human intrusion, institutional control, land use, post-closure subsurface activities, waste recovery, water resource management, and weapons training such as that occurring at nearby bombing ranges.

### Exposure

Exposure is an integral part of the conceptual model, and may result from reduced site performance. Exposure-relevant FEPs identified for evaluation include those related to dosimetry, exposure media, human exposure, ingestion pathways, and inhalation pathways. Dosimetry as a science is not a FEP *per se* but physiological dose response is accounted for in the PA model.

Transport pathways (e.g. food chains) that lead to foodstuff contamination, and human exposures due to inhalation of gaseous radionuclides and particulates are included. Exposure media include are foodstuffs, drinking water, and environmental media. Exposure pathways (ingestion, inhalation, etc.) and physiological effects from radionuclides and toxic contaminants (e.g. uranium) are also assessed.

### Model Settings

Model settings that were identified during the FEP compilation process include model parameterization, period of performance, regulatory requirements, and spatial domain. While these are not FEPs in and of themselves, they are important considerations in the performance assessment model and are included with the FEPs for completeness.

# 7.0 References


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# Appendix: FEP Listings

**This appendix lists the features, events, and processes (FEPs) identified for evaluation in the Conceptual Site Model and Performance Assessment Scenario development. Table 1 contains all initial FEP values, listed and numbered by reference document.**

Table 2 lists those FEPs retained for analysis, and Table 3 includes all those FEPs that were dismissed from further consideration.

## Table 1. List of Initial FEPs by Reference

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 1 | meteorite | Andersson et al., 1989 |
| 2 | change in sea level | Andersson et al., 1989 |
| 3 | desert and unsaturation | Andersson et al., 1989 |
| 4 | no ice age | Andersson et al., 1989 |
| 5 | glaciation | Andersson et al., 1989 |
| 6 | permafrost | Andersson et al., 1989 |
| 7 | creeping of copper | Andersson et al., 1989 |
| 8 | common cause canister defects - Quality control | Andersson et al., 1989 |
| 9 | cracking along welds | Andersson et al., 1989 |
| 10 | degradation of hole- and shaft seals | Andersson et al., 1989 |
| 11 | electro-chemical cracking | Andersson et al., 1989 |
| 12 | internal pressure | Andersson et al., 1989 |
| 13 | radiation effects on canister | Andersson et al., 1989 |
| 14 | random canister defects - Quality control | Andersson et al., 1989 |
| 15 | reactions with cement pore water | Andersson et al., 1989 |
| 16 | role of chlorides in copper corrosion | Andersson et al., 1989 |
| 17 | thermal cracking | Andersson et al., 1989 |
| 18 | corrosive agents, sulphides, oxygen etc | Andersson et al., 1989 |
| 19 | pitting | Andersson et al., 1989 |
| 20 | stress corrosion cracking | Andersson et al., 1989 |
| 21 | accumulation in peat | Andersson et al., 1989 |
| 22 | colloid generation and transport | Andersson et al., 1989 |
| 23 | colloid generation - source | Andersson et al., 1989 |
| 24 | colloids, complexing agents | Andersson et al., 1989 |
| 25 | accumulation in sediments | Andersson et al., 1989 |
| 26 | loss of ductility | Andersson et al., 1989 |
| 27 | matrix diffusion | Andersson et al., 1989 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 28 | saturation of sorption sites | Andersson et al., 1989 |
| 29 | solubility and precipitation | Andersson et al., 1989 |
| 30 | sorption | Andersson et al., 1989 |
| 31 | extreme channel flow of oxidants and nuclides | Andersson et al., 1989 |
| 32 | radiation effects on bentonite | Andersson et al., 1989 |
| 33 | solubility within fuel matrix | Andersson et al., 1989 |
| 34 | thermal buoyancy | Andersson et al., 1989 |
| 35 | thermochemical changes | Andersson et al., 1989 |
| 36 | diffusion - surface diffusion | Andersson et al., 1989 |
| 37 | dilution | Andersson et al., 1989 |
| 38 | dispersion | Andersson et al., 1989 |
| 39 | dissolution chemistry | Andersson et al., 1989 |
| 40 | dissolution of fracture fillings/precipitations | Andersson et al., 1989 |
| 41 | methane intrusion | Andersson et al., 1989 |
| 42 | accumulation of gases under permafrost | Andersson et al., 1989 |
| 43 | gas transport | Andersson et al., 1989 |
| 44 | gas transport in bentonite | Andersson et al., 1989 |
| 45 | flow through buffer/backfill | Andersson et al., 1989 |
| 46 | preferential pathways in the buffer/backfill | Andersson et al., 1989 |
| 47 | poorly designed repository | Andersson et al., 1989 |
| 48 | backfill effects on copper corrosion | Andersson et al., 1989 |
| 49 | backfill material deficiencies | Andersson et al., 1989 |
| 50 | changed hydrostatic pressure on canister | Andersson et al., 1989 |
| 51 | degradation of the bentonite by chemical reactions | Andersson et al., 1989 |
| 52 | erosion of buffer/backfill | Andersson et al., 1989 |
| 53 | excavation/backfilling effects on nearby rock | Andersson et al., 1989 |
| 54 | external stress | Andersson et al., 1989 |
| 55 | hydraulic conductivity change - excavation/backfilling effect | Andersson et al., 1989 |
| 56 | hydrostatic pressure on canister | Andersson et al., 1989 |
| 57 | movement of canister in buffer/backfill | Andersson et al., 1989 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 58 | thermal effects on the buffer material | Andersson et al., 1989 |
| 59 | voids in the lead filling | Andersson et al., 1989 |
| 60 | swelling of bentonite into tunnels and cracks | Andersson et al., 1989 |
| 61 | swelling of corrosion products | Andersson et al., 1989 |
| 62 | uneven swelling of bentonite | Andersson et al., 1989 |
| 63 | mechanical effects - excavation/backfilling effects | Andersson et al., 1989 |
| 64 | mechanical failure of buffer/backfill | Andersson et al., 1989 |
| 65 | mechanical failure of repository | Andersson et al., 1989 |
| 66 | sudden energy release | Andersson et al., 1989 |
| 67 | coagulation of bentonite | Andersson et al., 1989 |
| 68 | chemical toxicity of wastes | Andersson et al., 1989 |
| 69 | complexing agents | Andersson et al., 1989 |
| 70 | far field hydrochemistry - acids, oxidants. nitrate | Andersson et al., 1989 |
| 71 | change of ground-water chemistry in nearby rock | Andersson et al., 1989 |
| 72 | chemical effects of rock reinforcement | Andersson et al., 1989 |
| 73 | coupled effects (electrophoresis) | Andersson et al., 1989 |
| 74 | effects of bentonite on ground-water chemistry | Andersson et al., 1989 |
| 75 | isotopic dilution | Andersson et al., 1989 |
| 76 | near field buffer chemistry | Andersson et al., 1989 |
| 77 | oxidizing conditions | Andersson et al., 1989 |
| 78 | Pb-I reactions | Andersson et al., 1989 |
| 79 | pH-deviations | Andersson et al., 1989 |
| 80 | recrystallization | Andersson et al., 1989 |
| 81 | redox front | Andersson et al., 1989 |
| 82 | redox potential | Andersson et al., 1989 |
| 83 | diagenesis | Andersson et al., 1989 |
| 84 | accidents during operation | Andersson et al., 1989 |
| 85 | human-induced climate change | Andersson et al., 1989 |
| 86 | non-sealed repository | Andersson et al., 1989 |
| 87 | unsealed boreholes and/or shafts | Andersson et al., 1989 |
| 88 | explosions | Andersson et al., 1989 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 89 | geothermal energy production | Andersson et al., 1989 |
| 90 | enhanced rock fracturing | Andersson et al., 1989 |
| 91 | thermo-hydro-mechanical effects | Andersson et al., 1989 |
| 92 | altered surface water chemistry by humans | Andersson et al., 1989 |
| 93 | city on the site | Andersson et al., 1989 |
| 94 | underground dwellings | Andersson et al., 1989 |
| 95 | loss of records | Andersson et al., 1989 |
| 96 | archeological intrusion | Andersson et al., 1989 |
| 97 | postclosure monitoring | Andersson et al., 1989 |
| 98 | underground test of nuclear devices | Andersson et al., 1989 |
| 99 | unsuccessful attempt of site improvement | Andersson et al., 1989 |
| 100 | poorly constructed repository | Andersson et al., 1989 |
| 101 | future boreholes and undetected past boreholes | Andersson et al., 1989 |
| 102 | other future uses of crystalline rock | Andersson et al., 1989 |
| 103 | reuse of boreholes | Andersson et al., 1989 |
| 104 | chemical sabotage | Andersson et al., 1989 |
| 105 | nuclear war | Andersson et al., 1989 |
| 106 | waste retrieval, mining | Andersson et al., 1989 |
| 107 | human-induced actions on ground-water recharge | Andersson et al., 1989 |
| 108 | human-induced changes in surface hydrology | Andersson et al., 1989 |
| 109 | water producing well | Andersson et al., 1989 |
| 110 | weathering of flow paths | Andersson et al., 1989 |
| 111 | erosion on surface/sediments | Andersson et al., 1989 |
| 112 | geothermally induced flow | Andersson et al., 1989 |
| 113 | sedimentation of bentonite | Andersson et al., 1989 |
| 114 | changes of ground-water flow | Andersson et al., 1989 |
| 115 | enhanced ground-water flow | Andersson et al., 1989 |
| 116 | groundwater recharge/discharge | Andersson et al., 1989 |
| 117 | resaturation | Andersson et al., 1989 |
| 118 | saline or fresh ground-water intrusion | Andersson et al., 1989 |
| 119 | river meandering | Andersson et al., 1989 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 120 | microbes | Andersson et al., 1989 |
| 121 | repository induced Pb/Cu electrochemical reactions | Andersson et al., 1989 |
| 122 | Gas generation | Andersson et al., 1989 |
| 123 | gas generation: He production | Andersson et al., 1989 |
| 124 | radiolysis | Andersson et al., 1989 |
| 125 | radiolysis | Andersson et al., 1989 |
| 126 | recoil of alpha-decay | Andersson et al., 1989 |
| 127 | reconcentration | Andersson et al., 1989 |
| 128 | chemical reactions (copper corrosion) | Andersson et al., 1989 |
| 129 | I, Cs-migration to fuel surface | Andersson et al., 1989 |
| 130 | interactions with corrosion products and waste | Andersson et al., 1989 |
| 131 | internal corrosion due to waste | Andersson et al., 1989 |
| 132 | natural telluric electrochemical reactions | Andersson et al., 1989 |
| 133 | perturbed buffer material chemistry | Andersson et al., 1989 |
| 134 | radioactive decay; heat | Andersson et al., 1989 |
| 135 | release of radionuclides from failed canister | Andersson et al., 1989 |
| 136 | role of the eventual channeling within the canister | Andersson et al., 1989 |
| 137 | soret effect | Andersson et al., 1989 |
| 138 | earthquakes | Andersson et al., 1989 |
| 139 | faulting | Andersson et al., 1989 |
| 140 | intruding dikes | Andersson et al., 1989 |
| 141 | changes of the magnetic field | Andersson et al., 1989 |
| 142 | stress changes of conductivity | Andersson et al., 1989 |
| 143 | creeping of rock mass | Andersson et al., 1989 |
| 144 | intrusion into accumulation zone in the biosphere | Andersson et al., 1989 |
| 145 | uplift and subsidence | Andersson et al., 1989 |
| 146 | effect of plate movements | Andersson et al., 1989 |
| 147 | tectonic activity - large scale | Andersson et al., 1989 |
| 148 | undetected discontinuities | Andersson et al., 1989 |
| 149 | undetected fracture zones | Andersson et al., 1989 |
| 150 | volcanism | Andersson et al., 1989 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 151 | criticality | Andersson et al., 1989 |
| 152 | H2/02 explosions | Andersson et al., 1989 |
| 153 | co-storage of other waste | Andersson et al., 1989 |
| 154 | damaged or deviating fuel | Andersson et al., 1989 |
| 155 | decontamination materials left | Andersson et al., 1989 |
| 156 | near storage of other waste | Andersson et al., 1989 |
| 157 | stray materials left | Andersson et al., 1989 |
| 158 | Meteorites | Burkholder, 1980 |
| 159 | climate modification | Burkholder, 1980 |
| 160 | Glaciation | Burkholder, 1980 |
| 161 | corrosion | Burkholder, 1980 |
| 162 | Transport Agent Introduction | Burkholder, 1980 |
| 163 | fluid migration | Burkholder, 1980 |
| 164 | dissolutioning | Burkholder, 1980 |
| 165 | biochemical gas generation | Burkholder, 1980 |
| 166 | decay product gas generation | Burkholder, 1980 |
| 167 | differential elastic response | Burkholder, 1980 |
| 168 | dewatering | Burkholder, 1980 |
| 169 | canister movement | Burkholder, 1980 |
| 170 | fluid pressure changes | Burkholder, 1980 |
| 171 | material property changes | Burkholder, 1980 |
| 172 | non-elastic response | Burkholder, 1980 |
| 173 | shaft seal failure | Burkholder, 1980 |
| 174 | geochemical alterations | Burkholder, 1980 |
| 175 | diagenesis | Burkholder, 1980 |
| 176 | gas or brine pockets | Burkholder, 1980 |
| 177 | reservoirs | Burkholder, 1980 |
| 178 | undiscovered boreholes | Burkholder, 1980 |
| 179 | Undetected Past Intrusion | Burkholder, 1980 |
| 180 | Intentional Intrusion | Burkholder, 1980 |
| 181 | archeological exhumation | Burkholder, 1980 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 182 | irrigation | Burkholder, 1980 |
| 183 | establishment of new population center | Burkholder, 1980 |
| 184 | improper waste emplacement | Burkholder, 1980 |
| 185 | resource mining (mineral hydrocarbon, geothermal, salt) | Burkholder, 1980 |
| 186 | mine shafts | Burkholder, 1980 |
| 187 | sabotage | Burkholder, 1980 |
| 188 | war | Burkholder, 1980 |
| 189 | waste recovery | Burkholder, 1980 |
| 190 | intentional artificial ground-water recharge or withdrawal | Burkholder, 1980 |
| 191 | weapons testing | Burkholder, 1980 |
| 192 | Denudation and Stream Erosion | Burkholder, 1980 |
| 193 | sedimentation | Burkholder, 1980 |
| 194 | flooding | Burkholder, 1980 |
| 195 | radiolysis | Burkholder, 1980 |
| 196 | waste package - geology interactions | Burkholder, 1980 |
| 197 | breccia pipes | Burkholder, 1980 |
| 198 | diapirism | Burkholder, 1980 |
| 199 | far-field faulting | Burkholder, 1980 |
| 200 | near-field faulting | Burkholder, 1980 |
| 201 | faults, shear zones | Burkholder, 1980 |
| 202 | static fracturing | Burkholder, 1980 |
| 203 | impact fracturing | Burkholder, 1980 |
| 204 | surficial fissuring | Burkholder, 1980 |
| 205 | local fracturing | Burkholder, 1980 |
| 206 | Igneous emplacement | Burkholder, 1980 |
| 207 | intrusive magmatic activity | Burkholder, 1980 |
| 208 | hydraulic fracturing | Burkholder, 1980 |
| 209 | isostasy | Burkholder, 1980 |
| 210 | lava tubes | Burkholder, 1980 |
| 211 | Orogenic Diastrophism | Burkholder, 1980 |
| 212 | Epeirogenic Displacement | Burkholder, 1980 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 213 | undetected features | Burkholder, 1980 |
| 214 | extrusive magmatic activity | Burkholder, 1980 |
| 215 | criticality | Burkholder, 1980 |
| 216 | chemical liquid waste disposal | Burkholder, 1980 |
| 217 | storage of hydrocarbons or compressed air | Burkholder, 1980 |
| 218 | non-nuclear waste disposal | Burkholder, 1980 |
| 219 | Celestial bodies | Guzowski, 1990 |
| 220 | meteorite impact | Guzowski, 1990 |
| 221 | sea-level variations | Guzowski, 1990 |
| 222 | pluvial periods | Guzowski, 1990 |
| 223 | glaciation | Guzowski, 1990 |
| 224 | seiches | Guzowski, 1990 |
| 225 | formation of dissolution cavities | Guzowski, 1990 |
| 226 | excavation induced stress/fracturing in host rock | Guzowski, 1990 |
| 227 | subsidence and caving | Guzowski, 1990 |
| 228 | thermally induced stress/fracturing in host rock | Guzowski, 1990 |
| 229 | shaft and borehole seal degradation | Guzowski, 1990 |
| 230 | explosions | Guzowski, 1990 |
| 231 | Inadvertent Future Intrusions | Guzowski, 1990 |
| 232 | injection wells | Guzowski, 1990 |
| 233 | irrigation | Guzowski, 1990 |
| 234 | drilling | Guzowski, 1990 |
| 235 | mining | Guzowski, 1990 |
| 236 | damming of streams or rivers | Guzowski, 1990 |
| 237 | withdrawal wells | Guzowski, 1990 |
| 238 | mass wasting | Guzowski, 1990 |
| 239 | erosion/ sedimentation | Guzowski, 1990 |
| 240 | flooding | Guzowski, 1990 |
| 241 | hydrologic stresses | Guzowski, 1990 |
| 242 | hurricanes | Guzowski, 1990 |
| 243 | tsunamis | Guzowski, 1990 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 244 | diapirism | Guzowski, 1990 |
| 245 | faulting | Guzowski, 1990 |
| 246 | formation of interconnected fracture systems | Guzowski, 1990 |
| 247 | regional subsidence or uplift (also applies to subsurface) | Guzowski, 1990 |
| 248 | seismic activity | Guzowski, 1990 |
| 249 | magmatic activity | Guzowski, 1990 |
| 250 | volcanic activity | Guzowski, 1990 |
| 251 | meteorite impact | Hertzler and Atwood, 1989 |
| 252 | climatic change | Hertzler and Atwood, 1989 |
| 253 | sea level change | Hertzler and Atwood, 1989 |
| 254 | dam and reservoir formation from natural causes | Hertzler and Atwood, 1989 |
| 255 | glacial activity | Hertzler and Atwood, 1989 |
| 256 | radial dispersion | Hertzler and Atwood, 1989 |
| 257 | fluid interactions | Hertzler and Atwood, 1989 |
| 258 | dissolution | Hertzler and Atwood, 1989 |
| 259 | decay product gas generation | Hertzler and Atwood, 1989 |
| 260 | infiltration and evapotranspiration | Hertzler and Atwood, 1989 |
| 261 | thermal changes in burial zone caused by heat generation | Hertzler and Atwood, 1989 |
| 262 | mechanical effects | Hertzler and Atwood, 1989 |
| 263 | shaft/borehole seal failure | Hertzler and Atwood, 1989 |
| 264 | geochemical changes from natural causes | Hertzler and Atwood, 1989 |
| 265 | diagenesis | Hertzler and Atwood, 1989 |
| 266 | landslide | Hertzler and Atwood, 1989 |
| 267 | local subsidence/caving | Hertzler and Atwood, 1989 |
| 268 | climate control | Hertzler and Atwood, 1989 |
| 269 | fire and explosion | Hertzler and Atwood, 1989 |
| 270 | fire and explosion of waste after burial | Hertzler and Atwood, 1989 |
| 271 | geochemical changes from manmade causes | Hertzler and Atwood, 1989 |
| 272 | earthquake from man-made causes | Hertzler and Atwood, 1989 |
| 273 | human surface activities | Hertzler and Atwood, 1989 |
| 274 | hydrology change from man-made causes | Hertzler and Atwood, 1989 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 275 | unanticipated intrusion | Hertzler and Atwood, 1989 |
| 276 | undetected past intrusion | Hertzler and Atwood, 1989 |
| 277 | undetected features or processes | Hertzler and Atwood, 1989 |
| 278 | intentional intrusion | Hertzler and Atwood, 1989 |
| 279 | improper waste emplacement | Hertzler and Atwood, 1989 |
| 280 | mining inadvertent intruder | Hertzler and Atwood, 1989 |
| 281 | dam and reservoir, man-made | Hertzler and Atwood, 1989 |
| 282 | well-drilling inadvertent intruder | Hertzler and Atwood, 1989 |
| 283 | weapons testing | Hertzler and Atwood, 1989 |
| 284 | land erosion | Hertzler and Atwood, 1989 |
| 285 | sedimentation/ aggradation | Hertzler and Atwood, 1989 |
| 286 | lateral ground-water flow in the unsaturated zone | Hertzler and Atwood, 1989 |
| 287 | hydrology change from natural causes | Hertzler and Atwood, 1989 |
| 288 | hurricane | Hertzler and Atwood, 1989 |
| 289 | tornado | Hertzler and Atwood, 1989 |
| 290 | brush fire | Hertzler and Atwood, 1989 |
| 291 | chemical effects | Hertzler and Atwood, 1989 |
| 292 | diapirism | Hertzler and Atwood, 1989 |
| 293 | earthquake from natural causes | Hertzler and Atwood, 1989 |
| 294 | faulting | Hertzler and Atwood, 1989 |
| 295 | igneous activity | Hertzler and Atwood, 1989 |
| 296 | regional subsidence or uplift | Hertzler and Atwood, 1989 |
| 297 | criticality | Hertzler and Atwood, 1989 |
| 298 | chemical liquid waste disposal | Hertzler and Atwood, 1989 |
| 299 | unanticipated waste composition | Hertzler and Atwood, 1989 |
| 300 | permafrost affects repository | Hunter, 1983 |
| 301 | fluids do not recirculate in response to thermal gradients | Hunter, 1983 |
| 302 | fluids leave along new fault | Hunter, 1983 |
| 303 | fluids recirculate in response to thermal gradients | Hunter, 1983 |
| 304 | fluids recirculate in response to thermal gradients | Hunter, 1983 |
| 305 | normal flow increases | Hunter, 1983 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 306 | diffusive mixing occurs | Hunter, 1983 |
| 307 | flux through repository is altered | Hunter, 1983 |
| 308 | head is above outfall | Hunter, 1983 |
| 309 | head is below outfall | Hunter, 1983 |
| 310 | subsidence fractures end above repository | Hunter, 1983 |
| 311 | subsidence fractures reach repository | Hunter, 1983 |
| 312 | fluids carry waste to rivers or tributaries | Hunter, 1983 |
| 313 | fluids carry waste to wells or springs | Hunter, 1983 |
| 314 | ground-water flow paths are shortened | Hunter, 1983 |
| 315 | water from a confined aquifer enters repository | Hunter, 1983 |
| 316 | water from the unconfined aquifer enters repository | Hunter, 1983 |
| 317 | location of river channel changes | Hunter, 1983 |
| 318 | location of river channel changes and flow through repository is altered | Hunter, 1983 |
| 319 | flow channels close and reopen later | Hunter, 1983 |
| 320 | meteorite impact | Hunter, 1989 |
| 321 | climatic change | Hunter, 1989 |
| 322 | glaciation | Hunter, 1989 |
| 323 | leaching | Hunter, 1989 |
| 324 | diffusion out of the repository | Hunter, 1989 |
| 325 | dissolution | Hunter, 1989 |
| 326 | dissolution other than leaching | Hunter, 1989 |
| 327 | thermal effects | Hunter, 1989 |
| 328 | seal performance | Hunter, 1989 |
| 329 | subsidence | Hunter, 1989 |
| 330 | exhumation | Hunter, 1989 |
| 331 | drilling into repository | Hunter, 1989 |
| 332 | effects of mining for resources | Hunter, 1989 |
| 333 | sabotage | Hunter, 1989 |
| 334 | warfare | Hunter, 1989 |
| 335 | sedimentation | Hunter, 1989 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 336 | ground-water flow | Hunter, 1989 |
| 337 | migration of brine aquifer | Hunter, 1989 |
| 338 | migration of intracrystalline brine inclusions | Hunter, 1989 |
| 339 | effects of brine pocket | Hunter, 1989 |
| 340 | gas generation waste effect | Hunter, 1989 |
| 341 | radiolysis waste effect | Hunter, 1989 |
| 342 | waste/rock interaction | Hunter, 1989 |
| 343 | breccia-pipe formation | Hunter, 1989 |
| 344 | induced diapirism | Hunter, 1989 |
| 345 | faulting | Hunter, 1989 |
| 346 | Igneous intrusion | Hunter, 1989 |
| 347 | nuclear criticality | Hunter, 1989 |
| 348 | meteorite impact | IAEA 1983 |
| 349 | climatic change | IAEA 1983 |
| 350 | sea level change | IAEA 1983 |
| 351 | glacial erosion | IAEA 1983 |
| 352 | geochemical change | IAEA 1983 |
| 353 | corrosion | IAEA 1983 |
| 354 | transport agent introduction | IAEA 1983 |
| 355 | fluid interactions | IAEA 1983 |
| 356 | fluid migration | IAEA 1983 |
| 357 | decay-product gas generation | IAEA 1983 |
| 358 | faulty design | IAEA 1983 |
| 359 | exploration bore-hole seal failure | IAEA 1983 |
| 360 | thermal effects | IAEA 1983 |
| 361 | canister movement | IAEA 1983 |
| 362 | fluid pressure, density, viscosity changes | IAEA 1983 |
| 363 | differential elastic response | IAEA 1983 |
| 364 | material property changes | IAEA 1983 |
| 365 | mechanical effects | IAEA 1983 |
| 366 | non-elastic response | IAEA 1983 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 367 | shaft seal failure | IAEA 1983 |
| 368 | geochemical change | IAEA 1983 |
| 369 | diagenesis | IAEA 1983 |
| 370 | gas or brine pockets | IAEA 1983 |
| 371 | climate control | IAEA 1983 |
| 372 | reservoirs | IAEA 1983 |
| 373 | inadvertent future intrusion | IAEA 1983 |
| 374 | undetected past intrusion | IAEA 1983 |
| 375 | undiscovered boreholes | IAEA 1983 |
| 376 | Intentional intrusion | IAEA 1983 |
| 377 | archeological exhumation | IAEA 1983 |
| 378 | irrigation | IAEA 1983 |
| 379 | faulty operation | IAEA 1983 |
| 380 | faulty waste emplacement | IAEA 1983 |
| 381 | resource mining (mineral, water, hydrocarbon, geothermal, salt, etc) | IAEA 1983 |
| 382 | exploratory drilling | IAEA 1983 |
| 383 | mine shafts | IAEA 1983 |
| 384 | sabotage | IAEA 1983 |
| 385 | war | IAEA 1983 |
| 386 | waste recovery | IAEA 1983 |
| 387 | intentional artificial ground-water recharge or withdrawal | IAEA 1983 |
| 388 | denudation | IAEA 1983 |
| 389 | stream erosion | IAEA 1983 |
| 390 | sedimentation | IAEA 1983 |
| 391 | flooding | IAEA 1983 |
| 392 | ground-water flow | IAEA 1983 |
| 393 | brine pockets | IAEA 1983 |
| 394 | large-scale alterations of hydrology | IAEA 1983 |
| 395 | hydrology change | IAEA 1983 |
| 396 | gas generation | IAEA 1983 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 397 | radiolysis | IAEA 1983 |
| 398 | waste package-rock interactions | IAEA 1983 |
| 399 | breccia pipes | IAEA 1983 |
| 400 | diapirism | IAEA 1983 |
| 401 | faulting/seismicity | IAEA 1983 |
| 402 | faults, shear zones | IAEA 1983 |
| 403 | local fracturing | IAEA 1983 |
| 404 | intrusive | IAEA 1983 |
| 405 | intrusive dikes | IAEA 1983 |
| 406 | Isostatic | IAEA 1983 |
| 407 | lava tubes | IAEA 1983 |
| 408 | orogenic | IAEA 1983 |
| 409 | uplift/subsidence | IAEA 1983 |
| 410 | epeirogenic | IAEA 1983 |
| 411 | magmatic activity | IAEA 1983 |
| 412 | extrusive | IAEA 1983 |
| 413 | nuclear criticality | IAEA 1983 |
| 414 | chemical liquid waste disposal | IAEA 1983 |
| 415 | meteorites | Koplik et al., 1982 |
| 416 | climate modification | Koplik et al., 1982 |
| 417 | climatic fluctuations | Koplik et al., 1982 |
| 418 | glaciation | Koplik et al., 1982 |
| 419 | corrosion | Koplik et al., 1982 |
| 420 | biosphere alteration | Koplik et al., 1982 |
| 421 | local fluid migration | Koplik et al., 1982 |
| 422 | dissolutioning | Koplik et al., 1982 |
| 423 | decay product gas generation | Koplik et al., 1982 |
| 424 | Improper design of operation | Koplik et al., 1982 |
| 425 | Thermal effects | Koplik et al., 1982 |
| 426 | canister movement | Koplik et al., 1982 |
| 427 | change in local state of stress | Koplik et al., 1982 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 428 | readjustment of rock along joints | Koplik et al., 1982 |
| 429 | fluid pressure changes | Koplik et al., 1982 |
| 430 | canister migration | Koplik et al., 1982 |
| 431 | convection | Koplik et al., 1982 |
| 432 | differential elastic response | Koplik et al., 1982 |
| 433 | material property changes | Koplik et al., 1982 |
| 434 | Mechanical effects | Koplik et al., 1982 |
| 435 | nonelastic response | Koplik et al., 1982 |
| 436 | stored energy | Koplik et al., 1982 |
| 437 | shaft seal failure | Koplik et al., 1982 |
| 438 | seal - rock interactions | Koplik et al., 1982 |
| 439 | subsidence of canister | Koplik et al., 1982 |
| 440 | geochemical alterations | Koplik et al., 1982 |
| 441 | diagenesis | Koplik et al., 1982 |
| 442 | gas or brine pockets | Koplik et al., 1982 |
| 443 | reservoirs | Koplik et al., 1982 |
| 444 | Inadvertent future intrusion | Koplik et al., 1982 |
| 445 | Undetected past intrusion | Koplik et al., 1982 |
| 446 | undiscovered boreholes | Koplik et al., 1982 |
| 447 | Intentional intrusion | Koplik et al., 1982 |
| 448 | archeological exhumation | Koplik et al., 1982 |
| 449 | irrigation | Koplik et al., 1982 |
| 450 | establishment of population center | Koplik et al., 1982 |
| 451 | improper waste emplacement | Koplik et al., 1982 |
| 452 | resource mining (salt, mineral, hydrocarbon, geothermal) | Koplik et al., 1982 |
| 453 | mine shafts | Koplik et al., 1982 |
| 454 | sabotage | Koplik et al., 1982 |
| 455 | war | Koplik et al., 1982 |
| 456 | waste recovery | Koplik et al., 1982 |
| 457 | Perturbation of ground-water system | Koplik et al., 1982 |
| 458 | intentional artificial ground-water recharge or withdrawal | Koplik et al., 1982 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 459 | weapons testing | Koplik et al., 1982 |
| 460 | Denudation and stream erosion | Koplik et al., 1982 |
| 461 | Sedimentation | Koplik et al., 1982 |
| 462 | Flooding | Koplik et al., 1982 |
| 463 | Modification of hydrologic regime | Koplik et al., 1982 |
| 464 | gas generation | Koplik et al., 1982 |
| 465 | Radiation effects | Koplik et al., 1982 |
| 466 | radiolysis | Koplik et al., 1982 |
| 467 | Chemical effects | Koplik et al., 1982 |
| 468 | waste package - geology interactions | Koplik et al., 1982 |
| 469 | breccia pipes | Koplik et al., 1982 |
| 470 | diapirism | Koplik et al., 1982 |
| 471 | far-field faulting | Koplik et al., 1982 |
| 472 | near-field faulting | Koplik et al., 1982 |
| 473 | faults, shear zones | Koplik et al., 1982 |
| 474 | Static fracturing | Koplik et al., 1982 |
| 475 | impact fracturing | Koplik et al., 1982 |
| 476 | surficial fissuring | Koplik et al., 1982 |
| 477 | local fracturing | Koplik et al., 1982 |
| 478 | Igneous emplacement | Koplik et al., 1982 |
| 479 | intrusive magmatic activity | Koplik et al., 1982 |
| 480 | hydraulic fracturing | Koplik et al., 1982 |
| 481 | isostasy | Koplik et al., 1982 |
| 482 | lava tubes | Koplik et al., 1982 |
| 483 | Orogenic diastrophism | Koplik et al., 1982 |
| 484 | Epeirogenic displacement | Koplik et al., 1982 |
| 485 | Magmatic activity | Koplik et al., 1982 |
| 486 | extrusive magmatic activity | Koplik et al., 1982 |
| 487 | criticality | Koplik et al., 1982 |
| 488 | storage of hydrocarbons, compressed air, or hot water | Koplik et al., 1982 |
| 489 | non-nuclear waste disposal | Koplik et al., 1982 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 490 | chemical liquid waste disposal | Koplik et al., 1982 |
| 491 | Meteorite impact | Merrett and Gillespie, 1983 |
| 492 | determination of meteorite impact frequencies | Merrett and Gillespie, 1983 |
| 493 | probability of meteorite damage | Merrett and Gillespie, 1983 |
| 494 | Glaciation | Merrett and Gillespie, 1983 |
| 495 | glacial erosion | Merrett and Gillespie, 1983 |
| 496 | fracture mechanics analysis | Merrett and Gillespie, 1983 |
| 497 | vault-related events | Merrett and Gillespie, 1983 |
| 498 | presence of a heat source | Merrett and Gillespie, 1983 |
| 499 | excavation | Merrett and Gillespie, 1983 |
| 500 | use of explosive devices | Merrett and Gillespie, 1983 |
| 501 | drilling and mining | Merrett and Gillespie, 1983 |
| 502 | Denudation and fluvial erosion | Merrett and Gillespie, 1983 |
| 503 | denudation | Merrett and Gillespie, 1983 |
| 504 | fluvial erosion | Merrett and Gillespie, 1983 |
| 505 | alteration of hydrological conditions | Merrett and Gillespie, 1983 |
| 506 | new fault formation | Merrett and Gillespie, 1983 |
| 507 | rapid fault growth | Merrett and Gillespie, 1983 |
| 508 | slow fault growth | Merrett and Gillespie, 1983 |
| 509 | stress analysis | Merrett and Gillespie, 1983 |
| 510 | glacially induced faulting | Merrett and Gillespie, 1983 |
| 511 | subsidence and rebound | Merrett and Gillespie, 1983 |
| 512 | Seismic activity | Merrett and Gillespie, 1983 |
| 513 | jointed rock motion | Merrett and Gillespie, 1983 |
| 514 | Volcanic activity | Merrett and Gillespie, 1983 |
| 515 | hot-spot volcanic activity | Merrett and Gillespie, 1983 |
| 516 | rift system volcanic activity | Merrett and Gillespie, 1983 |
| 517 | Presence of a radioactive source | Merrett and Gillespie, 1983 |
| 518 | Meteorite impact | NEA OECD, 2000 |
| 519 | Climate change, Global | NEA OECD, 2000 |
| 520 | Climate change, regional and local | NEA OECD, 2000 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 521 | Ecological response to climate changes | NEA OECD, 2000 |
| 522 | Hydrological/hydrogeological response to climate changes | NEA OECD, 2000 |
| 523 | Sea Level change | NEA OECD, 2000 |
| 524 | Warm climate effects (tropical and desert) | NEA OECD, 2000 |
| 525 | Glacial and ice sheet effects, local | NEA OECD, 2000 |
| 526 | Periglacial effects | NEA OECD, 2000 |
| 527 | Container materials and characteristics | NEA OECD, 2000 |
| 528 | Atmospheric transport of contaminants | NEA OECD, 2000 |
| 529 | Vegetation | NEA OECD, 2000 |
| 530 | Animal populations | NEA OECD, 2000 |
| 531 | Biological/biochemical processes and conditions (in geosphere) | NEA OECD, 2000 |
| 532 | Biological/biochemical processes and conditions (in waste and EBS) | NEA OECD, 2000 |
| 533 | Species evolution | NEA OECD, 2000 |
| 534 | Animal, plant and microbe mediated transport of contaminants | NEA OECD, 2000 |
| 535 | Colloids. contaminant interactions and transport with | NEA OECD, 2000 |
| 536 | Contaminant transport path characteristics (in geosphere) | NEA OECD, 2000 |
| 537 | Chemical/complexing agents, effects on contaminant speciation/transport | NEA OECD, 2000 |
| 538 | Solid-mediated transport of contaminants | NEA OECD, 2000 |
| 539 | Sorption/desorption processes, contaminant | NEA OECD, 2000 |
| 540 | Speciation and solubility, contaminant | NEA OECD, 2000 |
| 541 | Dissolution, precipitation, and crystallization, contaminant | NEA OECD, 2000 |
| 542 | Noble gases | NEA OECD, 2000 |
| 543 | Volatiles and potential for volatility | NEA OECD, 2000 |
| 544 | Gas-mediated transport of contaminants | NEA OECD, 2000 |
| 545 | Geological resources | NEA OECD, 2000 |
| 546 | Geological units, other | NEA OECD, 2000 |
| 547 | Host rock | NEA OECD, 2000 |
| 548 | Repository assumptions | NEA OECD, 2000 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 549 | Thermal processes and conditions (in geosphere) | NEA OECD, 2000 |
| 550 | Excavation disturbed zone, host rock | NEA OECD, 2000 |
| 551 | Buffer/backfill materials and characteristics | NEA OECD, 2000 |
| 552 | Other engineered features materials and characteristics | NEA OECD, 2000 |
| 553 | Thermal processes and conditions (in wastes and EBS) | NEA OECD, 2000 |
| 554 | Emplacement of wastes and backfilling | NEA OECD, 2000 |
| 555 | Repository design | NEA OECD, 2000 |
| 556 | Mechanical processes and conditions (in geosphere) | NEA OECD, 2000 |
| 557 | Mechanical processes and conditions (in wastes and EBS) | NEA OECD, 2000 |
| 558 | Seals. cavern/tunnel/shaft | NEA OECD, 2000 |
| 559 | Closure and repository sealing | NEA OECD, 2000 |
| 560 | Dose response assumptions | NEA OECD, 2000 |
| 561 | Dosimetry | NEA OECD, 2000 |
| 562 | Drinking water, foodstuffs and drugs, contaminant concentrations in | NEA OECD, 2000 |
| 563 | Environmental media, contaminant concentrations in | NEA OECD, 2000 |
| 564 | Impacts or concern | NEA OECD, 2000 |
| 565 | Human characteristics (physiology, metabolism) | NEA OECD, 2000 |
| 566 | Chemical/organic toxin stability | NEA OECD, 2000 |
| 567 | Exposure modes | NEA OECD, 2000 |
| 568 | Non-food products, contaminant concentrations in | NEA OECD, 2000 |
| 569 | Nonradiological toxicity/effects | NEA OECD, 2000 |
| 570 | Radiological toxicity/effects | NEA OECD, 2000 |
| 571 | Radon and radon daughter exposure | NEA OECD, 2000 |
| 572 | Diet and fluid Intake | NEA OECD, 2000 |
| 573 | Food and water processing and preparation | NEA OECD, 2000 |
| 574 | Food chains, uptake of contaminants in | NEA OECD, 2000 |
| 575 | Chemical/geochemical processes and conditions (in geosphere) | NEA OECD, 2000 |
| 576 | Chemical/geochemical processes and conditions (In wastes and | NEA OECD, 2000 |
| 577 | Organics and potential for organic forms | NEA OECD, 2000 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 578 | Diagenesis | NEA OECD, 2000 |
| 579 | Gas sources and effects (in geosphere) | NEA OECD, 2000 |
| 580 | Human influences on climate | NEA OECD, 2000 |
| 581 | Social and Institutional developments | NEA OECD, 2000 |
| 582 | Excavation/construction | NEA OECD, 2000 |
| 583 | Explosions and crashes | NEA OECD, 2000 |
| 584 | Future human action assumptions | NEA OECD, 2000 |
| 585 | Future human behavior (target group) assumptions | NEA OECD, 2000 |
| 586 | Habits (non-diet related behavior) | NEA OECD, 2000 |
| 587 | Leisure and other uses of environment | NEA OECD, 2000 |
| 588 | Human response to climate changes | NEA OECD, 2000 |
| 589 | Surface environment, human activities | NEA OECD, 2000 |
| 590 | Technological developments | NEA OECD, 2000 |
| 591 | Adults, children, Infants and other variations | NEA OECD, 2000 |
| 592 | Human-action-mediated transport of contaminants | NEA OECD, 2000 |
| 593 | Community characteristics | NEA OECD, 2000 |
| 594 | Dwellings | NEA OECD, 2000 |
| 595 | Motivation and knowledge issues (inadvertent/deliberate human actions) | NEA OECD, 2000 |
| 596 | Administrative control , repository site | NEA OECD, 2000 |
| 597 | Records and markers, repository | NEA OECD, 2000 |
| 598 | Unintrusive site investigation | NEA OECD, 2000 |
| 599 | Site Investigation | NEA OECD, 2000 |
| 600 | Rural and agricultural land and water use (incl. fisheries) | NEA OECD, 2000 |
| 601 | Urban and Industrial land and water use | NEA OECD, 2000 |
| 602 | Wild and natural land and water use | NEA OECD, 2000 |
| 603 | Monitoring of repository | NEA OECD, 2000 |
| 604 | Remedial actions | NEA OECD, 2000 |
| 605 | Schedule and planning | NEA OECD, 2000 |
| 606 | Quality control | NEA OECD, 2000 |
| 607 | Retrievability | NEA OECD, 2000 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 608 | Drilling activities (human intrusion) | NEA OECD, 2000 |
| 609 | Mining and other underground activities (human intrusion) | NEA OECD, 2000 |
| 610 | Accidents and unplanned events | NEA OECD, 2000 |
| 611 | Water management (wells, reservoirs. dams) | NEA OECD, 2000 |
| 612 | Coastal features | NEA OECD, 2000 |
| 613 | Topography and morphology | NEA OECD, 2000 |
| 614 | Erosion and deposition | NEA OECD, 2000 |
| 615 | Erosion and sedimentation | NEA OECD, 2000 |
| 616 | Hydraulic/hydrogeological processes and conditions (in geosphere) | NEA OECD, 2000 |
| 617 | Hydraulic/hydrogeological processes and conditions (in wastes and EBS) | NEA OECD, 2000 |
| 618 | Hydrological/hydrogeological response to geological changes | NEA OECD, 2000 |
| 619 | Hydrothermal activity | NEA OECD, 2000 |
| 620 | Marine features | NEA OECD, 2000 |
| 621 | Soil and sediment | NEA OECD, 2000 |
| 622 | Aquifers and water-bearing features, near surface | NEA OECD, 2000 |
| 623 | Water-mediated transport of contaminants | NEA OECD, 2000 |
| 624 | Hydrological regime and water balance (near-surface) | NEA OECD, 2000 |
| 625 | Lakes, rivers, streams and springs | NEA OECD, 2000 |
| 626 | Atmosphere | NEA OECD, 2000 |
| 627 | Meteorology | NEA OECD, 2000 |
| 628 | Model and data Issues | NEA OECD, 2000 |
| 629 | Timescale of concern | NEA OECD, 2000 |
| 630 | Regulatory requirements and exclusions | NEA OECD, 2000 |
| 631 | Spatial domain or concern | NEA OECD, 2000 |
| 632 | Ecological/biological microbial systems | NEA OECD, 2000 |
| 633 | Microbial/biological/plant-mediated processes, | NEA OECD, 2000 |
| 634 | Gas sources and effects (in wastes and EBS) | NEA OECD, 2000 |
| 635 | Radioactive decay and in-growth | NEA OECD, 2000 |
| 636 | Radiation effects (In wastes and EBS) | NEA OECD, 2000 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 637 | Inorganic solids/solutes | NEA OECD, 2000 |
| 638 | Salt diapirism and dissolution | NEA OECD, 2000 |
| 639 | Discontinuities, large scale (in geosphere) | NEA OECD, 2000 |
| 640 | Metamorphism | NEA OECD, 2000 |
| 641 | Deformation, elastic, plastic or brittle | NEA OECD, 2000 |
| 642 | Seismicity | NEA OECD, 2000 |
| 643 | Undetected features (In geosphere) | NEA OECD, 2000 |
| 644 | Tectonic movements and orogeny | NEA OECD, 2000 |
| 645 | Volcanic and magmatic activity | NEA OECD, 2000 |
| 646 | Nuclear criticality | NEA OECD, 2000 |
| 647 | Inventory, radionuclide and other material | NEA OECD, 2000 |
| 648 | Waste form materials and characteristics | NEA OECD, 2000 |
| 649 | Waste allocation | NEA OECD, 2000 |
| 650 | meteorite impact | NEA, 1992 |
| 651 | no ice age | NEA, 1992 |
| 652 | sea-level rise/fall | NEA, 1992 |
| 653 | ecological response to climatic change | NEA, 1992 |
| 654 | glaciation (erosion/deposition, glacial loading, hydrogeological change) | NEA, 1992 |
| 655 | periglacial effects (permafrost, high seasonality) | NEA, 1992 |
| 656 | river flow and lake level changes | NEA, 1992 |
| 657 | fracturing | NEA, 1992 |
| 658 | embrittlement and cracking | NEA, 1992 |
| 659 | metallic corrosion (pitting/uniform, internal and external agents, gas generation e.g. H2) | NEA, 1992 |
| 660 | animal uptake | NEA, 1992 |
| 661 | plant uptake | NEA, 1992 |
| 662 | uptake by animal, plant, root | NEA, 1992 |
| 663 | uptake by deep rooting species | NEA, 1992 |
| 664 | soil and sediment bioturbation | NEA, 1992 |
| 665 | plant and animal evolution | NEA, 1992 |
| 666 | colloid formation, dissolution and transport | NEA, 1992 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 667 | accumulation in soils and organic debris | NEA, 1992 |
| 668 | advection and dispersion | NEA, 1992 |
| 669 | matrix diffusion | NEA, 1992 |
| 670 | multiphase flow and gas driven flow | NEA, 1992 |
| 671 | solubility limit | NEA, 1992 |
| 672 | sorption (linear/non-linear, reversible/irreversible) | NEA, 1992 |
| 673 | non-radioactive solute plume in geosphere (effect on redox, ph and sorption) | NEA, 1992 |
| 674 | diffusion | NEA, 1992 |
| 675 | mass, isotopic and species dilution | NEA, 1992 |
| 676 | dissolution, precipitation, and crystallization | NEA, 1992 |
| 677 | natural gas intrusion | NEA, 1992 |
| 678 | gas flow | NEA, 1992 |
| 679 | gas mediated transport | NEA, 1992 |
| 680 | inadequate backfill or compaction voidage | NEA, 1992 |
| 681 | dewatering of host rock | NEA, 1992 |
| 682 | common cause failures | NEA, 1992 |
| 683 | investigation borehole seal failure and degradation | NEA, 1992 |
| 684 | stress field changes, settling, subsidence or caving | NEA, 1992 |
| 685 | thermal effects (concrete hydration) | NEA, 1992 |
| 686 | Thermal (nuclear and chemical) | NEA, 1992 |
| 687 | canister or container movement | NEA, 1992 |
| 688 | changes in in-situ stress field | NEA, 1992 |
| 689 | subsidence / collapse | NEA, 1992 |
| 690 | differential elastic response | NEA, 1992 |
| 691 | material defects (e.g. early canister failure) | NEA, 1992 |
| 692 | material property changes | NEA, 1992 |
| 693 | Mechanical | NEA, 1992 |
| 694 | non-elastic response | NEA, 1992 |
| 695 | Design and construction | NEA, 1992 |
| 696 | design modification | NEA, 1992 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 697 | shaft or access tunnel seal failure and degradation | NEA, 1992 |
| 698 | altered soil or surface water chemistry | NEA, 1992 |
| 699 | chemical transformations | NEA, 1992 |
| 700 | chemical gradients (electrochemical effects and osmosis) | NEA, 1992 |
| 701 | complexing agents | NEA, 1992 |
| 702 | diagenesis | NEA, 1992 |
| 703 | land slide | NEA, 1992 |
| 704 | accidents during operation | NEA, 1992 |
| 705 | agricultural and fisheries practice changes | NEA, 1992 |
| 706 | anthropogenic climate changes (greenhouse effect) | NEA, 1992 |
| 707 | abandonment of unsealed repository | NEA, 1992 |
| 708 | poor closure | NEA, 1992 |
| 709 | tunneling | NEA, 1992 |
| 710 | underground construction | NEA, 1992 |
| 711 | geothermal energy production | NEA, 1992 |
| 712 | repository flooding during operation | NEA, 1992 |
| 713 | co-disposal of reactive wastes (deliberate) | NEA, 1992 |
| 714 | undetected past intrusions (boreholes, mining) | NEA, 1992 |
| 715 | injection of liquid wastes | NEA, 1992 |
| 716 | loss of records | NEA, 1992 |
| 717 | archeological investigation | NEA, 1992 |
| 718 | irrigation | NEA, 1992 |
| 719 | demographic change, urban development | NEA, 1992 |
| 720 | land use changes | NEA, 1992 |
| 721 | post-closure monitoring | NEA, 1992 |
| 722 | underground nuclear testing | NEA, 1992 |
| 723 | effects of phased operation | NEA, 1992 |
| 724 | Operation and closure | NEA, 1992 |
| 725 | poor quality construction | NEA, 1992 |
| 726 | radioactive waste disposal error | NEA, 1992 |
| 727 | Post-closure surface activities | NEA, 1992 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 728 | exploitation drilling | NEA, 1992 |
| 729 | exploratory drilling | NEA, 1992 |
| 730 | resource mining | NEA, 1992 |
| 731 | quarrying, near surface extraction | NEA, 1992 |
| 732 | sabotage | NEA, 1992 |
| 733 | malicious intrusion (sabotage, act of war) | NEA, 1992 |
| 734 | recovery of repository materials | NEA, 1992 |
| 735 | recovery of repository materials | NEA, 1992 |
| 736 | ground-water abstraction | NEA, 1992 |
| 737 | dams and reservoirs, built/drained | NEA, 1992 |
| 738 | coastal erosion and estuarine development | NEA, 1992 |
| 739 | denudation (eolian and fluvial) | NEA, 1992 |
| 740 | chemical denudation and weathering | NEA, 1992 |
| 741 | freshwater sediment transport and deposition | NEA, 1992 |
| 742 | fracture mineralization and weathering | NEA, 1992 |
| 743 | rock heterogeneity (permeability, mineralogy), affecting water and | NEA, 1992 |
| 744 | river, stream, channel erosion (downcutting) | NEA, 1992 |
| 745 | marine sediment transport and deposition | NEA, 1992 |
| 746 | extremes of precipitation, snow melt and associated flooding | NEA, 1992 |
| 747 | effects at saline-freshwater interface | NEA, 1992 |
| 748 | ground-water conditions (saturated/unsaturated) | NEA, 1992 |
| 749 | ground-water discharge (to surface water, springs, soils, wells, and marine) | NEA, 1992 |
| 750 | ground-water flow (Darcy, non-Darcy, intergranular fracture, | NEA, 1992 |
| 751 | recharge to ground water | NEA, 1992 |
| 752 | saline or freshwater intrusion | NEA, 1992 |
| 753 | natural thermal effects | NEA, 1992 |
| 754 | induced hydrological changes (fluid pressure, density convection, viscosity) | NEA, 1992 |
| 755 | site flooding | NEA, 1992 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 756 | rivers rechanneled | NEA, 1992 |
| 757 | river meander | NEA, 1992 |
| 758 | frost weathering | NEA, 1992 |
| 759 | solar insolation | NEA, 1992 |
| 760 | coastal surge, storms, and hurricanes | NEA, 1992 |
| 761 | precipitation, temperature, soil, water balance | NEA, 1992 |
| 762 | ecological change (ex. forest fire cycles) | NEA, 1992 |
| 763 | microbial interactions | NEA, 1992 |
| 764 | microbiological (effects on corrosion/degradation, solubility/complexation, gas generation, ex. CH.C02) | NEA, 1992 |
| 765 | pedogenesis | NEA, 1992 |
| 766 | gas effects (pressurization, disruption, explosion, fire) | NEA, 1992 |
| 767 | radioactive decay and ingrowth (chain decay) | NEA, 1992 |
| 768 | radiolysis | NEA, 1992 |
| 769 | Radiological | NEA, 1992 |
| 770 | heterogeneity of waste forms (chemical, physical) | NEA, 1992 |
| 771 | cellulosic degradation | NEA, 1992 |
| 772 | interactions of host materials and ground water with repository material (ex. concrete carbonation, sulphate attack) | NEA, 1992 |
| 773 | interactions of waste and repository materials with host materials (electrochemical corrosive agents) | NEA, 1992 |
| 774 | introduced complexing agents and cellulosics | NEA, 1992 |
| 775 | induced chemical changes (solubility sorption, species equilibrium, mineralization) | NEA, 1992 |
| 776 | diapirism | NEA, 1992 |
| 777 | fault activation | NEA, 1992 |
| 778 | fault generation | NEA, 1992 |
| 779 | host rock fracture aperture changes | NEA, 1992 |
| 780 | metamorphic activity | NEA, 1992 |
| 781 | changes in the earth's magnetic field | NEA, 1992 |
| 782 | uplift and subsidence (orogenic, isostatic) | NEA, 1992 |
| 783 | seismicity | NEA, 1992 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 784 | plate movement/tectonic change | NEA, 1992 |
| 785 | undetected features (faults, fracture networks, shear zones, brecciation, gas pockets) | NEA, 1992 |
| 786 | magmatic activity (intrusive, extrusive) | NEA, 1992 |
| 787 | nuclear criticality | NEA, 1992 |
| 788 | inadvertent inclusion of undesirable materials | NEA, 1992 |
| 789 | Recurrance of Lake Bonneville | Neptune |
| 790 | Wave action | Neptune |
| 791 | Animal burrowing | Neptune |
| 792 | Dust devils | Neptune |
| 793 | Barrier stability during inundation | Neptune |
| 794 | inhalation pathways | Neptune |
| 795 | human induced hydraulic fracturing | Neptune |
| 796 | natural hydraulic fracturing (hydrogeological) | Neptune |
| 797 | Sedimentation | Neptune |
| 798 | Inundation | Neptune |
| 799 | radon emanation | Neptune |
| 800 | natural hydraulic fracturing (tectonic/seismic/volcanic) | Neptune |
| 801 | Off-Site Residents: impacts on the site by people who might use the area but don't live on the site itself. | Neptune |
| 802 | On-Site Residents: water well with desalinization; construction-related activities like basements, footings, and utilities; enhanced infiltration from septic; altered plant/animal communities; effect of grading on infiltration; effect of buildings and pavement on evapotranspiration. | Neptune |
| 803 | Agricultural activities | Neptune |
| 804 | Explosions and Crashes related to plane crashes, bombs | Neptune |
| 805 | Accidental Intrusion, facility properties intact: mineral, oil and gas, geothermal or other resource exploration; water well with desalinization; construction-related activities | Neptune |
| 806 | Accidental Intrusion, facility properties altered due to prior volcanic or seismic event | Neptune |
| 807 | FEPs related to post-closure inhabitation of the area | Neptune |
| 808 | Deliberate Intrusion (purposeful waste retrieval; archeology; terrorism, etc) | Neptune |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 809 | FEPs related to post-closure intrusion by nonresidents who come looking for something, or to some kind of major accident like a plane crash either before or after closure | Neptune |
| 810 | meteorite | Prij et al. 1991 |
| 811 | climatic variability | Prij et al. 1991 |
| 812 | minor climatic changes | Prij et al. 1991 |
| 813 | sea-level changes | Prij et al. 1991 |
| 814 | ecological response to climate | Prij et al. 1991 |
| 815 | glaciation | Prij et al. 1991 |
| 816 | periglacial effects | Prij et al. 1991 |
| 817 | canister defects | Prij et al. 1991 |
| 818 | common cause (canister) failures | Prij et al. 1991 |
| 819 | fracturing | Prij et al. 1991 |
| 820 | embrittlement, cracking | Prij et al. 1991 |
| 821 | metallic corrosion | Prij et al. 1991 |
| 822 | bioturbation of soil sediment | Prij et al. 1991 |
| 823 | radiocolloid formation | Prij et al. 1991 |
| 824 | accumulation in soils, organic debris | Prij et al. 1991 |
| 825 | transport of radionuclides | Prij et al. 1991 |
| 826 | advection and dispersion | Prij et al. 1991 |
| 827 | matrix diffusion | Prij et al. 1991 |
| 828 | multiphase flow | Prij et al. 1991 |
| 829 | leaching of nuclides | Prij et al. 1991 |
| 830 | non-radioactive solute in geosphere | Prij et al. 1991 |
| 831 | diffusion | Prij et al. 1991 |
| 832 | dilution of mass | Prij et al. 1991 |
| 833 | dissolution/precipitation reactions | Prij et al. 1991 |
| 834 | natural gas intrusion | Prij et al. 1991 |
| 835 | gas mediated transport | Prij et al. 1991 |
| 836 | inadequate backfill compaction, voidage | Prij et al. 1991 |
| 837 | convergence of openings | Prij et al. 1991 |
| 838 | dewatering of host rock | Prij et al. 1991 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 839 | stress field changes | Prij et al. 1991 |
| 840 | thermal effects | Prij et al. 1991 |
| 841 | Thermal | Prij et al. 1991 |
| 842 | degradation of buffer/backfill | Prij et al. 1991 |
| 843 | canister or container movement | Prij et al. 1991 |
| 844 | changes in in-situ stress field | Prij et al. 1991 |
| 845 | readjustment of host rock along joints | Prij et al. 1991 |
| 846 | heat production | Prij et al. 1991 |
| 847 | fracture aperture changes | Prij et al. 1991 |
| 848 | canister migration | Prij et al. 1991 |
| 849 | dehydration of salt minerals | Prij et al. 1991 |
| 850 | differential elastic response | Prij et al. 1991 |
| 851 | material defects | Prij et al. 1991 |
| 852 | swelling of backfill (clay) | Prij et al. 1991 |
| 853 | swelling of corrosion products | Prij et al. 1991 |
| 854 | material property changes | Prij et al. 1991 |
| 855 | Mechanical | Prij et al. 1991 |
| 856 | non-elastic response | Prij et al. 1991 |
| 857 | release of stored energy | Prij et al. 1991 |
| 858 | Design and construction | Prij et al. 1991 |
| 859 | design modification | Prij et al. 1991 |
| 860 | seal failure | Prij et al. 1991 |
| 861 | subsidence, collapse | Prij et al. 1991 |
| 862 | alteration of soil, surface water chemistry | Prij et al. 1991 |
| 863 | Geochemical | Prij et al. 1991 |
| 864 | chemical transformations | Prij et al. 1991 |
| 865 | ionic strength | Prij et al. 1991 |
| 866 | speciation equilibrium reactions | Prij et al. 1991 |
| 867 | texture | Prij et al. 1991 |
| 868 | acidity | Prij et al. 1991 |
| 869 | adsorption and desorption reactions | Prij et al. 1991 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 870 | chemical equilibrium reactions | Prij et al. 1991 |
| 871 | counter, competitive, and potential determining ions | Prij et al. 1991 |
| 872 | physico-chemical characteristics influencing chemical equilibria | Prij et al. 1991 |
| 873 | redox conditions | Prij et al. 1991 |
| 874 | geochemical alterations | Prij et al. 1991 |
| 875 | diagenesis | Prij et al. 1991 |
| 876 | land slide | Prij et al. 1991 |
| 877 | accidents during operation | Prij et al. 1991 |
| 878 | agricultural developments and changes | Prij et al. 1991 |
| 879 | anthropogenic climate changes (greenhouse effect) | Prij et al. 1991 |
| 880 | abandonment of unsealed repository | Prij et al. 1991 |
| 881 | poor closure | Prij et al. 1991 |
| 882 | tunneling | Prij et al. 1991 |
| 883 | underground construction | Prij et al. 1991 |
| 884 | fisheries developments and changes | Prij et al. 1991 |
| 885 | geothermal energy production | Prij et al. 1991 |
| 886 | co-disposal of reactive wastes (deliberate) | Prij et al. 1991 |
| 887 | Human Induced Phenomena | Prij et al. 1991 |
| 888 | undetected past intrusions | Prij et al. 1991 |
| 889 | injection of fluids | Prij et al. 1991 |
| 890 | loss of records | Prij et al. 1991 |
| 891 | archaeological investigation | Prij et al. 1991 |
| 892 | irrigation | Prij et al. 1991 |
| 893 | changes in land use | Prij et al. 1991 |
| 894 | demographic developments and changes | Prij et al. 1991 |
| 895 | urban developments and changes | Prij et al. 1991 |
| 896 | post-closure monitoring | Prij et al. 1991 |
| 897 | underground nuclear testing | Prij et al. 1991 |
| 898 | Operation and closure | Prij et al. 1991 |
| 899 | phased operation effects | Prij et al. 1991 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 900 | attempt of site Improvement | Prij et al. 1991 |
| 901 | poor quality construction | Prij et al. 1991 |
| 902 | improper waste emplacement | Prij et al. 1991 |
| 903 | radioactive waste disposal error | Prij et al. 1991 |
| 904 | Post-closure sub-surface activities | Prij et al. 1991 |
| 905 | Post-closure subsurface activities (intrusion) | Prij et al. 1991 |
| 906 | Post-closure surface activities | Prij et al. 1991 |
| 907 | exploitation drilling | Prij et al. 1991 |
| 908 | exploratory drilling | Prij et al. 1991 |
| 909 | resource mining | Prij et al. 1991 |
| 910 | quarrying, surface mining | Prij et al. 1991 |
| 911 | sabotage | Prij et al. 1991 |
| 912 | malicious intrusion, sabotage/war | Prij et al. 1991 |
| 913 | ground-water abstraction/recharge | Prij et al. 1991 |
| 914 | construction of dams/reservoirs | Prij et al. 1991 |
| 915 | drainage of dams reservoirs | Prij et al. 1991 |
| 916 | coastal erosion development of estuaries | Prij et al. 1991 |
| 917 | denudation, erosion | Prij et al. 1991 |
| 918 | channel erosion | Prij et al. 1991 |
| 919 | chemical denudation | Prij et al. 1991 |
| 920 | channeling and preferential pathways | Prij et al. 1991 |
| 921 | effects on suberosion | Prij et al. 1991 |
| 922 | sediment transport | Prij et al. 1991 |
| 923 | solifluction | Prij et al. 1991 |
| 924 | rock heterogeneity | Prij et al. 1991 |
| 925 | subrosion | Prij et al. 1991 |
| 926 | flooding of repository during operation | Prij et al. 1991 |
| 927 | extreme precipitation | Prij et al. 1991 |
| 928 | flooding of site | Prij et al. 1991 |
| 929 | changes in ground-water system | Prij et al. 1991 |
| 930 | ground-water conditions | Prij et al. 1991 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 931 | ground-water discharge | Prij et al. 1991 |
| 932 | ground-water flow | Prij et al. 1991 |
| 933 | ground-water recharge | Prij et al. 1991 |
| 934 | saline-freshwater interface | Prij et al. 1991 |
| 935 | brine migration | Prij et al. 1991 |
| 936 | natural thermal effects | Prij et al. 1991 |
| 937 | induced hydrological changes | Prij et al. 1991 |
| 938 | changes in river regime, lake levels | Prij et al. 1991 |
| 939 | intrusion of saline/fresh water | Prij et al. 1991 |
| 940 | rechanneling of rivers | Prij et al. 1991 |
| 941 | meandering of river | Prij et al. 1991 |
| 942 | water table changes | Prij et al. 1991 |
| 943 | frost weathering | Prij et al. 1991 |
| 944 | solar insolation | Prij et al. 1991 |
| 945 | coastal surge, storms | Prij et al. 1991 |
| 946 | precipitation, temperature, soil, water balance | Prij et al. 1991 |
| 947 | temperature | Prij et al. 1991 |
| 948 | ecological response to sudden change (forest fires) | Prij et al. 1991 |
| 949 | evolution | Prij et al. 1991 |
| 950 | microbial interactions | Prij et al. 1991 |
| 951 | microbiological effects | Prij et al. 1991 |
| 952 | pedogenesis | Prij et al. 1991 |
| 953 | gas generation, explosions | Prij et al. 1991 |
| 954 | gas generation effects | Prij et al. 1991 |
| 955 | radioactive decay/ingrowth | Prij et al. 1991 |
| 956 | Radiological | Prij et al. 1991 |
| 957 | radiolysis | Prij et al. 1991 |
| 958 | heterogeneity of waste forms; chemical or physical | Prij et al. 1991 |
| 959 | cellulosic degradation | Prij et al. 1991 |
| 960 | electrochemical reactions | Prij et al. 1991 |
| 961 | introduced complexing agents, cellulosics | Prij et al. 1991 |

**Table 1 (continued)**

| FEP ID | Initial FEP | Reference[1] |
|---|---|---|
| 962 | material interactions | Prij et al. 1991 |
| 963 | redox potential, pH | Prij et al. 1991 |
| 964 | induced chemical changes | Prij et al. 1991 |
| 965 | diapirism, halokinesis | Prij et al. 1991 |
| 966 | fault activation | Prij et al. 1991 |
| 967 | fault generation | Prij et al. 1991 |
| 968 | fracturing | Prij et al. 1991 |
| 969 | metamorphic activity | Prij et al. 1991 |
| 970 | changes in magnetic field | Prij et al. 1991 |
| 971 | creep of rock | Prij et al. 1991 |
| 972 | uplift and subsidence | Prij et al. 1991 |
| 973 | seismicity | Prij et al. 1991 |
| 974 | undetected geological features | Prij et al. 1991 |
| 975 | plate tectonics | Prij et al. 1991 |
| 976 | undetected features | Prij et al. 1991 |
| 977 | magmatic activity | Prij et al. 1991 |
| 978 | nuclear criticality | Prij et al. 1991 |
| 979 | inadvertent inclusion of undesirable materials | Prij et al. 1991 |
| 980 | radon emanation | Neptune |
| 981 | resuspension | Neptune |

[1] References for Andersson et al. (1989), Burkholder (1980), Guzowski (1990), Hertzler and Atwood (1989), Hunter (1983), Hunter, (1989), IAEA (1983), Koplik et al. (1982), Merrett and Gillespie, NEA (1992) and Prij et al. (1991) were found in Guzowski and Newman (1993).

**Table 2. List of consolidated FEPs evaluated for inclusion in the conceptual site model and scenarios**

**Table 2 (continued)**

| Neptune Subgroup | Normalized FEP (accepted) | Discussion | Representative FEP IDs[1] |
|---|---|---|---|
| Climate change | climate change | Climate change can have a large influence on site performance. Climate change includes natural and anthropogenic changes and its effects on hydrology (including lake effects), hydrogeology, glaciation, biota, and human behaviors. | 2, 3, 4, 159, 221, 222, 252, 253, 254, 321, 349, 350, 416, 417, 519, 520, 521, 522, 523, 524, 651, 652, 653, 811, 812, 813, 814 |
| | lake effects | A large lake could have detrimental effects on the repository. Lake effects include appearance/ disappearance of large lakes and associated phenomena (sedimentation, wave action, erosion/inundation, isostasy). This is covered within climate change scenarios. Regulations suggest consideration. | 656, 789 |
| | wave action | Wave action, including seiches, could influence site performance and is included in long-term scenarios. See lake effects and erosion/inundation. | 224, 790 |
| Containerization | containment degradation | A number of processes can contribute to degradation of waste containment. These are accounted for in release of the source term. It is expected that no credit will be given to containment. Regulations suggest consideration. | 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 352, 496, 527, 657, 658, 817, 818, 819, 820 |
| | corrosion | Corrosion is one of the processes that would contribute to degradation of waste containment. Regulations suggest consideration. | 18, 19, 20, 161, 353, 419, 659, 821 |
| Contaminant Migration | biotically-induced transport | Plant uptake and burrow excavation are potential contaminant transport (CT) pathways. Modeling includes biotic (plant- and animal-mediated) processes leading to contaminant transport, and the evolution of these processes in response to climate change and other influences, including bioturbation, burrowing, root development, and contaminant uptake and translocation. Regulations suggest consideration. | 21, 420, 529, 530, 531, 532, 533, 534, 661, 662, 663, 664, 665, 791, 822 |
| | colloid transport | Colloid formation could be a CT pathway. This process will be considered in the geochemistry conceptual model. | 22, 23, 24, 535, 666, 823 |

**Table 2 (continued)**

| Neptune Subgroup | Normalized FEP (accepted) | Discussion | Representative FEP IDs[1] |
|---|---|---|---|
| | contaminant transport | CT is a large class of processes that govern the migration of contaminants in the environment, including transport media (water, air, soil) processes (advection-dispersion, diffusion, plant uptake, soil translocation) and partitioning between phases; much overlap with atmospheric, groundwater, surface water, and biotically-induced transport.<br>Regulations suggest consideration. | 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 162, 163, 257, 301, 302, 303, 304, 305, 323, 354, 355, 356, 421, 536, 537, 538, 539, 540, 667, 668, 669, 670, 671, 672, 673, 824, 825, 826, 827, 828, 829, 830 |
| | diffusion | Diffusion is a basic CT process that could affect performance. Diffusion occurs in gas and water phases. | 36, 306, 324, 674, 831 |
| | dilution | Dilution is a basic CT process that could affect performance. Dilution occurs when mixing with less concentrated water. | 37, 675, 832 |
| | dispersion | Dispersion is a basic CT process that could affect performance. Hydrodynamic dispersion is associated with water advection. | 38 |
| | dissolution | Dissolution will govern leaching of the waste form into water, limited by aqueous solubility. | 39, 40, 164, 225, 258, 325, 326, 422, 541, 676, 833 |
| | dust devils | Dust devils are common on the flats, and could disperse contaminants. These are included in atmospheric dispersion. | 792 |
| | gas transport | Radon produced in the waste is likely to be transported via gaseous diffusion. Transport in the gas phase includes gas generation in the waste, partitioning between air and water phases, diffusion in air and water, and radioactive decay and ingrowth. | 42, 43, 44, 165, 166, 259, 357, 423, 542, 543, 544, 678, 679, 835 |
| | infiltration | Infiltration through the cap materials, the waste, and unsaturated zone could be an important CT mechanism. This includes infiltration of meteoric water (precipitation minus abstractions) through the cap, into wastes, and potentially to the groundwater. | 45, 260, 307 |
| | local geology | This feature will control some aspects of CT and is included implicitly in other processes.<br>Regulations suggest consideration. | 545, 546, 547 |

**Table 2 (continued)**

| **Neptune Subgroup** | **Normalized FEP (accepted)** | **Discussion** | **Representative FEP IDs[1]** |
|---|---|---|---|
| | preferential pathways | Preferential pathways could contribute to CT. Their presence is accounted for in the definition of advective and diffusive processes. Regulations suggest consideration. | 46 |
| Engineered Features | compaction error | Inadequate compaction could result in subsidence. This overlaps with subsidence and closure failure. | 680, 836 |
| | engineered features | Many engineered features are intended to improve performance. This large collection of features is intended to promote containment and inhibit migration of contaminants. Regulations suggest consideration. | 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 167, 168, 169, 170, 226, 227, 228, 261, 308, 309, 327, 359, 360, 361, 362, 363, 425, 426, 427, 428, 429, 430, 431, 432, 497, 498, 548, 549, 550, 551, 552, 553, 554, 555, 681, 682, 683, 684, 685, 686, 687, 688, 689,690 |
| | material properties | Material properties are an essential feature of any model, and include density, porosity, hydraulic conductivity, permeability, texture, tortuosity, etc. of waste, backfill, cap materials, and naturally occurring materials. | 60, 61, 62, 171, 364, 433, 692, 852, 853, 854 |
| | repository design | Respository design clearly influences its performance. This is accounted for implicitly in the modeling of the repository. Regulations suggest consideration. | 695, 696, 858, 859 |
| | source release | Source release is an essential part of the model, and can result from many mechanisms, including containment failure, leaching, radon emanation, plant uptake, and translocation by burrowing animals. | 128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 196, 291, 342, 398, 467, 468, 637, 770, 771, 772, 773, 774, 775, 958, 959, 960, 961, 962, 963, 964 |

**Table 2 (continued)**

| Neptune Subgroup | Normalized FEP (accepted) | Discussion | Representative FEP IDs[1] |
|---|---|---|---|
| | subsidence of repository | Subsidence can compromise performance, leading to failure of the cap, and enhanced infiltration. Regulations suggest consideration. | 310, 311, 329, 439, 861 |
| | waste | Waste form and inventory are essential parts of the model. Inventory and source release includes initial inventory of radionuclides and its physical and chemical form, container performance, matrix performance, leaching, and other release mechanisms. | 517, 647, 648, 649 |
| Exposure | animal ingestion | Human ingestion of livestock and game exposed to contaminants is an exposure pathway, and is implemented as part of the human exposure model, as ingestion of fodder and feed by livestock, and ingestion of livestock by humans, and similar pathways for game. Regulations suggest consideration. | 660 |
| | dosimetry | Dosimetry hints at human dose response, which is an integral part of PA. Physiological dose response will be estimated in the PA model. Dosimetry as a science is not a FEP, *per se.* Regulations suggest consideration. | 560, 561 |
| | exposure media | Exposure media are a fundamental part of exposure pathways, and include foodstuffs, drinking water, other environmental media. These are included in the human exposure model. Regulations suggest consideration. | 562, 563 |
| | human behavior | Behavior is part of human exposure pathway. Future human behaviors include activities and their frequency and duration, distinct from food and water ingestion. Regulations suggest consideration. | 584, 585, 586, 587, 588 |
| | human exposure | Human exposure, in terms of dose and toxicity, is considered in the model, and includes exposure pathways (ingestion, inhalation, etc.) and physiological effects from radionuclides and toxic contaminants. Regulations suggest consideration. | 68, 564, 565, 566, 567, 568, 569, 570, 571, 801, 802 |
| | ingestion pathways | Ingestion of food, water, and soils are modeled human exposure pathways. These include human exposures due to ingestion of water and foodstuffs, and transport pathways (e.g. food chains) that lead to foodstuffs. Regulations suggest consideration. | 572, 573, 574 |

**Table 2 (continued)**

| Neptune Subgroup | Normalized FEP (accepted) | Discussion | Representative FEP IDs[1] |
|---|---|---|---|
| | inhalation pathways | Inhalation of gases and fine particles are modeled human exposure pathways. Regulations suggest consideration. | 794 |
| Geochemical | geochemical effects | Geochemical processes control CT in waste sources, water, and geologic media. These include chemical sorption and partitioning between phases, aqueous solubility, precipitation, chemical stability, complexing, changes in water chemistry (redox potential, pH, Eh), fluid interactions, halokinesis, diagenesis, speciation, cellulosic degradation effects, interactions with clays and other host materials, effects of corrosion products, effects of cementitious materials, and leaching. | 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 174, 264, 368, 440, 575, 576, 577, 698, 699, 700, 701, 862, 863, 864, 865, 866, 867, 868, 869, 870, 871, 872, 873, 874 |
| Human Processes | anthropogenic climate change | This is addressed as part of climate change in general. | 85, 580, 706, 879 |
| | community development | Development of communities and other human habitation overlaps with land use and habitation, and is considered in the human exposure assessment, albeit unlikely. See inhabitation, land use. Regulations suggest consideration. | 581 |
| | excavation | Excavation includes construction of basements and other construction, and is included as part of the human intrusion scenarios. | 330, 499, 582, 709, 710, 882, 883 |
| | explosions | Human-caused explosions include bombs, plane crashes, and conventional weapons training. | 230, 500, 583, 804 |
| | human-induced processes | Human-induced processes are limited to repository design, inadvertent human intrusion, or human-induced climate change. Engineered features include repository design and new technological developments. Intentional intrusion is not considered. Anthropogenic climate change is considered under climate change. | 90, 91, 92, 177, 271, 272, 372, 443, 589, 590, 712, 713, 886 |
| | human-induced transport | Human activities that could contribute to release are considered. Humans can induce contaminant transport through a variety of activities. See inadvertent human intrusion. | 273, 274, 591, 592, 795, 887 |
| | inadvertent human intrusion | Inadvertent human intrusion into the waste is considered in the development of exposure pathways. Regulations suggest consideration. | 178, 179, 231, 275, 276, 277, 373, 374, 375, 444, 445, 446, 714, 805, 806, 888 |

**Table 2 (continued)**

| Neptune Subgroup | Normalized FEP (accepted) | Discussion | Representative FEP IDs[1] |
|---|---|---|---|
| | inhabitation | Inhabitation on or near the site, including the establishment of surface or underground dwellings, communities, or cities, is extremely unlikely. See community development, land use. Regulations suggest consideration. | 93, 94, 593, 594, 807 |
| | institutional control | Institutional control affects human exposures, and includes records of site knowledge, markers, barriers, and security, and the loss thereof. Regulations suggest consideration. | 95, 595, 596, 597, 716, 890 |
| | land use | Land use in general could affect exposure scenarios. Land use changes are related to demographics, including development of agricultural, industrial, urban, or wild land uses. Regulations suggest consideration. | 183, 450, 600, 601, 602, 719, 720, 893, 894, 895 |
| | post-closure subsurface activities | Subsurface human activities are covered to the extent that they are inadvertent. This could include intrusion, construction, investigation, drilling, or mining. Regulations suggest consideration. | 727, 904, 905, 906 |
| Hydrogeological | denudation | Denudation could expose wastes, and is combined with erosion and inundation. Regulations suggest consideration. | 192, 388, 460, 502, 503, 739, 917 |
| | erosion | Erosion of the repository resulting from pluvial, fluvial, or aeolian processes can result from extreme precipitation, changes in surface water channels, and weathering. Regulations suggest consideration. | 110, 238, 284, 389, 504, 613, 740, 918, 919, 920, 921 |
| | erosional transport | Erosional (sediment) transport could be a CT mechanism. Sediments may move during erosion; includes solifluction. Regulations suggest consideration. | 111, 239, 614, 615, 741, 742, 922, 923 |
| | hydrogeological effects | Hydrogeological and groundwater hydraulics changes may occur in response to geological changes, including hydrothermal activity. This is generally covered under groundwater transport. Regulations suggest consideration. | 112, 616, 617, 618, 619, 743, 744, 796, 924 |
| | sedimentation | Sedimentation would occur on a lake bottom, and could affect performance. This includes sedimentation/aggradation onto the repository. | 113, 193, 285, 335, 390, 461, 621, 797 |

**Table 2 (continued)**

| **Neptune Subgroup** | **Normalized FEP (accepted)** | **Discussion** | **Representative FEP IDs[1]** |
|---|---|---|---|
| Hydrology | groundwater transport | Groundwater transport includes waterborne contaminant transport (CT) in the unsaturated and saturated zones, and is a principal CT mechanism. Groundwater flow and transport mechanisms include advection-dispersion, diffusion, fluid migration, waterborne contaminant transport, changes in the flow system, recharge and discharge, water table movements, and brine interactions. | 114, 115, 116, 117, 118, 286, 312, 313, 314, 315, 316, 336, 337, 338, 339, 392, 393, 622, 623, 747, 748, 749, 750, 751, 752, 929, 930, 931, 932, 933, 934, 935, 942 |
| | hydrological effects | Hydrological processes are considered under the topics of surface water and groundwater. Regulations suggest consideration. | 463, 505, 624, 753, 754, 936, 937 |
| | inundation | Inundation by a large lake or reservoir is likely to affect the site in the long term. (See also: wave action, and lake effects).<br>Regulations suggest consideration. | 755, 798, 938, 939 |
| Meteorology | frost weathering | Weathering from frost cycles is included in cap degradation modeling. | 758, 943 |
| | meteorology | Meteorology is considered indirectly; meteorology as a science is not a FEP, *per se*, but contributes to other processes, such as precipitation and atmospheric dispersion, which are covered elsewhere.<br>Regulations suggest consideration. | 626, 627, 761, 946, 947 |
| | resuspension | Resuspension will affect site performance, allowing particulates from surface soils to be redistributed by atmospheric dispersion. | 981 |
| | atmospheric dispersion | Atmospheric dispersion is a potential CT pathway and is modeled. See also: dust devils. Regulations suggest consideration. | 256, 528 |
| | tornado | Tornados are possible in the area. | 289 |
| Model Settings | model parameteri-zation | Parameterization is a fundamental part of modeling, though is not a FEP, *per se*. | 628 |
| | period of performance | Definition of a period of performance is a fundamental part of PA modeling, though is not a FEP, *per se*. | 629 |
| | regulatory requirements | Regulatory requirements drive much of the modeling in PA, though is not a FEP, *per se*. | 630 |
| | spatial domain | Definition of a spatial domain is a fundamental part of modeling, though is not a FEP, *per se*. | 631 |

**Table 2 (continued)**

| Neptune Subgroup | Normalized FEP (accepted) | Discussion | Representative FEP IDs[1] |
|---|---|---|---|
| Other Natural Processes | ecological changes | Changes in the types and abundance of plants and animals could affect performance. Changes in the ecology can be associated with catastrophic events (e.g. fire, inundation), evolution, or climate change. | 762, 948, 949 |
| | gas generation | Uranium wastes are expected to produce radon which will affect site performance in terms of doses. See also gas transport. | 122, 123, 340, 396, 464, 634, 766, 953, 954 |
| | pedogenesis | Soils are likely to develop on the cap and may affect performance. | 765, 952 |
| | radioactive decay and in-growth | Radioactive decay and ingrowth processes are essential to the model. | 635, 767, 799, 955 |
| | radon emanation | Radon emanation directly affects the mass of radon released into the environment, and hence site performance. | 980 |
| | reconcentration | Possible reconcentration of radiological materials during transport is accounted for in the CT modeling. | 127 |
| Tectonic/ Seismic/ Volcanic | geophysical effects | Geophysical changes to the engineered features of the site are accounted for in degradation. Geophysical effects include pressure, stress, density, viscosity, deformation, magnetics, creep, and elasticity. | 141, 142, 143, 509, 641, 781, 970, 971 |

[1] The Representative FEP IDs correspond to the FEP IDs given in Table 1.

**Table 3. List of FEPs dismissed from further consideration.**

**Table 3 (continued)**

| Neptune Subgroup | Normalized FEP (dismissed) | Discussion | Representative FEP IDs[1] |
|---|---|---|---|
| Celestial | meteorite impact | The occurrence and consequences of a direct hit by a meteorite are out of the scope of this model. | 1, 158, 219, 220, 251, 320, 348, 415, 491, 492, 493, 518, 650, 810 |
| Climate change | glacial effects | Glacial effects include presence of continental glaciers and resulting isostatic effects, glacial erosion, and periglacial effects. Glaciers in the basin are not modeled. Return of a large lake is expected should a glacial epoch return and is covered within climate change scenarios. | 5, 160, 223, 255, 322, 351, 418, 494, 495, 525, 526, 654, 655, 815, 816 |
| | permafrost | The effects of permafrost are bounded by those of cap degradation, which considers more damaging freeze/thaw cycles. See frost weathering. | 6, 300 |
| Contaminant Migration | gas intrusion | No mechanism for intrusion of naturally-produced gases into the repository has been identified. | 41, 677, 834 |
| Engineered Features | convergence of openings | This FEP applies to mined repositories only. | 837 |
| | design error | Errors in design could compromise performance but are not included in the modeling. Design error is distinct from construction or operational error. | 47, 358, 424 |
| | material defects | Material defects are covered by degradation, and include material defects in source containment, closure cap, and other engineered materials. | 691, 851 |
| | mechanical effects | Mechanical effects are covered implicitly by degradation, and include changes in mechanical properties and conditions, including failure. | 63, 64, 65, 172, 262, 365, 366, 434, 435, 556, 557, 693, 694, 855, 856 |
| | release of stored energy | No significant energy is stored within the wastes. | 66, 436, 857 |
| | repository seals | Regulations suggest consideration, but, the sealing of the repository shafts, boreholes, and construction and failure of such is applicable only to mined repositories. | 67, 173, 229, 263, 328, 367, 437, 438, 558, 559, 697, 860 |

**Table 3 (continued)**

| Neptune Subgroup | Normalized FEP (dismissed) | Discussion | Representative FEP IDs[1] |
|---|---|---|---|
| Exposure | agriculture | Agriculture includes establishment, evolution, and abandonment of agriculture and aquaculture at and near the site. Regulations suggest consideration, however, none of these are expected to occur because of the high salinity of soils and groundwater at the site. | 705, 803, 878 |
| Geological | diagenesis | Diagenesis in local lacustrine sediments could include the formation of interstitial evaporites, but is not expected to change site performance. | 83, 175, 265, 369, 441, 578, 702, 875 |
| | gas or brine pockets | No gas or brine pockets have been identified below the site. | 176, 370, 442, 579 |
| | landslide | Regulations suggest consideration, but landslides are not expected to occur in the flat lacustrine basin. Mass wasting of the site itself is covered under erosion. | 266, 703, 876 |
| | local subsidence | Geological subsidence in the area is unlikely to seriously affect performance, and is not expected in the basin of lacustrine sediments. | 267 |
| Human Processes | accidents during operations | Regulations suggest consideration, but operational performance is not within the scope of the PA model. | 84, 704, 877 |
| | climate control | No climate control at the facility is assumed. Climate control is a feature of certain mined repositories. | 268, 371 |
| | closure failure | Regulations suggest consideration; however, poor closure includes abandonment or other failure to close the facility as planned, and is not modeled. | 86, 87, 707, 708, 880, 881 |
| | fire | The waste is not combustible or explosive. Fires in the waste itself or following explosions are distinct from wildfire. | 269, 270 |
| | fisheries | Regulations suggest consideration, but development of fisheries is not credible at the site. | 884 |
| | geothermal energy production | No geothermal resources are identified at the site. | 89, 711, 885 |
| | injection wells | Given the regional history, the construction of injection wells nearby for disposal of liquid wastes is possible. The effect of drilling such wells in the vicinity would be negligible, however. | 232, 715, 889 |

**Table 3 (continued)**

| Neptune Subgroup | Normalized FEP (dismissed) | Discussion | Representative FEP IDs[1] |
|---|---|---|---|
| | intentional intrusion | Intentional intruders are not protected and are not modeled as receptors. Intentional intrusion includes exhumation of waste, sabotage, terrorism, or archeological research. | 96, 180, 181, 278, 376, 377, 447, 448, 717, 808, 891 |
| | investigation | Site investigation is considered intentional, and receptors are not covered. | 598, 599, 809 |
| | irrigation | Regulations suggest consideration, and irrigation could affect site performance, but will not occur since there is no suitable water source. | 182, 233, 378, 449, 718, 892 |
| | monitoring | Monitoring of the site is required, but persons performing the activity are not protected since it is intentional and informed. Monitoring activities will not affect the performance of the site. | 97, 603, 721, 896 |
| | nuclear testing | Regulations suggest consideration; however, testing of nuclear devices underground, at the ground surface, or in the atmosphere is considered intentional disruption of the site and is not covered. | 98, 722, 897 |
| | operational effects | Operations could affect performance, and include normal site operation, closure, and later attempts at site improvement. Regulations suggest consideration; however, operations are not part of the PA. | 99, 604, 605, 723, 724, 898, 899, 900 |
| | operational error | Covered under operational effects. Operational errors include poor quality site construction, waste emplacement, and site closure. Regulations suggest consideration, however, operations are not part of the PA. | 100, 184, 279, 379, 380, 451, 725, 726, 901, 902, 903 |
| | quality control | Quality control is important to site operations, but is not a FEP that lends itself to modeling. | 606 |
| | resource extraction | Regulations suggest consideration. Resource extraction is a type of intentional intrusion, including drilling, mining, or quarrying into the repository, or in such a way as to affect performance, in search of resources such as petroleum, natural gas, salt, rock, or geothermal resources. See intentional intrusion. | 101, 102, 103, 185, 186, 234, 235, 280, 331, 332, 381, 382, 383, 452, 453, 501, 608, 609, 728, 729, 730, 731, 907, 908, 909, 910 |
| | sabotage | Sabotage is by its nature intentional. See intentional intrusion. | 104, 187, 333, 384, 454, 732, 733, 911, 912 |

**Table 3 (continued)**

| Neptune Subgroup | Normalized FEP (dismissed) | Discussion | Representative FEP IDs[1] |
|---|---|---|---|
| | unplanned events | This category is too vague to be considered explicitly; unplanned events are generally subsumed by other FEPs. | 610 |
| | war | Intrusion or disruption as part of an act of war would be intentional. See intentional intrusion. | 105, 188, 334, 385, 455 |
| | waste recovery | Regulations suggest consideration, but waste recovery, retrieval, or mining are considered intentional acts. See intentional intrusion. | 106, 189, 386, 456, 607.734, 735 |
| | water resource management | Water resource activities include construction of dams, reservoirs, and wells, and could affect the site as water is extracted or retained. Regulations suggest consideration; however, this is not specifically modeled, as it is bounded by the large lake scenario. | 107, 108, 109, 190, 236, 237, 281, 282, 387, 457, 458, 611, 736, 737, 913, 914, 915 |
| | weapons testing | Any nuclear and conventional weapons testing would be done with cognizance of the site, and is intentional. See also explosions and intentional intrusion. | 191, 283, 459 |
| Hydrogeological | subrosion | No subsurface erosion has been reported in the vicinity. | 925 |
| Hydrology | flooding | Regulations suggest consideration; however, temporary flooding of the site due to extreme precipitation is not plausible due to site topography in the midst of the flats. This is distinct from inundation by the return of a large lake, which is included. | 194, 240, 391, 462, 746, 926, 927, 928 |
| | surface water transport | Surface water transport includes formation and changes in rivers, lakes, and streams, and transport of dissolved and suspended solids, and sediments. Such effects are not anticipated at the facility. This is distinct from inundation by the return of a large lake, which is included. | 119, 241, 287, 317, 318, 319, 394, 395, 625, 756, 757, 940, 941 |
| Marine | coastal processes | Coastal processes will not apply at the site, since no sea or ocean is expected in relevant time frames. However, see wave action. | 612, 738, 760, 916, 945 |
| | hurricanes | No hurricanes occur in the area. | 242, 288 |
| | insolation | Insolation (the amount of sunshine on the site) has no direct effect on site performance. See ecological changes. | 759, 944 |

**Table 3 (continued)**

| Neptune Subgroup | Normalized FEP (dismissed) | Discussion | Representative FEP IDs[1] |
|---|---|---|---|
| | marine effects | Marine processes will not apply at the site, since no sea or ocean is expected in relevant time frames. Marine processes include sea-level change. See also coastal processes and tsunami. | 620, 745 |
| | tsunami | No tsunami will occur at the site. See coastal processes and marine effects. | 243 |
| Natural Processes | microbial effects | Microbial action is not expected to affect performance. Microbial processes include corrosion, changes in chemistry, and dissolution of glasses, but biotically-induced transport is limited to macrobiological processes. | 120, 632, 633, 763, 764, 950, 951 |
| | radiological effects | Regulations suggest consideration. Radiological processes such as radiolysis are a concern for waste containment in some geological repositories, but are not modeled here, since waste containment is not given credit. | 124, 125, 126, 195, 341, 397, 465, 466, 636, 768, 769, 956, 957 |
| | wildfire | Occasional wildfire (brush fire, forest fire, either local or widespread) is not likely to affect site performance in the long run, since this is a natural part of plant community dynamics. | 290 |
| Source Release | electrochemical effects | Electrochemical effects are not a relevant process at the site. Electrochemical reactions are a concern for the SKB repository. | 121 |
| | explosions | Explosive gases are not present in the repository. | 88 |
| Tectonic/ Seismic/ Volcanic | breccia pipes | Regulations suggest consideration, and the formation of breccia pipes or mud volcanoes could affect performance, but is considered highly unlikely. | 197, 343, 399, 469 |
| | diapirism | Salt deposits in the strata below the site will not result in the formation of diapirs. | 198, 244, 292, 344, 400, 470, 638, 776, 965 |
| | discontinuities | No major geological discontinuities are envisioned at the site. | 639 |
| | earthquake | Earthquakes, either from natural or man-made causes, would not change the performance of this shallow unconsolidated site. | 138, 293 |

**Table 3 (continued)**

| Neptune Subgroup | Normalized FEP (dismissed) | Discussion | Representative FEP IDs[1] |
|---|---|---|---|
| | faulting | Faulting is unlikely to significantly affect performance of this shallow unconsolidated site and is not explicitly modeled. Geologic faulting includes all type of faults, shear zones, diastrophism, existing and future. See also see fracturing. | 139, 199, 200, 201, 245, 294, 345, 401, 402, 471, 472, 473, 506, 507, 508, 777, 778, 966, 967 |
| | fracturing | Tectonic fracturing will not affect unconsolidated site performance. | 202, 203, 204, 205, 246, 403, 474, 475, 476, 477, 779, 968 |
| | geological intrusion | Magmatic and intrusive igneous activity has not been identified in the vicinity of the site. Geological intrusion includes dikes, intrusive and magmatic activity, and metamorphism due to such activity. This is distinct from breccia pipes (mud volcanoes) and human intrusion. | 140, 206, 207, 295, 346, 404, 405, 478, 479, 640, 780, 969 |
| | hydraulic fracturing | Hydraulic fracturing is performed in solid rock, and has no applicaton at the site. Hydraulic fracturing ("hydrofracking") is induced by humans to enhance resource recovery or liquid waste disposal by injection. | 208, 480 |
| | intrusion into accumulation zone in the biosphere | No accumulation zone in the biosphere has been identified at the site. | 144 |
| | isostatic effects | Isostatic changes could influence lake levels, which are accounted for elsewhere. Isostasy includes that caused by tectonics, large bodies of water, and by continental glaciers. | 209, 406, 481, 510, 511 |
| | lava tubes | No lava tubes exist at the site or are expected in the future. | 210, 407, 482 |
| | orogeny | No significant orogeny is expected in relevant time frames. Orogeny (mountain-building) caused by tectonic movements or regional uplift. | 211, 247, 296, 408, 483 |
| | regional subsidence | Regional subsidence could influence lake levels, which are accounted for elsewhere. | 145, 409, 782, 972 |
| | seismic effects | Regulations suggest consideration, but effects of seismic activity (see also earthquakes) would be insignificant for shallow land burial. | 248, 512, 513, 642, 783, 973 |

**Table 3 (continued)**

| Neptune Subgroup | Normalized FEP (dismissed) | Discussion | Representative FEP IDs[1] |
|---|---|---|---|
| | tectonic effects | Tectonic effects could influence lake levels, which are accounted for elsewhere. | 146, 147, 148, 149, 212, 213, 410, 484, 643, 644, 784, 785, 974, 975, 976 |
| | volcanism | No significant volcanism is expected in relevant time frames. | 150, 214, 249, 250, 411, 412, 485, 486, 514, 515, 516, 645, 786, 800, 977 |
| Waste | nuclear criticality | Nuclear criticality, while a concern for repositories of used nuclear fuel, is not a concern at this LLW site. | 151, 152, 215, 297, 347, 413, 487, 646, 787, 978 |
| | other waste | The current analysis is constrained to examine depleted uranium wastes only, including associated "contaminant" waste. This rather vague reference to "other waste" will be addressed as the scope of wastes under consideration expands. | 153, 154, 155, 156, 157, 216, 217, 218, 298, 299, 414, 488, 489, 490, 788, 979 |

1 The Representative FEP IDs correspond to the FEP IDs given in Table 1.