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The joint SKI/SKB scenario development project

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THE JOINT SKI / SKB SCENARIO DEVELOPMENT PROJECT

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ABSTRACT

The Swedish Nuclear Power Inspectorate (SKI) and the Swedish Nuclear Waste Management Co. (SKB) have carried through a joint scenario development exercise of a hypothetical repository for spent nuclear fuel and high level waste based on the KBS-3 concept as disposal method.

The starting point of the scenario development strategy has been the "Sandia methodology", but the actual implementation of the steps in this method has required new strategy development. The work started with a relatively large internationally composed group meeting, which identified an extensive list (approximately 150 items) of features, events and processes (FEPs) that might influence the long term performance of a repository. All these FEPs and a memo-text containing a description of the FEP as well as its possible causes and consequences have been entered into a computer database.

The next step in the development was to remove from the list approximately 30 FEPs of low probability or negligible consequence. In a following step a large number of the FEPs on the original list were assigned to the "PROCESS SYSTEM". The PROCESS SYSTEM comprises the complete set of "deterministic" chemical and physical processes that might influence the release from the repository to the biosphere. A scenario is defined by a set of external conditions which will influence the processes in the PROCESS SYSTEM.

Approximately 50 FEPs were left representing external conditions. These remaining FEPs have been grouped (lumped) into a few (10) primary FEPs of external conditions. The remaining FEPs could all be combined to form scenarios, but it is concluded that it is not meaningful to discuss combinations without first analyzing the consequence and probability of the individual conditions.

An important aspect of the work is that the developed strategy includes a framework for the documentation of the complete chain of scenario development. Such a transparent documentation makes possible an extensive review and updating of the set of scenarios. A reviewing process, open to very broad groups in the society, is probably the best means of assuring reasonable completeness and of building up a general consensus on what are the critical issues for the safe disposal of radioactive waste.

In conclusion, the strategy developed within the project appear to be a feasible approach to scenario development, but it must be stressed that the present project is a first stage and that the complete analysis must be reiterated several times.

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SUMMARY

The Swedish Nuclear Power Inspectorate (SKI) and the Swedish Nuclear Waste Management Co. (SKB) have carried through a joint scenario development exercise of a hypothetical repository for spent nuclear fuel and high level waste based on the KBS-3 concept as disposal method. An incentive for the project has been the perceived need for a common understanding of principles and procedures for scenario selection well in advance of the actual licensing process. Also the value of developing an internationally available and well documented data post on possible features, events and processes that could be of importance in scenario development was recognized. A well defined structure for the scenario development and documentation will also facilitate later phases of scenario development including interactions with broader groups in society. Besides the efforts for the development of a common understanding and an internationally available information basis, the work on development and evaluation of scenarios is performed separately in SKI and SKB.

The starting point of the scenario development strategy has been the "Sandia methodology". However, the actual implementation of the steps in this method has required new strategy development.

The work started in 1988 with a relatively large internationally composed group meeting. This large group also met in early 1989. However, the major development has been carried out by a smaller working group within SKI and SKB. The work has been made in interaction with an international working group on scenario development within the OECD/NEA.

The initial large meeting resulted in an extensive list (approximately 150 items) of features, events and processes (FEPs) that might influence the long term performance of a repository. This list and all further documentation have been entered into a computer database. The first effort of the working group was to write a memo-text for each FEP. This text contains a description or an explanation of each FEP as well as its possible causes and consequences. The memo-text has provided the basis for the further structuring of the original list. The next step in the development was to remove (screen out) from the list approximately 30 FEPs of low probability or negligible consequence.

In order to structure the remaining parts of the list it was necessary to introduce the concepts of the "PROCESS SYSTEM" and "external conditions". The PROCESS SYSTEM comprises the complete set of "deterministic" chemical and physical processes that might influence the release from the repository to the biosphere. The external conditions are events or processes that are not repository induced and may occur (relatively) independent of the processes in the PROCESS SYSTEM. A scenario is defined by a set of external conditions which will influence the processes in the PROCESS SYSTEM. The external conditions determine how to actually model and combine the processes in the PROCESS SYSTEM when evaluating the consequence of the scenario. Furthermore, most processes in a scenario have conceptual and parameter uncertainties. These uncertainties may be analyzed by evaluating a set of cases with different parameter values or different conceptual models. This set of cases are not scenarios but represent the sensitivity of the scenario to conceptual and parameter uncertainty. With these definitions most of the FEPs on the original list were assigned to the PROCESS SYSTEM and only a smaller number (approximately 50) were left as FEPs representing external conditions.

The remaining FEPs representing external conditions have been grouped (lumped) into a few (10) primary FEPs of external conditions. The objective of this lumping is to reduce the number of combinations that need to be analyzed. One criterion for lumping FEPs to the same group is when the (modelling) consequence for the FEPs are similar. Another possibility may be to lump FEPs with the same and only primary cause.

The primary external conditions could all be combined to form scenarios. In order to reduce the number of combinations to be carefully analyzed it is necessary to introduce restrictions in these combinations. One important restriction is introduced by the term "ISOLATED SCENARIO", which should not be combined with other FEPs. The possibility to introduce other restrictions in the combinations have been discussed within the working group, but it was concluded that it probably is not possible to discuss meaningful restrictions of combinations without first analyzing the consequence and probability of the individual conditions. Furthermore, a more clear understanding of the time aspects of the external conditions are needed as the importance of a combination of events may depend on in which order they occur. Finally, well defined criteria are needed for screening scenarios.

In conclusion, the strategy developed within the project appear to be a feasible approach to scenario development. It must be stressed that the present project is a first stage and that the complete analysis must be reiterated several times. Still, the developed strategy includes a framework for the documentation of the complete chain of scenario development. This documentation is the key to the following analysis. Even if a scenario development strategy never will produce a complete set of scenarios one must strive for completeness. In this context it is extremely important to document all steps in the development. A transparent documentation makes possible an extensive review and updating of the set of scenarios. Such a reviewing process, open to very broad groups in the society, is probably the best means of assuring reasonable completeness and of building up a general consensus on what are the critical issues for the safe disposal of radioactive waste.

1 INTRODUCTION

1.1 GENERAL

The Swedish Nuclear Power Inspectorate (SKI) and the Swedish Nuclear Waste Management Co. (SKB) have decided to carry through a joint scenario development exercise of a hypothetical repository for spent fuel and high level waste based on the KBS-3 concept as disposal method. An important motivation for this project is that there is a need for a common understanding on principles and procedures for scenario selection well in advance of the actual licensing process. After this first phase, scenario development, as well as consequence analysis of the derived scenarios will be performed within each organization separately.

The basic objective of a scenario development is to make sure that all relevant future evolutions of a repository is properly considered. For public confidence it is important that the scenario development is well documented and made in a transparent way. A well defined structure for the scenario development and documentation will also facilitate for later phases of scenario development in Sweden including interactions with broader groups in society. These requirements imply that it is not only important to obtain sensible scenarios, but it is also essential to prove the sensibility of the scenario selection procedure.

The objective of the present project is to initiate efforts in a structured approach to scenario development. The starting point for the project has been to apply the "Sandia Methodology" (as described in the report NUREG/CR-1667) [1]. This method has been discussed by the NEA/PAAG "Working Group on the Identification and Selection of Scenarios for Performance Assessment of Nuclear Waste Disposal" and found to be an apparently systematic and well documented approach. The Sandia methodology has been applied by US NRC for demonstration purposes on disposal concepts for disposal in salt, basalt and tuff. However, it must be stressed that the Sandia method is not the only approach to scenario analysis. The motivation for its application in the present project is that it was considered to be a fruitful starting point for the work.

In the present project the scenario development is applied to the KBS-3 concept for disposal of spent fuel and high level waste. It has been assumed that the repository is located at a site in "typical Swedish crystalline rock". During the project there has been little need for actual site specific geological data. Had such a need arisen it was planned to use the generic SKI Project-90 reference site (SKI TR 89:2) [2]. This site has no correspondence with any potential disposal site in Sweden, although the aim has been to make the site as realistic as possible in terms of the features included and their associated parameter values.

The main interest in the present project is to develop methodologies for scenario development. The technical results need to be updated and the analysis reiterated for the evaluation of a real potential repository site. In particular, a future analysis has to be fully adopted to the actual disposal method, barrier design, repository layout etc., that will be suggested.

As a final remark it could be mentioned that the scenario project happens to fall well in time with the SKI Project-90, which is a performance assessment exercise. Some of the scenarios and issues identified in the present project will be analyzed within Project-90.

1.2 ORGANIZATION OF WORK – THE SKI/SKB WORKING GROUP

The start of the project was a workshop in Kolmården in September 26–28, 1988. The participants were representatives from SKI, SKI consultants including Sandia, SKB, SKB consultants, the SKI Project-90 expert group and the Swedish National Institute of Radiation Protection (SSI). In addition, one observer each from the NEA secretariat and the Finnish organizations TVO and VTT attended the workshop.

At this first workshop a large number of features, events and processes to be included in the scenario development were identified and principles for further work discussed. It then was decided to form a joint SKI and SKB working group. The working group, which has met fairly regularly, tried to follow the different steps in the Sandia methodology. In this process the problems of implementing this methodology were highlighted. The members of the working group are:

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Torbjörn Carlsson (SKI)
Torsten Eng (SKB)
Fritz Kautsky (SKI)
Erik Söderman (ES-Konsult/SKB)
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In addition to the efforts and meetings within the SKI/SKB working group there has been two larger meetings. In December 15–16, 1988 there was a meeting with participation of the SKI/SKB working group, other SKI and SKB personnel and a few external experts. The objective of this meeting was to review the current status of the work. A second workshop was held in Stockholm, February 14–16, 1989. The participants of the second workshop were basically the same as the participants of the first workshop in Kolmården. In addition, a new working group on the biosphere [3] was initiated at the meeting involving SSI, SKI and SKB as well as new experts. The main objective of the workshop was to review the work of the SKI/SKB working group and to clarify the future development of scenario analysis. In particular, problems encountered in implementing the different steps in the Sandia methodology were discussed. Appendix A:5 lists all participants at the different meetings.

2 METHODOLOGY

2.1 OBJECTIVES OF SCENARIO DEVELOPMENT

In principle, the safety analysis of a radioactive waste repository involves the consideration of all possible relevant Features, Events, and Processes, FEPs, that could, directly or indirectly, influence the release and transport of radionuclides from the repository. Each FEP has to be analysed not only with regard to its cause, its probability of occurrence and its consequences, but also with regard to its eventual interactions with other FEPs. It should be pointed out, that these interactions often affect the probabilities and consequences associated with a given FEP.

In order to handle properly the huge and complex amount of information involved in the safety analysis of a repository a thoroughly worked out performance assessment methodology is needed. An important part of such a methodology consists of a scenario development procedure.

The basic objective for scenario development is to make sure that the relevant possible future evolution of the repository is properly considered. However, this objective is very general. The scenario development strategy also has to be related to the criteria used in the performance assessment and safety analysis.

The criteria may, for example, be formulated as upper bounds on doses, total risk interpreted as (integrated) probability times dose or activity inflow to the biosphere. These different criteria imply different demands on the level of ambition needed in the scenario development strategy.

With criteria specified as total risk the set of studied scenarios principally should be **complete** and **realistic**. Furthermore, in order to make it possible to obtain total probabilities the individual scenarios need to be **mutually exclusive**. However, these requirements may be unrealistic and the efforts in fulfilling them may lead to that the most critical phenomena related to the performance of the repository may in fact be overlooked. Furthermore, the Swedish criteria for performance assessment do not specifically require total risk estimates.

One of the most important aspects of scenario development is that it should aid in identifying **critical issues**. In particular, formulating scenarios could be an important means of estimating (pin-pointing) probabilities of a series of smaller events. For example, oxidizing conditions at the canister could probably only occur if there exists a short-cut from the biosphere to the repository (e.g. by damage to the seals of bore holes and shafts 5.9). Such reasoning would imply that the probability for oxidizing conditions combined with a short-cut from the repository to the biosphere could be much larger than the product of the probabilities for these two states individually. In fact, synergetic effects may cause the probabilities for a series of smaller of events to be many orders of magnitude larger compared to the probability if these events where statistically independent.

Even if a scenario development strategy never will produce a complete set of scenarios one must strive for completeness. In this context it is extremely important to document all steps in the development. A transparent **documentation** makes possible an extensive review and updating of the set of scenarios. Such a reviewing process, open to broad groups in the society is probably the best means of assuring reasonable completeness and of building up a general consensus on what are the critical issues for the safe disposal of radioactive waste.

Scenario development and performance assessment are iterative processes. The SKI/SKB scenario development project is a first step in longer process for scenario development. At this stage the main objective is to investigate the feasibility of the Sandia scenario development strategy (see section 2.2). Furthermore, the appropriate steps in further scenario development should be identified. In the long term the level of ambition for scenario development may certainly differ from what has been reasonably achievable for the SKI/SKB working group.

2.2 THE SANDIA METHOD OF SCENARIO DEVELOPMENT

The present project includes an evaluation of a scenario development methodology developed by the Waste Management Systems Division of Sandia National Laboratories, Albuquerque, USA. This procedure, herein referred to as the Sandia method, is not the only approach to scenario analysis but it was considered to be a fruitful starting point for the present work.

The main objective of the Sandia method is to combine FEPs into scenarios and to produce, by means of an objective and consistent procedure, a set of scenarios that is important in a potential disposal site analysis. The term "scenario", as used in the original Sandia method [1], refers to "a set of naturally occurring and/or human-induced conditions that represent realistic future states of the repository, geologic systems, and ground-water flow systems that could affect the repository and transport of radionuclides from the repository to humans".

An important concept in the Sandia method is the "base case scenario". This represents "the initial conceptualization of the disposal system including the repository and emplaced waste. All components of the engineered barrier system are assumed to perform as designed."

According to the above definitions, a scenario (with the exception of the base case scenario) may be regarded as a perturbation of a repository system that functions as expected under the base case conditions.

2.2.1 Scheme

The Sandia method is meant to be a systematic procedure for arriving at a set of scenarios for use in the analysis of a potential disposal site. Furthermore, is intended that the selection of relevant scenarios should be based on well-defined criteria. In short, the Sandia method consists of the following steps:

1. An initial comprehensive identification of those FEPs that are considered to be important to the long-term isolation of radioactive waste in a repository.
2. A classification scheme is needed in order to make the list of FEPs as complete as possible.
3. A screening of these FEPs based on well-defined criteria.
4. The formation of scenarios by taking specific combinations of those FEPs remaining after the screening process.
5. An initial screening of these scenarios.
6. The selection of a final set of scenarios for use in evaluating a potential disposal site.

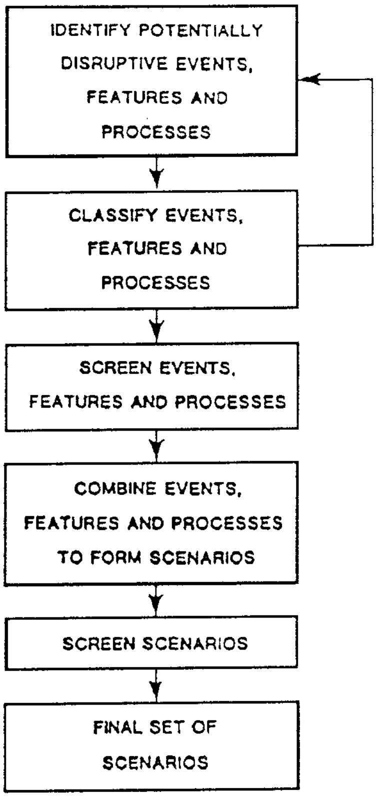

Figure 2-1. Simplified scheme of the Sandia scenario selection procedure. [From ref 1].

Figure 2-1 presents a simplified graphical description of the Sandia scenario development procedure. The loop connecting classification back to identification indicates that the first two steps in the procedure may have to be iterated several times before the third step is executed.

2.2.2 Identification of Features, Events, and Processes

The first step in the Sandia method consists of the identification of a large number of FEPs, both natural and human-induced, which are believed to be important to the isolation of radioactive waste with regard to the site and the time periods under consideration. This identification could be accomplished by means of meetings, workshops or panel discussions among knowledgeable individuals representing earth sciences, waste-management, chemistry etc. in order to assure that important FEPs are not overlooked.

2.2.3 Classification of Features, Events, and Processes

The identification process produces a number of FEPs. In the next step of the method, or during the identification phase, these FEPs are classified into different groups. Examples of classification schemes are

– natural, human induced, waste and repository induced phenomena,
– likely, unlikely but possible, very unlikely,
– near field, far field, biosphere,
– 0 – 100 years, 100 – 10^4 years, 10^4 – 10^6 years, > 10^6 years.

The objective of classification procedure is to aid in assuring that important scenarios will not be overlooked. Furthermore it is believed that the classification provides the organization needed in order to begin developing and analyzing scenarios.

2.2.4 Screening of Features, Events, and Processes

The identified FEPs could be combined into scenarios. However, in practice the number of combinations considering all identified FEPs will be an extremely large number. By screening FEPs the number of scenarios that have to be considered in the scenario development can be drastically reduced. The following screening criteria are suggested in [1]:

1. Physical reasonableness of the FEPs.
2. Probability of significant release of radionuclides from these FEPs.
3. Potential consequences associated with the occurrence of these FEPs.

It is assumed that screening based on physical considerations largely should be site (and design) specific while screening based on probabilities largely should be associated with judgmental decisions which have to be consistent with appropriate regulations.

Screening based on consequences is assumed to take place in several ways. For example, it is suggested that FEPs with insignificant consequences can be screened out, while FEPs having similar consequences can conceivably be lumped together provided that the probabilities are properly combined. Thus, lumping should reduce the number of FEPs that has to be technically handled in the following steps of the scenario development process since all FEPs that are lumped together are treated as one FEP. (This should of course not mean that lumping reduces the number of FEPs being considered.)

Finally it is noted that the screening process has to be repeated for each repository site and the screening criteria have to be adjusted to the regulations of the national authorities.

2.2.5 Scenario Development

The next step in the Sandia scenario development method consists of the formation of scenarios by taking meaningful combinations of the FEPs remaining after the screening. It is stated that the use of a logic diagram, as illustrated in Figure 2-2, will help assure that all possible FEP-combinations are identified. Scenarios are created by choosing either the "yes" or "no" alternative associated with each FEP. According to the Sandia method, this organizational method is preferable to the classical event-tree, fault-tree techniques frequently used in the analysis of engineered systems.

Using the logic diagram for constructing combinations of FEPs implies that the Sandia method does not separate between two combinations of FEPs consisting of the same FEPs but with different order. Assuming the order between FEPs to be irrelevant implies that n FEPs can be combined into 2^n scenarios (cf. Figure 2-2). However, if the temporal order between FEPs is included the number of possible scenarios would considerably exceed 2^n. The Sandia method claims that the problem of temporal order can be handled by only considering the most important temporal order of the FEPs.

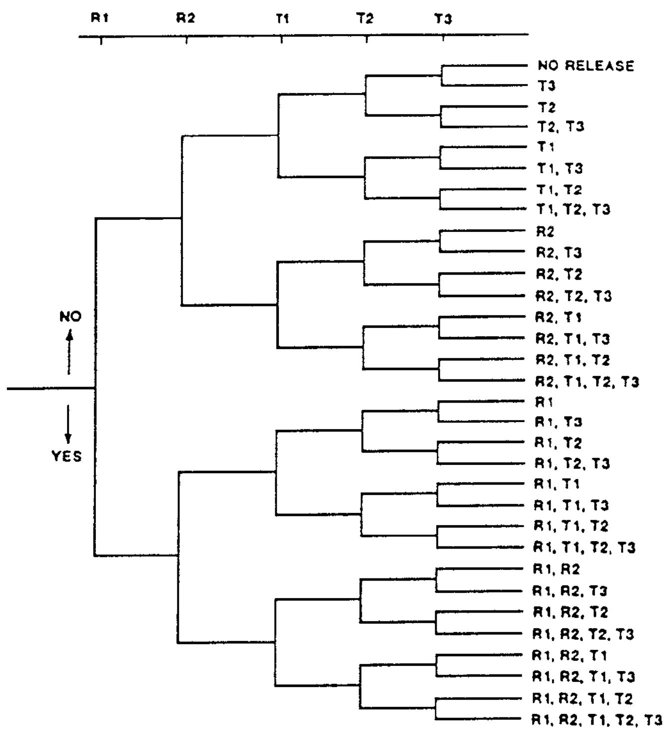

Figure 2-2. Logic diagram showing the possible combinations of five FEPs (two release and three transport phenomena). [From ref 1.]

As a final remark may be noted that the need of screening among the FEPs is clearly understood from the fact that n FEPs can be combined into 2^n scenarios. Combining 100 FEPs would result in approximately 10^{30} scenarios, whereas combining 10 FEPs "only" results in 1024 scenarios.

2.2.6 Screening of Scenarios

The final step in the Sandia method involves the screening of scenarios developed by taking combinations of the various FEPs. The initial screening of these scenarios is based on physical reasonableness, probability, and consequences.

Screening based on physical reasonableness should lead to the elimination of scenarios containing e.g. mutually exclusive FEPs. Screening based on probability considerations simply means that scenarios are screened out if their probability of occurrence is below a certain value (e.g. 10^{-8}/yr). Screening based on consequences means that scenarios of minor importance are screened out.

The Sandia report [1] states that "a final screening of the scenarios remaining at this point can be accomplished using combined probability and consequence arguments, namely risk. However, unless regulations for disposal are risk-based, the use of risk in screening scenarios is generally not applicable."

2.3 THE WORKING GROUP APPLICATION OF THE SANDIA METHOD

The SKI/SKB working group has so far carried through the three first steps in the Sandia method (cf. Figure 2-1), i.e. the identified FEPs have been organized (classified, screened etc.) but not combined to scenarios. However, the SKI/SKB application of the method differs somewhat from the original Sandia method [1]. The details of the performed analysis will be given in chapter 3.

Already at this point it is possible to make some general comments on the applicability of the Sandia methodology as experienced by the working group. The first step – **Identification of FEPs** – appear to be straightforward and could be made even more fruitful by clearly documenting not only the name of the identified FEP but also a by writing an explanatory text (memo-comment) to each FEP. The second step – **Classification of FEPs** – seems reasonable for assuring completeness in the original list of FEPs but appear to be of little value in the following scenario analysis.

The third step – **Screening of FEPs** – was found to be considerably more complicated and time-consuming than the preceding ones. As screening implies that some FEPs will obtain less (or no) attention in the following scenario evaluation it was found that the screening process is intimately linked with the scenario development procedure. Thus, in addition, to apply screening as a means for removal of FEPs for further analysis it was considered fruitful to define a **PROCESS SYSTEM** (see next section) and screen FEPs to this PROCESS SYSTEM. Finally, some FEPs where grouped or **Lumped** together into groups, where the groups and not the individual FEPs where considered in the following analysis.

The present project had little time over for the subsequent steps in the scenario development. The suggestions discussed in Chapter 4 are the result of different working groups during the second workshop of the project. However, the suggestions discussed there have not been analyzed within this project.

Finally, it is interesting to note that the tedious discussions concerning semantics often experienced by the SKI/SKB working group seem to be unescapable. This conclusion can be drawn not only from the work within the working group, but also from the expert meetings arranged by SKI/SKB, and from the extensive glossaries produced e.g. by IAEA and NEA.

2.4 INTRODUCTION OF THE PROCESS SYSTEM CONCEPT

2.4.1 Identification of a Need for a PROCESS SYSTEM

Very soon in the discussions on the screening of FEPs it was recognized that the FEPs belonged to several different categories, and therefore, that they had to be treated differently in scenario development. First of all, in the great span of FEPs ranging from large scale climate changes to the detailed description of mechanisms for fuel dissolution, some distinction must be made between major external events and the phenomena that these events in turn would control more or less automatically. Such "primary causes" (or "external conditions") would, of course, be the first candidates for FEPs to be combined into scenarios. On the other hand, the more detailed phenomena could be regarded as always operative, but to highly varying degree depending on the initial and boundary conditions governed by the primary causes.

In fact, a similar distinction was made already at the first workshop in September 1988, when it was concluded that those FEPs that "are sure to occur" should be screened to "the base case scenario" (BCS). On that occasion nothing was concluded about how to combine these FEPs to a scenario or how they should be treated in other scenarios.

Parts of a solution to these problems were eventually found according to the following line of reasoning.

- Systematic permutation of the many FEPs in the BCS would be out of question due to the outrageous number of possible combinations as already mentioned earlier. In addition, a non-systematic permutation of FEPs would lead to inconsistencies. Instead they should be linked together according to cause and effect, and this linking could be made once and for all.
- Grouping (or "lumping") of FEPs in the BCS is of little value and should preferably be replaced by linking as mentioned above.
- Even FEPs that would be of importance only at extreme conditions should be screened to the BCS as far as they do not belong to external conditions.

At this stage the greatest problem was that the meaning of the word "scenario" in "base case scenario" (or "reference scenario") had been lost. The working group found one feasible way out of this dilemma by creating a new concept, the PROCESS SYSTEM (PS), which should replace the BCS as described above.

Application of the PS in screening of FEPs and in scenario development is described in sections 3.4.3 and 3.5.2, respectively. The following two sections provide a definition of PS and a discussion of alternative methods to describe the PS.

2.4.2 Definition of the PS

The PROCESS SYSTEM is the organized assembly of all phenomena (FEPs) required for description of barrier performance and radionuclide behaviour in a repository and its environment, and that can be predicted with at least some degree of determinism from a given set of exteral conditions.

2.4.3 Different Approaches for Description of the PS

One of the most straightforward descriptions of the PS is to compare the repository and its geological environment with a chemical plant – or rather its processing system. The different barriers would then correspond to blocks in the plant, the geological structure and rock fractures to the piping network, etc. Combination of FEPs to scenarios would then correspond to different settings of controls in the control room of the plant. The recharge groundwater is to be likened with the raw material and the discharge to the biosphere with the product stream. Our task is to predict the product quality, i.e. the radionuclide content in the discharge, accounting for various operating modes and qualities of raw material.

Now, leaving the "hardware" of the PS, our tools to perform this task is a (sketchy) process scheme and a heap of computer codes and data bases for simulation of the industrial process. (The real problem in doing so might be that we should also account for stochastic phenomena and uncertainties, i.e. erratic behaviour in the control room and in the design and construction of the plant.) This more or less mathematical representation of the PROCESS SYSTEM is what we deal with in performance and safety analyses of a repository.

In the design of a PROCESS SYSTEM information is needed from many professional disciplines, e.g. geology, hydrology, chemistry etc. Classification and organization of phenomena according to these subject areas are not fruitful in scenario development, however. Instead the available knowledge has to be integrated in an effort to understand the behaviour of the PROCESS SYSTEM for all scenarios of importance. A suitable starting point in this work is the set of barriers. The performance and evolution of each barrier will have to be described from given initial conditions and considering interactions on the macro scale with other barriers and/or different external conditions. It should be noted that this development of the PS from state to state will in general not be influenced by the presence of radionuclides, which are to be treated as micro components of the system. Rather, the barrier states will provide the setting for radionuclide behaviour.

On the most fundamental level we are concerned with flow of mass and energy in the PS. The main potentials ("driving forces") for flow correspond to differences in temperature (T), hydraulic head (H), mechanical stress (M) and chemical potential (C). The resistance to flow is mainly provided by the geometrical structure and other physical properties of the system (S). Combinations of the entities THMCS can be ascribed to the phenomena (FEPs) belonging to the PS of different barriers and also for classification of interactions between barriers. By proper use of the THMCS concept "coupled" processes can also be identified and a checklist be derived for assertion that no important phenomena have been overlooked. This logic scheme for classification and derivation of phenomena in the PS is similar to, but not the same as, the scheme suggested by Tsang for discussion of coupled processes [4]. Although presented already at the February workshop in 1989 little time has been available for pursuing these lines of thought since then.

A more lucid and useful description of the PS would be a graphic representation of linking, i.e. a process flow sheet or diagram that shows how phenomena act together and influence each other within barriers and over boundaries between barriers. Such a diagram could also be used for visualisation of the parameter and information flow in a comprehensive safety analysis.

In a safety analysis report a verbal description of the PS must accompany the approaches mentioned above. An outline of how this can be made is found in Appendix A:4.

On the next level of abstraction the PS is described by a set of conceptual models and their mathematical representations. It would also be possible to construct a flow sheet of the PS transformed to this "model and parameter space".

The final level of abstraction for the PS is the set of numerical (computer) codes used for a safety analysis. At this stage it will also be necessary to more precisely define and possibly also visualize the information flow.

This somewhat lengthy characterization has been deemed necessary to preclude any ambiguousness of what the PS might be. From above it should be clear that depending on circumstances it might be the real world as well as conceptual descriptions and representations of this reality on different levels of abstraction. In scenario development and safety analyses it will be necessary to consider several, if not all, of these descriptions.

3 INITIAL ANALYSIS AND CLASSIFICATION

3.1 IDENTIFICATION OF FEATURES, EVENTS, AND PROCESSES

3.1.1 Initial Lists

The first step of the Sandia methodology: Identification of Features, Events and Processes (FEPs) was initiated, and basically completed at the first workshop in Kolmården. The workshop participants were divided into four groups with five persons in each group. The groups were selected rather arbitrarily but it was tried to cover as wide area of knowledge and experience as possible in each group.

The groups worked individually for about four hours. Each group used a different classification scheme for FEPs in order to illustrate the benefits of different schemes. Each group should be comprehensive and cover all aspects. The classification schemes for the individual groups were

1) Likely, Unlikely but possible, Very unlikely.
2) Near field, Far field, Biosphere.
3) 0 – 100 years, 100 – 10^4 years, 10^4 – 10^6 years, $>10^6$ years.
4) Repository induced, Human induced, Natural processes.

Each group produced a list of FEPs. The lists from the different groups were not equal and each list contained events or processes not covered in the other lists. However, it is hard to decide if these differences are caused by the different classification schemes, the specific group members or just expresses that the time allotted to producing the list was short.

Group 1 (classification based on probability) found that "likely" was by far the largest group. Group 2 found that many processes were relevant both for the near field and the far field. Group 3 found that the time classification was not very helpful in organizing thoughts with the exception that it puts attention to the very early times. Group 4 produced the most extensive list and it appears that this classification scheme is useful. However, the main objective for the classification schemes is to aid in assuring that "everything" is covered. Thus there are benefits in all schemes provided that not only one scheme is used.

3.1.2 Final List of FEPs – The Merged List

The individual group lists were combined into a joint **merged list** including all the events and processes in the group lists. This merged list is the list entered to the **scenario database** (see Appendix B) and has been the basis for the further development by the SKI/SKB working group. Initially it was intended to classify the merged list into **near field**, **far field** and **biosphere** phenomena. However, during this process it was found that many phenomena that are relevant for the near field also affect the far field. Thus the classification in the merged list should not be taken too seriously.

The merged list did contain inappropriate entries such as duplicates and the inclusion of processes expressed as conceptual uncertainties that should be treated with uncertainty analysis separate from the scenario development. However, when making the lists it is important to include as many features, events and processes as possible. In principle, inappropriate entries should be removed during the screening process.

3.1.3 Completeness

All participants at the first workshop were encouraged to add new items on the list and to produce arguments for the inclusion or screening of the particular items, but only 10 FEPs have been added to the merged list as it appeared initially. The merged list is not complete but it is extensive. It should be stressed that this list is not definite but open to adjustment all times. Scenario development should be an iterative long term process.

The present list of FEPs was produced within a very limited time period and applies in principle only to the KBS-3 concept.

In reality the scenario development should take considerable time and should be adjusted to the relevant storage concept. Much more time should be used and special expert opinions need to be gathered. However, already at present it is important to identify critical issues that need research as these will affect the research plans. On the other hand there may be a danger of specifying the critical issues prematurely as there is a risk that too much resources then would be allocated in the wrong direction.

It is especially important to remember that the present list only contains a few FEPs relevant to the biosphere. Biosphere aspects of scenario development are treated in another project [3]. It can be noted that the prediction of biosphere changes poses a major difficulty. However, with the exception of some processes with common causes (e.g. ice age), most biosphere processes are independent from the geosphere processes. Therefore, it should be possible to decouple the biosphere from the analysis.

3.2 MEMO-COMMENTS

3.2.1 Motivation for Writing Memo-comments

The initial list of FEPs is just a long catalogue of headings. These headings need to be better defined before it is possible to continue the development of the list. Furthermore, it is essential that all steps in a scenario development should be traceable which implies that it is necessary to document how and why FEPs were added, removed or grouped.

In order to meet the above demands a relatively short memo-text has been written to each FEP and entered into the Scenario Database. The outline of a memo should ideally contain:

1) Definition and explanation
2) Cause
3) Consequence / effect
4) How to model
5) Motivation for screening

6) If applicable: Motivation for lumping

7) References

3.2.2 Writing Memo-comments – Conclusions

Appendix B:1 contains a complete printout of the contents of the Data Base including the full memo text. The main effort of the working group, especially in the beginning, has been to write the memo-comments to the individual FEPs. It is the opinion of the working group that given enough time there are few principle problems in writing the memo-comments. Furthermore, it is definitely worthwhile to go through the effort of writing these comments in order to facilitate the remaining steps in the scenario development.

The time that could be spent for writing the memo-comments was limited. Obviously the texts need to be reviewed. In particular, most memos are written without proper references to original scientific work. Parts of the memos have been reviewed by external experts but more review is needed.

3.3 CLASSIFICATION OF FEATURES, EVENTS, AND PROCESSES

The next step in the Sandia methodology is to classify the different FEPs. The motivation for this classification is that it should help assure that important FEPs will not be overlooked. Furthermore, the classification should provide the organization needed to begin developing scenarios.

Four different schemes of classifying FEPs were tried at the meeting in Kolmården (see 2.2.3). The different schemes contributed to the completeness of the lists. The final "merged list" classified under the headings: **Near field**, **Far field** and **Biosphere**. Furthermore, it was tried to substructure the list into waste, canister, buffer, nearby rock, far field rock and biosphere. The INDEX_1 number of the database is constructed from this original classification.

The SKI/SKB working group has not continued with the classification. Furthermore, it was felt that the scheme near field – far field – biosphere was difficult to apply. Many FEPs are not restricted to a single region. In addition, a FEP may originally occur at a well defined location (i.e. canister failure) but its occurrence will affect FEPs at other locations (i.e. radionuclide migration). This implies that the INDEX_1 number in the Data Base is basically used for reference. The index number does not anymore imply grouping or classification. Grouping and sorting of the FEPs should be made through proper fields (currently not updated) in the database.

In conclusion, it is felt that in order to assure completeness the classification is well motivated but this point was illustrated already at the meeting in Kolmården. Classification in order to structure scenarios is probably also a good idea but the adopted scheme has to be well defined in order to be useful. In fact, the SKI/SKB working group has not felt that the lack of proper classification has been the main obstacle in the further scenario analysis.

3.4 SCREENING OF FEATURES, EVENTS, AND PROCESSES

3.4.1 Different Elements of Screening

The next step of the Sandia methodology is to screen the initial list of FEPs in order to reduce the number of FEPs to consider in the future development. When starting the screening process it was found that there are at least three different methods of reducing the list. One possibility is to remove a FEP from the list because it is considered to be unimportant or irrelevant based on some criteria. A second possibility is to classify the FEP to the PROCESS SYSTEM. The third possibility is to group (lump) FEPs and only consider the group in the following analysis.

3.4.2 Removing FEPs from Further Analysis

The following criteria for screening out (removing) FEPs were suggested at the first workshop:

1) **Low probability** ($P < 10^{-8}$/year).
2) **Negligible consequence** (relative unimportance compared to other phenomenon taken into account, obviously negligible impact on repository and site characteristics or future impact of event is significantly greater than radiological consequence).
3) **Physical reasonableness.**
4) **Unplanned options,** (e.g. unforeseen changes in the repository design such as co-storage of other waste).
5) **Unscreening criteria** (keep processes that clearly should be screened out based on the other criteria but still should be analyzed as what-if scenarios).

In addition to the strict probability, consequence and physical reasonableness criteria, the working group has also used

6) **Responsibility** (KBS-3 p. 21:6 [5] "...each generation must take the responsibility for its own conscious actions", e.g. for FEP 5.30 Underground test of nuclear devices).
7) **Administrative** (For removing multiple entries, poorly defined FEPs etc.).
8) **Biosphere** (A FEP that only affects the biosphere is screened out as the biosphere is treated separately in [3]).

The working group has examined the total list of FEPs and removed FEPs according to the screening criteria. Appendix B:2 is a list of the removed FEPs. This screening was relatively straight forward, but the individual decisions have to be reviewed.

Out of the 156 FEPs on the original list 37 FEPs have been screened out. The physical reasonableness criterion and the Administrative criteria are the most widely used. Some suggested processes like 2.1.6.2 "Natural telluric electrochemical reactions" may eventually be screened out as unimportant or unreasonable. However, today these phenomena are not well analyzed. This lack of analysis should not be forgotten.

The probability criterion has been difficult to apply with few exceptions (5.29 Meteorite). Obtaining probabilities of other FEPs would require more careful analysis. Furthermore, it is not clear that the probability for individual FEPs left really could be as low as 10^{-8} per year. (The probability of a combination of FEPs could still be much lower than 10^{-8}).

It has been discussed to use risk as a screening criterion, especially in relation to 1.1.1 Criticality. However, for individual FEPs it should be possible to use either (or both) probability and consequence. A need to use risk in such cases only indicates that the phenomenon needs further analysis for determining if the other criteria apply.

3.4.3 Screening FEPs to the PROCESS SYSTEM

According to the definition of the PROCESS SYSTEM in section 2.4.2, FEPs that could be predicted with at least some degree of determinism should be assigned (screened) to the PROCESS SYSTEM. This statement may be interpreted such that FEPs that can be predicted ones the external conditions or settings are specified can be assigned to PS. With this interpretation scenarios are basically formed by defining settings of external conditions or stochastic events of the FEPs that are not screened to the PROCESS SYSTEM.

An analysis of the list of FEPs showed that a large portion of the FEPs could be screened to the PS. However, the list of FEPs screened to PS, shown in Appendix B:3, does not define the PROCESS SYSTEM. It should rather be used as a check list that a given model of a repository contains all relevant processes.

The links between different external conditions (and other FEPs that can be regarded as primary causes within a given scenario) should be defined both for the external conditions themselves and for the input stages in the PROCESS SYSTEM. For example, a change in climate (external condition and primary cause) can influence the groundwater head and thereby also groundwater flow (input stage). This example also shows that the existing list of FEPs belonging to the PS is far from complete, since groundwater head would suitably be a FEP in its own right. This problem has to be dealt with in a more detailed description of the PS.

A well-defined PROCESS SYSTEM connected to primary causes might facilitate checking and proving that important links are not omitted. Of special importance in this context is the possible occurrence of "common cause failures", e.g coupling of disturbances in groundwater flow and hydrochemistry. This aspect has seldom been dealt with properly in earlier safety assessments. In this respect and many others the PS concept is believed to be useful in any method for scenario development and analysis.

The distinction between a PROCESS SYSTEM and the "outer world" was briefly discussed at the February-89 meeting. Theoretically the PS could be regarded as a submodel to an "Earth" (or even "Universe") model. For example, if it would be possible to predict the occurrence and distribution in time of glaciations this feature could be built into the PS. In that way the time aspect of at least some external conditions could be treated with a certain degree of determinism. From the practical point of view these problems might as well be treated separated from the PS, although it could be admitted that the idea of an enlarged PS would possibly have some advantages when defining the couplings between geosphere and biosphere.

3.4.4 Screening by Lumping FEPs into Groups

The objective of lumping is to reduce the number of FEPs that are to be combined into scenarios by grouping "similar" FEPs together and only work with the

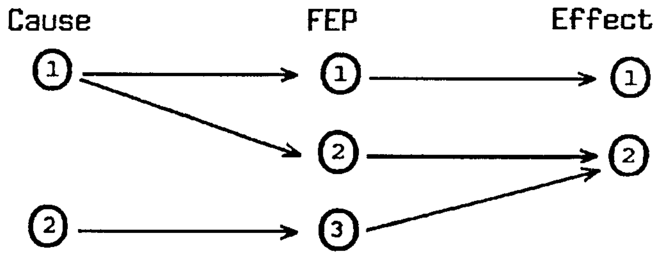

Figure 3-1. Demonstration of the conflict between different lumping-criteria: lumping based on similar cause implies that the FEPs 1 and 2 should be lumped together, while lumping based on effect (consequence) implies lumping of FEPs 2 and 3.

groups in the following scenario analysis. Clearly, when formulating lumping criteria the key issue is to identify how the lumping will affect the later scenario formulation. In particular, certain combinations and linkings might be overlooked if too much is lumped together. Furthermore too much lumping will complicate the consequence analysis such that the lumping was of no use. On the other hand, in practice, it is necessary to resort to lumping in order to reduce the number of FEPs such that the final number of formed scenarios is manageable. In fact, the number of FEPs remaining after the screening processes (removal, PROCESS SYSTEM and lumping) has to be in the order of 10.

First, it must be noted that FEPs in the PROCESS SYSTEM should not be lumped. In particular, these FEPs will not contribute to the number of combinations that need to be analyzed. However, as discussed in section 2.4 they should be linked in order to make a logical structure of the processes in PS.

The lumping (grouping) of FEPs could be based on both "similar consequence (effect)" and "similar cause". These rules are sometimes in conflict with each other (see Figure 3-1) and it is not always quite obvious which rule offers the best result, i.e. the minimum amount of FEPs to be handled in the scenario development. However, mostly the lumping has been based on the "similar consequence"-rule.

The lumping rules have a purely technical nature which means that each one of them offers several possible applications. For example, the "similar consequence" rule does not indicate whether the consequence to be considered is chemical, physical, hydrological or something else. Furthermore, it is far from obvious what kind of e.g. chemical consequences that should be considered as most important.

Numerous discussions within the SKI/SKB working group resulted finally in a set of lumping decisions. Table 3-1 lists the FEPs that remained after the lumping process. Appendix B:4 contains the complete set of lumping decisions. The working group does not claim that the result from this lumping necessarily is the "best" one. Clearly FEPs with the same and only primary cause may be lumped together as these FEPs always will occur in combination. Furthermore, FEPs with similar (modelling) consequence may be lumped provided that the probabilities are appropriately combined. However, the lumping performed by the SKI/SKB working group has not always followed these strict criteria.

Table 3-1. **List of primary FEPs KEPT outside th :PROCESS SYSTEM including ISOLATED SCENARIOS (see section 3.5.3).**

2.5.1	Random canister defects – quality control
3.2.11	Backfill material deficiencies
4.2.6	Faulting
5.3	Stray materials left
5.9	Unsealed boreholes and/or shafts
5.16	Uplift and subsidence
5.17	Permafrost
5.27	Human induced actions on groundwater recharge
5.31	Change in sea level
5.42	Glaciation
7.8	Altered surface water chemistry by humans
5.2	Non-sealed repository (ISOLATED)
5.10	Accidents during operation (ISOLATED)
5.33	Waste retrieval, mining (ISOLATED)
5.38	Explosions " Sabotage (ISOLATED)
5.39	Postclosure monitoring (ISOLATED)

In addition to the strict lumping criteria above much of the lumping is based on more vague criteria. For example, the FEPs lumped to "(2.5.1) Random canister defects" basically represents different reasons (i.e. causes) why a canister may be imperfect, the FEPs lumped to "(3.2.11) Backfill material deficiencies" are basically consequences of imperfect backfill behaviour, whereas the FEPs lumped to "(5.9) Unsealed boreholes and shafts" represent different examples of boreholes and wells that may affect the repository. With this lumping the final set of KEPT FEPS are basically headings of sets of related or similar FEPs. Of course it may be questioned if this lumping is allowable for the scenario development.

One may argue that the lumping performed is premature. On the other hand it is not easy to follow strict lumping criteria when the FEPs are formulated in general. With distinctly formulated FEPs such as a borehole placed at a certain location with a specific withdrawal rate or faulting at a specified location, it may be possible to only rely on consequence lumping combined with additional screening on probability and consequence. However, in the present situation with a generic study such detailed FEPs cannot be formulated.

At the present stage lumping may be viewed as means of structuring the KEPT FEPs and making simplistic consequence analysis more efficient. At a later stage all lumped FEPs must be decoupled and considered in a detailed scenario formulation. After having analyzed the FEPs and their relevance within each group of lumped FEPs it may be possible to describe the FEPs in more detail, to screen these detailed FEPs and finally apply more strict lumping criteria.

3.5 INITIAL ATTEMPTS OF FORMING SCENARIOS

3.5.1 Introduction

The Sandia methodology was designed to provide a comprehensive set of mutually exclusive, potentially disruptive scenarios. In order to obtain this comprehensive set the remaining FEPs are combined. The combinations may be illustrated by a tree diagram (Figure 2-2). However, even if neglecting the order in time between FEPs and neglecting that conditions may apply to different degrees, the number of combinations is 2^M, if M is the number of KEPT FEPs. This number is usually too large (e.g if M=40 the number of combinations are 10^{12}) and some means of reducing this number is needed.

The reduction of the number of combinations may be obtained by restricting the combinations of certain FEPs in the tree diagram (based on an argument that these combinations are illogical) and then screen the remaining relatively long list of combinations using probability, consequence or risk.

3.5.2 Application of the PS in the Scenario Formulation

Scenarios are formed by combining the PROCESS SYSTEM with one or a combination of the FEPs KEPT outside PS. The processes in PS should, as discussed earlier, be linked together according to cause and effect. This linking of processes in the PS should not be confused with the permutation of FEPs KEPT outside PS. However, one must note that the specific modelling of (many of) the processes in PS must be properly adopted to the specific scenario. This adoption, which probably constitutes a major modelling effort, can wait until the actual consequence analysis of the scenario (cf 3.4.3).

Even for a particular scenario many processes in PS have conceptual or parameter uncertainties. These uncertainties may be analyzed by evaluating a set of cases with different parameter values or different conceptual models. This set of cases are not new scenarios but represent the sensitivity of the PS with respect to conceptual and parameter uncertainty for the particular scenario analyzed.

A problem which must be recognized is that the sensitivity and uncertainty analysis made for a particular scenario may be insufficient for another scenario. In practice it would be unrealistic to perform a complete sensitivity and uncertainty analysis for each scenario and it is necessary to define a strategy for limiting this analysis.

One possible strategy that may work in some instances is to evaluate the effect of parameter distributions caused by the new scenario and compare with the parameter distributions used in the first sensitivity analysis. If the new scenario affects the parameters less than what is already considered in the first analysis a new set of uncertainty and sensitivity analyses is unnecessary. However, if the new scenario changes the parameters, or their uncertainty, more than what is considered in the original sensitivity analysis a new evaluation is necessary. Another possibility is to start with a global sensitivity analysis of the PS that encompasses the maximum parameter ranges for any scenario.

3.5.3 Restricting the Number of Combinations – ISOLATED SCENARIOS

In the original Sandia method (e.g. [1]) is stated that it is possible to eliminate illogical combinations of FEPs in the tree diagram. In trying to apply this possibility to all two by two combinations of the remaining FEPs, the SKI/SKB working group found that in most cases it was not possible to claim that a given combination of FEPs was illogical and therefore could be disregarded. Thus it appears that the a priori elimination of combinations on logical grounds will aid little in reducing the number of combinations. However, the SKI/SKB working group found that another but similar restriction, which was labeled ISOLATED SCENARIO, may indeed be useful.

Table 3-1 also contains which of the FEPs left after the lumping procedure that were labeled ISOLATED SCENARIOS. A FEP labeled ISOLATED SCENARIO should not be combined with other FEPs to form new scenarios.

The reason for this special treatment could be that the "normal" release and transport mechanisms considered in PS are unimportant in comparison to the ISOLATED SCENARIO. For example Waste retrieval and mining (5.33) is by far a much more effective release and transport mechanism than e.g. canister corrosion, canister failure and radionuclide migration through buffer and geosphere. Another cause for labeling a FEP with ISOLATED SCENARIO could be that the phenomenon merely is a separate issue which needs to be taken care of and may require a special discussion on ethics. Examples of such later isolated scenarios are 5.2 Non-sealed repository or 5.39 Post-closure monitoring.

3.5.4 Problems with the Initial Formulation of Scenarios

The lists of primary FEPs KEPT outside PS and the ISOLATED scenarios represent the present level of the scenario development made by the SKI/SKB working group. The remaining steps of the Sandia methodology have not been executed. Limited time is one reason why the development have halted at this level but there are also other problems that need to be settled before it is worthwhile to continue the work with combining FEPs to scenarios.

The present definitions of the FEPs are general and vague. Combinations of FEPs and especially restrictions or screening of combinations require that the individual FEPs are more well defined. In particular, the present definitions are not mutually exclusive. For example, 5.42 glaciation may cause 4.2.6 faulting but faulting and glaciation cannot be lumped together as both glaciation without faulting and faulting without glaciation are possible conditions. The logistics of combining the FEPs would be simplified if the FEP glaciation only causes faulting if explicitly combined with the FEP faulting.

Another unresolved matter is time. The Sandia method does not use time explicitly. It is assumed that future and evolutionary FEPs may be combined for maximum effect and should be modelled for the full length of the time frame considered. However, the applicability of this strategy may be questioned as the probability of a FEP and the consequence of a FEP can strongly depend upon time and the order of occurrence.

In this context it may be advisable to divide the FEPs into effects during "the active period" and the "remaining effects". For example 5.42 glaciation implies ice cover over a limited time (active period) but may cause remaining effects on faulting or erosion. During the active period many combinations of FEPs may be outscreened as the probability of simultaneous occurrence may be very low. Furthermore, FEPs in the active period may be anti-correlated (for example 5.42 glaciation and 5.27 human induced actions on groundwater recharge). The "remaining effect" part of a FEP (e.g. a fault caused by a glaciation) may, on the other hand, be lumped into a limited set of FEPs (e.g. faults caused by glaciation could eventually be lumped into 4.2.6 faulting).

4 POSSIBILITIES FOR FURTHER DEVELOPMENT

As noted in the previous section it is not straight forward to strictly adopt the Sandia methodology and develop scenarios from even a short list of FEPs. Furthermore, it may even be questionable if the proposed method is at all possible or if other techniques for developing scenarios should be applied.

At the second scenario development workshop in Stockholm the problem of scenario development was analyzed in a special group session. The workshop participants were divided into three different groups. Each group tried to develop and apply a different technique for developing scenarios based on the list of FEPs supplied by the SKI/SKB working group. The following approaches were studied:

– Further application of the Sandia methodology.
– Identification of critical issues.
– Top – down analysis.

The result of these efforts are presented in the following sections.

4.1 FURTHER APPLICATION OF THE SANDIA METHODOLOGY

4.1.1 Introduction

The working group discussing the possibilities of a further application of the Sandia methodology first noted that the scenario development by the SKI/SKB working group represents preliminary results in an iterative process. Furthermore, it was concluded that at this stage it is not really fruitful to go further with the Sandia methodology until the tedious FEP lumping/screening process has been carefully re-examined and all the memo-comments meet with acceptable standards.

The completion of memo-comments is considered to be a straight-forward work. However, the re-examination of the FEP processing is more complicated. According to some participants at the February 1989 meeting, it may not only be necessary to check that all FEPs have been processed in a logical and consistent way, but also to split up some of the FEPs into smaller ones before repeating the screening/lumping process. It was also stressed that it may be advantageous to distinguish carefully between lumping based on cause and consequence, respectively.

Furthermore, the FEP processing contains problems that have not yet been sufficiently dealt with, namely how the time ordering between FEPs should be involved in the scenario development and how the binary yes/no alternatives associated with the FEPs in many cases should be exchanged by a continuous variation between these extremes. In this context, "time ordering" refers to the temporal order of occurrence of the FEPs in a certain scenario.

The original Sandia method considers FEPs that may or may not be time dependent processes but it does not explicitly consider the time order between FEPs. Thus, in a strict sense each scenario formulated in the original Sandia method, represents a whole set of scenarios which can be obtained by permutating among the FEPs and by including arbitrary time order of FEPs.

For example, provided that each FEP occurs only once and that the FEPs may either occur at separate times or simultaneously, a scenario containing e.g. 3 FEPs in the logic diagram (cf. Figure 4-3) represents in fact 25 different scenarios, when all possible temporal orders and permutations are considered. The example clearly indicates the considerable increase in the number of scenarios to be handled when "time order" is introduced in the scenario development. Yet, this number is small in comparison to the number of scenarios that has to be treated when "time" in all its aspects is considered.

4.1.2 Possibilities for Scenario Development

It was pointed out at the February 1989 meeting that the above limitations concerning time order and binary yes/no options can be eliminated by including in the Sandia methodology one or more of the following parameters: (1) probabilities, (2) time, (3) time order, and (4) multiple options in stead of yes/no options.

The development of a repository does not only depend on what kind of FEPs that occur, but also on their time of occurrence. As an example, the importance of glaciation may highly depend on whether it occurs at an early, intermediate, or late stage during the life time of the repository. Therefore, it is recommendable to divide this FEP into new FEPs corresponding to different time periods. In the logic diagram presented in Figure 4-1 glaciation has been divided into glaciation occurring during the arbitrarily chosen periods 0 – 10^4 years, 10^4 – 10^5 years, and 10^5 – 10^6 years, respectively. (Times longer than 10^6 years were not considered in this case.)

Figure 4-1 also demonstrates the possibility of including in the logic diagram, if wanted, probabilities of occurrences associated with each FEP. In cases when a FEP has been split up into several successive FEPs, as "glaciation" above, the probability of occurrence is highly dependent on the time period considered. Thus, since each period is about ten times longer than the preceding one, it may be reasonable to consider the probability of glaciation within 10^4 years, P(A) in Figure 4-1, to be "low", while the corresponding probabilities , P(B) and P(C), for the two following periods may be regarded as "medium" and "high", respectively. The qualitative measures should of course, if possible be exchanged by exact numbers in order to obtain the best results.

The multiple option can be used e.g. when a FEP is known to occur but the time for its occurrence is unknown. Figure 4-2 demonstrates the use of this option in association with the FEP "faulting". The probability assigned to faulting is highly dependent on what time period is considered. Since one of the main reasons for faulting is glaciation, it may be reasonable to assign increasingly higher probabilities for faulting occurring at an early, intermediate, and late stage, respectively. The probabilities presented in Figure 4-2 are for demonstration purposes only.

Multiple options may also be used in order to present all possible time orders of FEPs in a scenario ("scenario" is here used in accordance with the Sandia terminology). As an example, the logic diagram in Figure 4-3 presents all possible time orders of three FEPs (A, B, and C) provided that each FEP occurs only once and that all FEPs may occur simultaneously or at different times.

It is obvious that the introduction of probabilities, time, time order, and multiple options considerably increases the work to be done in the scenario development. Nevertheless, in order to carry through a complete scenario analysis these factors have to be considered. From practical points of view the above stresses

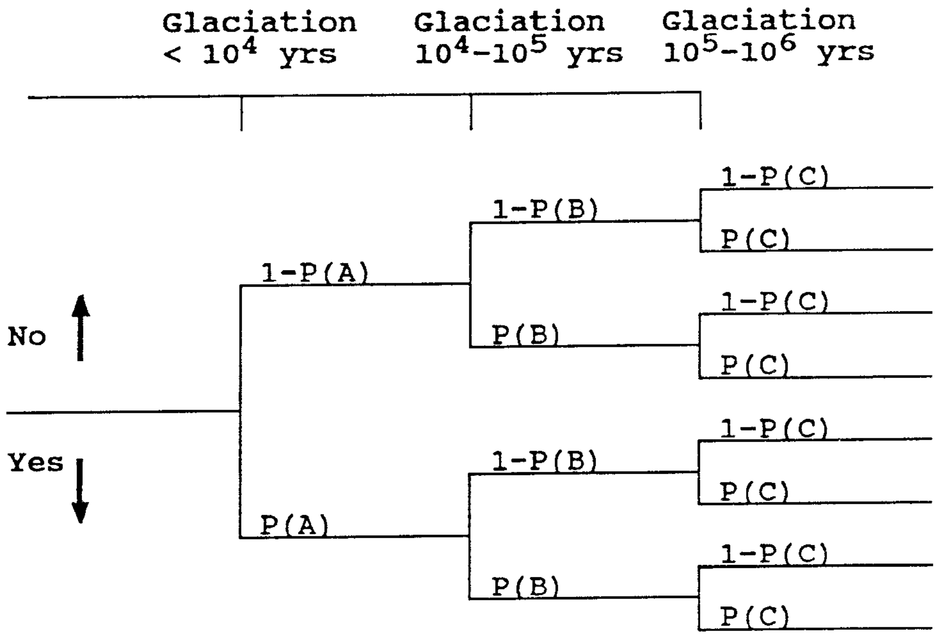

Figure 4-1. Logic diagram in which the FEP "glaciation" has been divided into three parts corresponding to different time periods. P(A), P(B), and P(C) represent the probability of glaciation occurring during the time period under consideration.

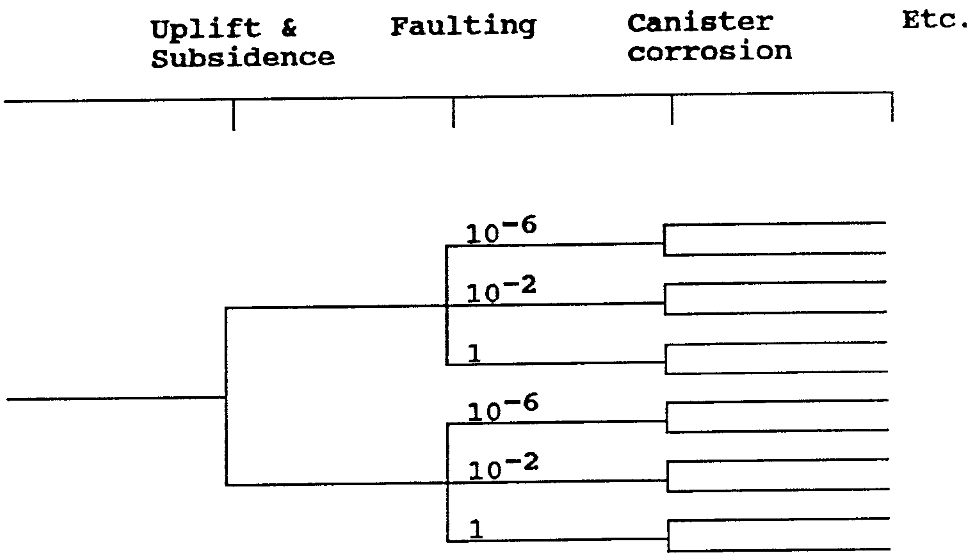

Figure 4-2. Simplified tree diagram indicating the possibility of having a multiple option associated with a FEP.

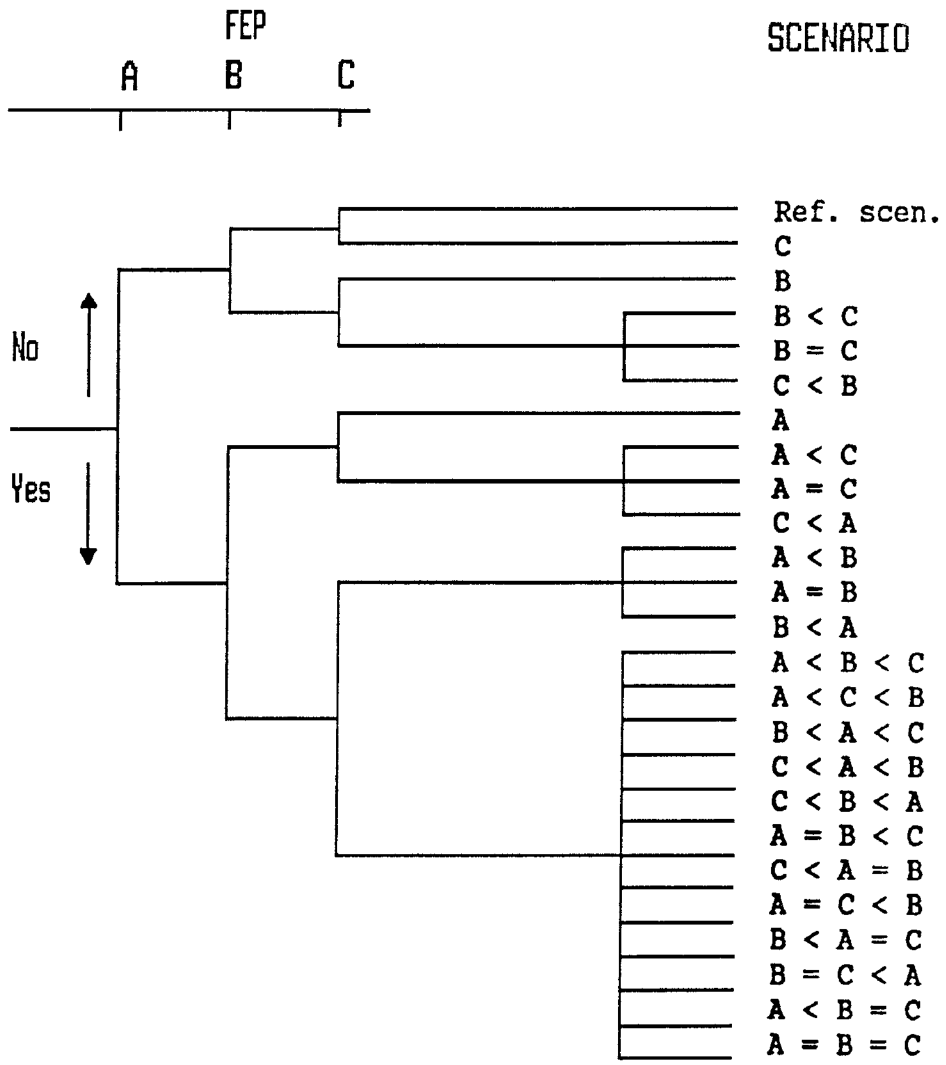

Figure 4-3. Logic diagram showing all possible time orders among the three FEPs A, B, and C. The signs < and = means "occurs earlier than" and "occurs at the same time as", respectively.

the need of a carefully prepared strategy concerning the screening and lumping among the FEPs (cf. Chapter two).

4.2 IDENTIFICATION OF CRITICAL ISSUES

The attractiveness of the Sandia approach is that it appears to produce a complete set of scenarios. However, this apparent completeness may be misleading as the lumping and screening process includes many ill-defined decisions. Furthermore, the method directs a lot of effort in sorting out details and there may be a risk that the overall critical questions are lost in this process. For example, a key parameter for the performance of the KBS-3 concept is the canister life time distribution. Will a bottom-up scenario evaluation really show this? As an alternative it may be much more fruitful to, based on expert judgement, select a few scenarios and analyze them first before putting too much emphasis on obtaining a complete set of scenarios.

A possible strategy for selecting the few critical scenarios may be to:

i divide the future into different time frames (e.g. 10^4, 10^5 and 10^6 years).

ii) formulate scenarios for each particular time frame by asking what may cause a release in that particular time frame. In answering this question the identified FEPs are used as a check list.

Some of the FEPs on the final list of KEPT FEPs may be regarded as design problems (see Table 4-1). The main reason for separating design problems from other FEPs is that the causes for the design problems are uncorrelated with the causes for the other FEPs. Thus, the design problems may be left out from the scenario development and instead be treated as uncertainties regarding the source and near field properties.

Table 4-1. Design problems selected from the final list of KEPT FEPs.

2.5.1	(Random) canister defect
3.2.11	Backfill (material) deficiencies
5.3	Stray materials left

The remaining FEPs were used for constructing scenarios for the 10^4 time frame and the 10^5 time frame. Tables 4-2 and 4-3 display the FEPs selected in the respective time frames.

Table 4-2. Potential causes for release in the 10^4 time frame selected from the final list of KEPT FEPs.

5.9	"Unsealed boreholes and shafts" (including all types of wells)
7.8	"Altered water chemistry by humans"
5.16	"Uplift/subsidence"

Table 4-3. Potential causes for release in the 10^5 time frame selected from the final list of KEPT FEPs.

5.9	"Unsealed boreholes and shafts" (including all types of wells)
7.8	"Altered water chemistry by humans"
4.26	"Faulting"
5.42	"Glaciation"
5.16	"Uplift/subsidence"

Tables 4-2 and 4-3 illustrate that most FEPs selected to be potentially critical for a particular time frame are potentially critical for all later time frames. Thus, the definition of the time frame does not aid much in the selection of which FEPs to be considered. However, the probability, consequence and analysis of a FEP may be very different in different time frames.

At present combinations of FEPs do not seem crucial just for identifying critical scientific problems. It is probably more important to analyze and specify the individual FEPs, for example to identify the consequences of glaciation or evaluating the extent and location of faulting, than to worry about which combinations of FEPs to consider and not consider. Especially the intermediate combinations of FEPs are mainly only interesting when the objective is to determine probability density functions of releases, but are of minor importance for highlighting critical issues.

In any time frame it is possible to construct a human induced scenario which will result in large releases. For example, a set of wells for geothermal production drilled right through canister deposition holes (5.9 Unsealed boreholes and shafts). However, the scenario may in fact be very far fetched. Thus it is not easy to formulate "a realistic" critical scenario and probably the only solution to this problem is to introduce probability of occurrence combined with screening out such human induced scenarios which may be labeled "conscious actions".

As a general conclusion it appears that the suggested strategy of using "expert judgement" for the scenario development is not really constructive in adding information on how to develop the final list of KEPT FEPs into scenarios. In fact, all the KEPT FEPs need to be analyzed. Furthermore, it is not always possible to formulate the most critical scenario without being overly pessimistic. Thus probability and risk estimates are sometimes needed.

On the other hand the philosophy of concentrating on critical issues should be valuable for the scenario development strategy. The formal scenario building should be aimed at providing a framework giving insight into critical issues and processes. Clearly, probabilistic parameters such as the canister life time distribution or possible well locations need to be considered and may prove to be critical. It may also prove necessary to evaluate the risk of certain scenarios. However, the main effort should be spent on how to deterministically or probabilistically evaluate the particular phenomena already identified on the final list of KEPT FEPs at different time frames. Evaluating total risk or pdf's of releases or doses integrated over all time and all possible scenarios, which may be an objective of the scenario development, is such a large undertaking that it may divert the resources from the critical issues.

4.3 AN EXAMPLE OF A "TOP–DOWN" APPROACH – THE BARRIER STATE METHOD

An alternative to the Sandia approach would be to disregard the detailed phenomena and their coupling from the outset and just look upon combinations of different barrier performance. In practice this means that the PROCESS SYSTEM is divided in a set of barriers, e.g. canister, nearfield and farfield. Initially, it is then assumed that the performance of each such barrier might be denoted by either of three states: ordinary, less efficient or short circuited. In performance assessment calculations these states correspond to different sets of parameters according to the following scheme.

Barrier performance	**Set of parameters**
Ordinary (O)	Realistic
Less efficient (LE)	Pessimistic
Short circuit (SC)	(None)

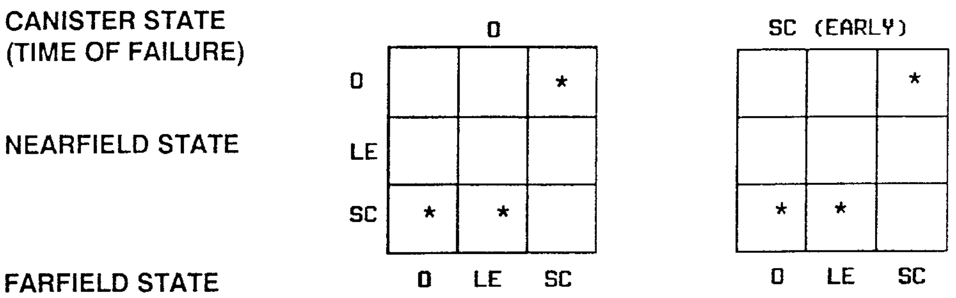

Figure 4-4. Formulation of scenarios by combining different barrier states. (*) denotes an improbable combination.

This scheme might not apply to a copper canister, however. According to the evaluation of KBS-3 it is very difficult to assign any barrier function to an already failed canister, which means that the canister only exist in two states, breached, i.e. non-existent, or not yet breached. Thus the LE state might be excluded for the canister. Ordinary performance means that its life-time is as expected and short circuit corresponds to an initial canister failure (or earlier failure than expected). An alternative would be to denote the time frame of canister failure instead of the state of the canister, i.e. initial, early and as expected.

The total set of scenarios according to this method can be represented by Figure 4-4, where each box means a scenario.

For each of the 18 combinations of states (scenarios) in Figure 4-4 it might be possible to assign some measure of probability. Screening might also be possible since the simultaneous occurrence of different states are not always independent. For example, a short circuited nearfield would most probably not occur together with an undisturbed farfield. A reduction to 12 combinations is achieved after such screening.

In order to further develop this method it is necessary to more carefully analyse the interdependence of barrier states. Evidently such an analysis must be based on the PROCESS SYSTEM and its development in time. It should also be recognized that (a) the starting point in time for each scenario (i.e. time for canister failure) is a parameter of major importance, and (b) scenarios might only apply for part of the repository.

An advantage of the barrier state method seems to be the little need for analysis of couplings within the PROCESS SYSTEM. Considering the importance of possible common cause failures, as described in section 2.4, this is not quite true, however. Still it might be useful for construction of "bad cases" which can be used for regulatory purposes or as a starting point for development of more realistic scenarios.

In order to be useful in a safety assessment the scenarios according to this method should be combined with realistic sets of primary causes, e.g. according to the list of KEPT FEPs. In that way it is possible to get clues both how to distribute scenarios in time and how to achieve couplings in the PROCESS SYSTEM. The easiest way to do this is to assign to each FEP a set of barrier states, (Table 4-4).

Table 4-4. **Illustration of consequences on the barrier states caused by individual FEPs.**

KEPT FEPs	BARRIER STATES Canister	Nearfield	Farfield
Faulting	SC*	LE	SC*
Nearfield deficiencies		LE	
Unsealed boreholes			SC*
Uplift/subsidence			LE
Glaciation	SC*	LE	SC*
Human actions on groundwater flow and composition			LE

(* means for part of repository only)

4.4 THE SITE EVOLUTION METHOD

The most important objection to the already described methods for scenario development is lack of the arrow of time. It is evidently of tremendous importance whether the failure of canisters or other barrier functions occur early or after long periods of time. In principle, a solution to this problem would be to replace the scenario development with a total simulation in time of all aspects of the repository development, where uncertain parameters are described by probability density functions and the result of the total simulation is expressed in probability space. In fact, the UK Department of the Environment have developed a code (VANDAL) /Thompson, 1987/ [6], with this ambition. However, the practicality of the approach and the interpretation of the analysis is still in question.

A slight modification of the approach of a total simulation might be to first develop scenarios for the large scale evolution of the site, including the repository, i.e. the macro system and in a second step superimpose on the large scale scenarios the more detailed scenarios that also includes the dispersion of radionuclides, i.e. the microsystem. The greatest advantage with this approach would be to account for the accumulation of detrimental effects on the repository from internal and external primary causes. This aspect is very difficult to handle in a logic and defensible way in other methods of scenario development.

A serious objection to this method, as well as to the total simulation approach, is the necessity to include predictions of the future that are extremely uncertain, e.g. with regard to glaciations, faulting, biosphere development and human behaviour. Such difficulties have to be discussed in the scientific community, of course. Anyhow, the prospects for consensus are favourable keeping in mind that it is the relative accuracy in estimated time of occurrence that is important. If needed the order in time could then always be chosen as to maximize the effect.

5 DISCUSSION AND CONCLUSIONS

5.1 PRESENT STATE OF SCENARIO DEVELOPMENT WORK

The scenario development project has resulted in an extensive list of features, events and processes. These FEPs have been sorted into different groups, i.e. outscreened, PROCESS SYSTEM and FEPs KEPT outside the PROCESS SYSTEM. Furthermore, the FEPs KEPT outside the processes system are grouped (lumped) together into a limited set of primary FEPs.

The structure given to the initial list of FEPs is constructive in the sense that the final list of KEPT FEPs appears to represent the key external events and processes that could be of critical importance for a radioactive waste repository. Furthermore, even if this list is incomplete it should be straight forward to update it with new FEPs.

It has not been possible to continue the evaluation and actually combine FEPs into scenarios. The reasons for this fact are basically:

- a too general specification of the KEPT FEPs,
- uncertainty with regard to the proper scenario development strategy,
- limited time for the working group.

Thus in order to continue the scenario development it is necessary to analyze each KEPT FEP in detail, analyze the potentials of different scenario development strategies and finally start a new iteration of the scenario development chain.

5.2 DETAILED ANALYSIS OF KEPT FEPs

It is necessary to work out the details of the KEPT FEPs and perform (limited) consequence analysis of each individual FEP before it is really meaningful to start to discuss combinations of FEPs.

For example glaciations may imply a series of phenomena like small movements along fractures intersecting canister deposition holes, faults through the repository, temporal permeability changes or temporal extreme groundwater heads. Establishing the probabilities and consequences of such more well defined events is first of all necessary in evaluating the consequences of glaciations. Furthermore, this increased detailed knowledge will make combinations of glaciations with other primary FEPs more straight forward.

5.3 SCENARIO DEVELOPMENT

At least three different methods of formulating scenarios by combining FEPs have been discussed. Even if the identification of critical issues is a key objective of the scenario development it must be stated that "expert judgment alone" appears to be insufficient for formulating scenarios. A predefined strategy for the scenario development is needed. Without a strategy for selecting scenarios it will become extremely difficult to defend if the selected scenarios are on one side overly pessimistic or on the other side incomplete.

The discussion in section 4.1 shows that it is possible to carry on with the Sandia methodology for selecting scenarios, especially if the general FEPs are further specified as discussed in 4.1. Also the top-down "barrier-state" method (as discussed in section 4.3) appears to be a practical approach.

Both the Sandia approach and the "barrier-state" approach provide a framework for incorporating probabilities and thereby solving the problem of overly pessimistic scenarios. Furthermore, both methods comprehensively analyze all suggested FEPs and thus address the question of completeness. However, the success of the methods depend upon the quality of the detailed consequence analysis and the quality of the probability estimates. Neither of the suggested methods provide guidance for how to obtain this crucial information. Thus it may be stated that provided that the consequences and probabilities of the PROCESS SYSTEM and the individual FEPs KEPT outside the PROCESS SYSTEM are properly understood the actual technique for the scenario development may be of a secondary importance.

As has been stated in section 4.4 neither the Sandia method nor the top-down (barrier-state) method explicitly include time evolution and the time ordering between events. The "site-evolution-method", as discussed in 4.4, appears to be attractive as it includes time explicitly. However, solving the repository evolution in a fully transient mode would in practice be extremely complicated which in turn may lead to undesired simplifications of the involved processes. One alternative to explicit time evolution is to divide the future into different time frames and to combine the FEPs for maximum effect for each time frame, as discussed in section 4.1, appear to be a sensible approach.

5.4 DOCUMENTATION AND REITERATION

Clearly, a given set of scenarios could always be questioned for various reasons. Thus, it is extremely important to remember that scenario development, safety analysis and peer review should be iterative processes. In order to make possible for constructive iterations and review, a transparent documentation is of key importance. The documentation strategy adopted by the SKI/SKB working group based on computerized scenario database should be very constructive in this sense.

5.5 CONCLUSIONS

In conclusion, the strategy developed within the project appears to be a feasible approach to scenario development. In particular, the strategy includes a framework for the documentation of the complete chain of scenario development. This documentation is the key to the following analysis.

It must be stressed that the present project is a first stage and that the complete analysis must be reiterated several times. In particular for some of the FEPs, (e.g. glaciation, faulting or unsealed boreholes and shafts) a proper scenario formulation can only be made after a limited consequence analysis of the individual FEPs. After these analyses it should be possible to continue with the scenario formulation.

ACKNOWLEDGEMENT

The SKI/SKB working group gratefully acknowledge the input and interaction with all participants at the workshops and meetings within the joint SKI/SKB scenario development exercise. In fact, most of the contents of the present report originate from the participants of these meetings.

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APPENDICES

CONTENTS OF APPENDICES

Appendix A:

GENERAL INFORMATION

Appendix

A:1 GLOSSARY

This glossary discusses some of the most frequently used terms in the report. The objective is not primarily to provide strict definitions of the terms but to illustrate how some of the terms have been interpreted and how they are used in this work.

BASE CASE

The Sandia report [1] gives little information about the **Base Case** but notes that it represents the site without any disruptions and that it needs to be considered as a possible scenario. Scenarios are formed by taking meaningful combinations of the Base Case and the other phenomena remaining after the screening process.

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found that the actual definition of the Base Case is crucial for the scenario development and that the original definition was difficult to apply. In combinations with other phenomena the Base Case has been superseded by the new concept PROCESS SYSTEM (q.v.).

CONSEQUENCE

Risk Methodology for Geologic Disposal of Radioactive Waste:
Scenario Selection Procedure [1]:

Consequence can have different interpretations, depending upon the stage of the screening process. For example, in the earlier stages of the screening process, "consequence" generally refers to the effects that a certain event or process might have on the natural properties of the site (e.g., hydraulic head distribution). Thus, only flow and possibly thermo-mechanical analyses are needed at this point. In the screening of scenarios, "consequence" generally refers to the amount of radionuclides being discharged to the environment and the health effects associated with these discharges. Thus, radionuclide transport and health effects calculations are needed at this point. The reason for this breakdown is that in the early stages of the screening process, detailed transport and health effects calculation should be avoided because of the higher computer and man-power costs associated with these efforts.

EXTERNAL CONDITIONS

The SKI/SKB Working Group:

The **external conditions** are events or processes that are not repository induced and may occur (relatively) independent of the processes in the PROCESS SYSTEM. In this work, external conditions are included in FEPs KEPT outside RS.

KEPT

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divided the FEPs into four mutually exclusive categories:

(1) Isolated FEPs, which represent isolated scenarios that are not further considered in the present work,
(2) Outscreened FEPs, which are excluded from the scenario development,
(3) FEPs which belong to the PROCESS SYSTEM PS,
(4) KEPT FEPs which does not belong to the PS but may interact with the FEPs inside the PS.

Thus, scenarios are formed by combining FEPs in the PS with KEPT FEPs.

LUMPING

The SKI/SKB Working Group:

The main objective of **lumping** is to decrease the number of FEPs that is to be technically handled in the later steps of the scenario development process. Lumping does however not reduce the number of FEPs being considered.

FEPs can be lumped together if they have the same cause or effect or if one FEP is part of a greater FEP. Lumping is restricted to FEPs KEPT outside the PROCESS SYSTEM, since only these FEPs affect the number of possible scenarios.

PROCESS SYSTEM, PS

The SKI/SKB Working Group:

The **PROCESS SYSTEM** comprises the complete set of "deterministic" chemical and physical processes that might influence the release of radionuclides from the repository to the biosphere. See also section 2.4.2 for a more detailed and stringent definition.

REFERENCE SITE

The SKI/SKB Working Group:

The **reference site** in this work is synthetic and has no correspondence to any potential disposal site in Sweden, although the aim has been to make the site as realistic as possible in terms of the features included and their associated parameter values.

RISK

The SKI/SKB Working Group

has used the following widely accepted definition:

Risk is the product of probability and consequence associated with a certain event.

It must be recognized that risk is closely related to the time period under consideration; an event associated with a high risk in the one million years perspective may very well be associated with a low annual risk.

SCENARIO

Scenario is the most important concept in this work. Still no generally accepted definition exists.

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use the following definition:

A **scenario** is defined by a set of external conditions which will influence processes in a process system. The external conditions determine how to actually model and combine the processes in the PROCESS SYSTEM when evaluating the consequence of the scenario.

SCREENING

The SKI/SKB Working Group:

The objective of **screening** is to eliminate less important FEPs and scenarios from the scenario development by means of firm and well-defined screening criteria. The great practical advantage of screening FEPs is that the number of possible scenarios is considerably reduced.

Appendix

A:2 SUBJECT INDEX FOR FEPs IN THE DATABASE

Appendix

A:3 STRUCTURE OF THE SCENARIO DATABASE

A:3.1 Introduction

The list of features, events and processes (FEP) has been entered into a Database created by dBASE III Plus. The motivation for working with a database is that it allows for

- continuous updating including bookkeeping of altered decisions,
- a referencing system,
- sort and search possibilities.

At present the database contains the following fields:

Structure for database: E:FEPSN1.dbf
Number of data records: 157
Date of last update: 26/01/89

Field	Field Name	Type	Width	Dec
1	PHENOMENON	Character	60	
2	LOCAT_BEH	Character	25	
3	REACT_TYPE	Character	30	
4	INDEX1	Character	10	
5	LUMPING_1	Character	40	
6	SCREENING	Character	15	
7	PHEN_COMM	Memo	10	
8	REP_INDUCE	Logical	1	
9	HUM_INDUCE	Logical	1	
10	NAT_PHENOM	Logical	1	
11	FUEL	Logical	1	
12	CANISTER	Logical	1	
13	BUFFER_BAC	Logical	1	
14	NEAR_FIELD	Logical	1	
15	FAR_FIELD	Logical	1	
16	BIOSPHERE	Logical	1	
17	NFB_COMM	Memo	10	
18	SCR_CR_NF	Numeric	3	
19	SCR_CR_FF	Numeric	3	
20	SCR_CR_BIO	Numeric	3	
21	SCR_CR_COM	Memo	10	
22	SCE_GR_REF	Memo	10	
23	SCE_GR_COD	Character	20	
24	SCE_GR_COM	Memo	10	
25	LITT_REF	Memo	10	
26	GEN_COMM	Memo	10	
** Total **			289	

A:3.2 Actively Used Fields in the Data Base

Of the 26 fields of the Data Base only a few are used actively. These are PHENOMENON, INDEX1, LUMPING_1, SCREENING and PHEN_COM. The other fields may be altered, deleted or updated at a later stage. New fields may also be added.

A:3.2.1 The Field PHENOMENON

This field contains the **title** of the Feature, Event or Process (FEP) that was entered on the merged list or later added.

A:3.2.2 The Field INDEX1

This field contains the **number** of the FEP as given in the merged list enclosed with the Minutes of the September 1988 meeting. FEPs added to the list obtain a new index. The index number is basically used for reference. The index number **does not** imply any grouping or classification (although they did indicate grouping on the original merged list). Grouping and sorting of the FEPs should be made through proper fields in the database. Classification is further discussed in section 3.3.

A:3.2.3 The Field LUMPING_1

This field contains **pointers** to the FEP(s) to which this FEP is lumped. The pointer address is the INDEX1 number of the FEP. Lumping is further discussed in section 3.4.4.

A:3.2.4 The Field SCREENING

This field contains the **decision** of the screening process (see section 4 to 7). The possible decisions are:

PROCESS SYSTEM
This FEP belongs to the PROCESS SYSTEM (see section 4).

KEPT
This FEP should be part of a considered scenario (see section 3.5).

OUT (.....)
This FEP is screened out. The text between the parenthesis indicate on what criterium (see section 3.4.2).

UNDECIDED
Not decided.

ISOLATED SCENARIO
This FEP represent a very special situation with no (few) references to other FEPs (see section 3.5.3).

A:3.2.5 The Field PHEN_COM

This field is a (memo) text of arbitrary length which should serve as a **background** for the other entries in the Database. The memo should preferably contain:

1) Definition and explanation of the FEP
2) What may cause the FEP
3) Consequence / effect of the FEP
4) How to model the FEP
5) Motivation for lumping and screening
6) References

Appendix

A:4 DESCRIPTION OF THE PROCESS SYSTEM FOR A REPOSITORY OF THE KBS-3 TYPE

Various alternatives for description of the PROCESS SYSTEM of a repository and its environment have already been presented in the main part of this document (Ch 2.4.3). One of these alternatives that has to be integrated with all the others is the verbal description, which also should form the basis for the description in a safety analysis report. It is possible to organize a text of that kind in many ways. When scenario development is considered, the structure chosen here might be preferred, however.

The main principle is that the system is described starting from the outside and going inwards. The inner features of the system are accounted for as perturbations of the larger system described earlier. In that way the evolution of the larger scale features are defined before discussion of phenomena on a smaller scale. This approach will more or less automatically provide the insight about the chains of causes and effects necessary for scenario formulation. Scenarios will in turn define barrier performance and, finally, provide the setting for radionuclide behaviour.

Of course, time and space do not allow a full description of the PS, e.g. as required in a safety analysis report. Thus, the following text should only be regarded as an outline, only giving examples of the most important issues.

A:4.1 The Barrier System

Since this report only concern the situation in Sweden, the KBS-3 concept has been chosen for repository design. Many issues might be considered relevant for most other repository designs in crystalline rock, however. Although the KBS-3 repository should be rather familiar by now, a short recapitulation of its system of barriers is given in this section.

Starting from the innermost barrier, i.e. the spent fuel itself, the radionuclides are surrounded by a set of joint barriers that prevents and/or delay their migration towards the biosphere. The fuel is first surrounded by encapsulations of metal such as zircaloy, stainless steel, titanium, lead, copper or carbon steel. According to the KBS-3 method the spent fuel elements are enclosed in a copper canister filled with either lead or copper. After that follows a clay buffer, i.e. a layer of highly compacted bentonite, between the canister and the rock wall in the emplacement borehole. Attention must also be paid to the backfilling in tunnels, shafts and investigation drillholes. Together with those portions of rock that has been or ever will be disturbed by the presence of a repository these parts form what often is called the near field. The remaining parts of the undisturbed geosphere form the last barrier, the far field (commonly but not quite correctly referred to as the geosphere).

Thus, we see that the physical structure of the PROCESS SYSTEM in this case is comprised by the following seven barriers (or barrier elements),

– the spent fuel itself,
– the copper canister,
– the clay buffer,

– the backfill,
– the near field rock,
– the far field rock.

A:4.2 States and Evolutionary Processes in the Undisturbed Geosphere

Any prediction of the behaviour of a repository and the migration of radionuclides must be based on an organized knowledge of the present state and possible evolution of the chosen geological formation. This knowledge forms the basis for our conception of the "natural" part of the PROCESS SYSTEM. However, in scenario development it is suitable to also include the humanity and its actions in a description of the "natural" system. Thus, the only result of human actions that is not included is the repository itself. The needed knowledge mainly concerns parts of the geophysical sciences: mineralogy, lithology, geohydrology, rock mechanics, properties of the fracture network, tectonics and geochemistry.

Ideally, the available knowledge should be organized in a complete hydrogeochemical model of the repository site. This model is then our mathematical realization of the natural PROCESS SYSTEM. It should describe the groundwater flow field from recharge to discharge, weathering of rock minerals and formation of fracture minerals, the convergence, mixing and divergence of different groundwaters, and how fractures and fracture zones are developed and influenced by tectonic movements, climate changes and human actions – in short a model that describes possible transport paths for groundwater and radionuclides in space and time.

Details in this part of the PROCESS SYSTEM that require more serious attention are,

– the regional and local groundwater flow fields and their characteristics of importance for radionuclide migration (dispersion and channeling effects, correlation of flowrates and fracture mineralogy/rock porosity),
– the mechanical stability of the rock formation and its behaviour during internal and external stresses,
– weathering processes, including the effects on deep groundwater chemistry from disturbances in surface water chemistry.

Depending on our knowledge about the initial (present) state of the natural PS and its uncertain features and different (uncertain) assumptions about coming external events it would then be possible to predict possible future states. First when such a state, and the evolutionary processes leading to that state, have been identified it will be possible to predict the state of the other barriers consistently by superposition.

A:4.3 States and Evolutionary Processes in the Near Field

With the excavation, construction, operation, sealing and the following mere existence of the repository the rock formation is subjected to a disturbance that varies with time and is limited in space. The extension of this disturbance is commonly assumed to define the outer boundaries of the near field in performance assessments. This distinction between near field and far field does not only arise from the fact that the migration models for the near field are quite different from those for the far field. The near field modelling must also comprise the sou.ce term for radionuclides and account for more complex phenomena than encountered in the far field.

The disturbances within the near field are primarily of a thermal, mechanical, chemical or hydraulic nature. By way of couplings between them they might give rise to a row of complex and potentially important phenomena, e.g. change in redox state, convection flow and colloid formation.

In this section we will give a description of evolutionary processes that determine the possible future states of the barriers within the near field. Only after that it will be possible to describe the behaviour of the radionuclides in the following section. The reason for why such a distinction will work is that most radionuclides can be regarded as micro components in the PROCESS SYSTEM. As such they are assumed not to influence on other radionuclides and not on the macrosystem, i.e. the barriers and their components. Exceptions from this rule do exist, however, see below.

A:4.3.1 States and Evolutionary Processes in the Near Field Rock

Superimposed on the processes identified for the evolution of the undisturbed geosphere it will, in principle, be possible to describe the evolution of the near-field rock. Examples of important initial states and processes to consider are,

- the groundwater flowfield on repository scale (including the same aspects as for the undisturbed geosphere),
- mechanical disturbances from the excavation (skinzones etc),
- the changes in redox state due to aeration and resaturation,
- thermal effects on geochemistry, groundwater flow, and mechanical stresses,
- influence of buffer and backfill materials: changes in geochemistry, mechanical stress, groundwater flow, colloid generation and thermal behaviour,
- propagation of the redox front (including redistribution of uranium as a macro-component, cf above).

A:4.3.2 States and Evolutionary Processes in the Backfill

The main issues to consider for the backfill of tunnels and shafts are the abilities to provide mechanical support for the excavated host rock and resistance against groundwater flow. Important phenomena to consider are almost the same as for the buffer, see below.

A:4.3.3 States and Evolutionary Processes in the Buffer

The mechanical and chemical stability of the buffer (and backfill) is of importance for its ability to limit groundwater flow and provide a stable and beneficial chemical environment for the embedded copper canisters. The following issues have to be addressed.

- The initial state of the buffer, i.e. QA in materials selection and for emplacement techniques (mechanical and physico-chemical properties, including redox capacity, and their variations).
- Alteration in clay mineralogy as possible consequence of chemical interactions with groundwater components, reaction with corrosion products, and temperature changes.
- Effects on the physico-chemical properties (swelling ability, rheology, diffusivity and hydraulic conductivity) of clay as a result of mineral alteration, varia-

tion in salinity, and mechanical behaviour of surrounding barriers (rock and canister).
- Behaviour during and after disruptive events (mechanical and thermomechanical effects) in the repository for different time-frames.

A:4.3.4 States and Evolutionary Processes for the Canister

Considering the states and evolutionary processes in the surrounding outer barrier elements it should be possible to estimate the time for failure of canisters or even calculate a distribution of life-times. The overall distribution in time of canister failures is of fundamental importance for a repository concept like that of KBS-3 where the expected life-time ranges over more than millions of years. Examples of phenomena to be analysed are

- the initial state of canisters, i.e. QA, and the probability of "immediate" canister failure,
- corrosion chemistry and availability of corrodants (oxygen, sulfides, sulphate),
- corrosion reaction rates, transport of corrodants,
- possible mechanical failure modes of canisters, e.g. due to rock movements and internal pressure.

The only barrier function that could be ascribed a failed canister would probably be some redox capacity. (For sure, the corroded material will remain and act as a strong barrier, but it would be immensely difficult to say anything definite about its transport properties.)

A:4.4 Radionuclide Transport

The time of a canister failure marks the time for start of a scenario, and the initial setting for radionuclide behaviour and transport is provided by the then existing state of other barriers, including the spent fuel itself. In a strict analysis the subsequent evolution of the total barrier system should be considered.

A:4.4.1 Transport Processes in the Near Field

A:4.4.1.1 Release of Radionuclides from the Fuel

Some important aspects to be covered under this heading are

- initial state of fuel at the time of canister failure (nuclide distribution),
- production of oxidants by radiolysis,
- dissolution/conversion of the fuel matrix,
- availability and rate of radionuclide release irrespective of matrix behaviour ("gap" and grain boundary release),
- radionuclide solubilities.

A:4.4.1.2 Transport of Radionuclides through the Buffer and Backfill and Release to the Geosphere

Important aspects on the nearfield transport are

- the initial (and developing) states of buffer and surrounding rock (mineralogy, groundwater chemistry incl. redox properties, hydraulic parameters and diffusivities),

- diffusion through buf.er (backfill), into the rock matrix, and with release to fracture flow or precipitation at a redox front as outer boundary conditions,
- distribution of transport parameters between emplacement boreholes and the coupling to corresponding canister life-times,
- the temperature field for early scenarios (and possibly some other Onsager effects, e.g. osmotic phenomena),
- interactions with solid phase: sorption, matrix diffusion.

A:4.5 Transport Processes in the Far Field

The setting for radionuclide transport in the "undisturbed" zone of the geosphere has already been described in section A:4.2. In addition to the phenomena mentioned there the following should be considered:

- dispersion and its variation with scale and in different zones,
- retardation by surface sorption and/or matrix diffusion,
- the chemical state of radionuclides in solution including complexation with organic substances,
- colloid transport.

Appendix

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Appendix B:

CONTENTS OF THE SCENARIO DATABASE

PREFACE

Appendix B is a printout of the contents of the Scenario Data Base including the full memo text. The main effort of the working group has been to write the memo-comments to the individual FEPs. However, the time that could be spent for writing the memo-comments was limited and therefore the database is by no means complete. Further work to enhance the quality of the database is needed as well as external reviews by competent experts.

Appendix

B:1 FULL MEMO COMMENTS ON FEPs

1.1.1 Criticality

Lumping
Screening OUT (Cons)

PROCESS

Plutonium criticality could theoretically occur within the canister during the first 50 000 years of storage. This would call for selective dissolution and transport of uranium and part of the canister filling material. Uranium criticality could only occur outside the canisters. This would call for selective deposition of dissolved uranium in the bentonite. A minimum amount of 4 400 kg of uranium is necessary for criticality. The consequences have been calculated to be insignificant, max 130 kW power in one tunnel.

EFFECTS

Criticality would impact the radionuclide inventory and thermal behaviour of the repository, i.e. the near field models.

The far field and biosphere models would not be influenced, only some input data of nuclides and thermal impact.

REFERENCES

The case has been studied in the KBS-2 study by ASEA-ATOM.

Reference to KBS-2, volume 2, page 255 and KBS Technical Report 108, "Criticality in a spent fuel repository in wet crystalline rock", 1978-05-30.

SCREENING

According to the reference reports, the case could be screened out. The possible thermal heat produced is restricted, as the increase in fission product inventory. The probability is also shown to be very low, although the phenomenon cannot be ruled out.

1.1.2 Radioactive decay; heat

Lumping
Screening PROCESS SYSTEM

PROCESS

The radioactive decay of the fuel in the repository is well known. It is modelled in the fuel model, which keeps track of the timely isotope inventory in the fuel matrix. Even the heat generated by the radioactive decay is modelled, as an input to near field and far field calculations.

Whether or not the model corrects the inventory for amounts of different isotopes, that have left the fuel by dissolution is not known.

The far field model does keep track of radioactive decay of species that occur in the transport path, but not for the heat generation. This should be fully acceptable.

EFFECTS

The heat generated in the fuel is the driving force for convective ground water movement. It also may have impact on ground water chemistry.

SCREENING

This representation should be included in the PROCESS SYSTEM.

1.1.3 Recoil of alpha-decay

Lumping 1.2.6
Screening PROCESS SYSTEM

PROCESS

Concerns the possible destruction of the fuel pellet structure induced by high energy alpha-particles from alpha-decay. Could also include the liberation of atoms from the fuel surface.

EFFECTS

Probably unimportant effect as the fuel has experienced a lot of alpha-decay before the canister emplacement. Its impact on the fuel matrix should thus be screened out, using conservative assumptions concerning fuel pellet structure.

SCREENING

The alpha-decay recoil may affect solubility of alpha decay daughters and should perhaps be further investigated or alternatively lumped into solubility estimates, 1.2.6.

1.1.4 Gas generation: He production

Lumping 2.3.8
Screening PROCESS SYSTEM

PROCESS

Helium production is a consequence of alpha-decay in the fuel.

EFFECTS

It is important only with respect to the pressure build-up inside the canister. KBS-3 calculations showed that the internal pressure will exceed the environmental pressure after 10^6 years.

SCREENING

Shall be included in the PROCESS SYSTEM.

Note that Helium production inside the canister is not included in the radiolysis calculation but rather of radioactive decay.

1.2.1 Radiolysis

Lumping
Screening PROCESS SYSTEM

PROCESS

Only radiolysis due to gamma and neutron radiation is possible as long as the canisters are intact. It will have some impact on water chemistry in the vicinity of the canister.

Alpha and beta radiolysis, occurring up to .03 mm from the fuel pellets, will be of importance after canister failure, when water gets in close contact with the fuel matrix.

EFFECTS

In KBS-3 it is shown that the impact of radiolysis on chemistry and canister corrosion is negligible outside and intact copper canister with a reasonable thickness.

Alpha-radiolysis will lead to the formation of hydrogen and oxidizing species such as hydroperoxide. Conservative calculations have been made in the KBS-3 report and references.

REFERENCES

KBS-TR 83-24.

SCREENING

Radiolysis should be taken into account in the PROCESS SYSTEM and be subject to sensitivity analysis. Far field impact has been marked in the Merged list. This should be deleted, the impact being negligible.

1.2.2 H_2/O_2 explosions

Lumping
Screening OUT (CONS)

PROCESS

The gases may be formed by alpha and beta-radiolysis. The probability that they gather in gaseous form, in an explosive composition, and in a cavity in the repository area, are judged to be very small. The fuel itself, the canister or its corrosion products, the backfill (bentonite) and surrounding rock and groundwater will in general act as a reductant and consume the oxygen.

EFFECTS

Should it occur, the energy released is very small and the canisters, buffer and backfill are well suited to withstand the pressure wave initiated.

Experience from mining explosions show the low impact of an explosion on rock and excavations.

SCREENING

H_2/O_2 explosions should be a scenario to screen out at an early stage. However, some more reference material needs to back up this screening decision.

1.2.3 Pb-I reactions

Lumping 1.5
Screening PROCESS SYSTEM

PROCESS

Pb-I reactions refer to the possibility that iodine is bound to the lead in the filling of the canister, and thus not subject to release. Several similar reactions, I-Cu, Cs-Mo etc. are possible but difficult to assess.

EFFECTS

The reactions will increase the release resistance from the spent fuel material.

SCREENING

Shall be included in the PROCESS SYSTEM. Probably the best way to handle the problem is to make a conservative assumption.

1.2.4 Gas generation

Lumping
Screening PROCESS SYSTEM

PROCESS

Gas generation could be caused by radiolysis, helium production, carbon dioxide, organic decomposition, corrosion or changing water chemistry.

EFFECTS

The gas generation might impair the buffer, change the ground water flow locally and may also provide the source for gas transport. It is thus a divergent basis for a group heading.

SCREENING

Gas generation should be included in the PROCESS SYSTEM. Special effects may later form separate scenarios.

1.2.5 I, Cs-migration to fuel surface

Lumping
Screening PROCESS SYSTEM

PROCESS

Migration of I and Cs to the fuel surface could impact the fission product release after canister failure. Considerable experience exists on this subject from analysis of spent fuel.

Conservative assumptions with respect to burn-up and operational history of the fuel can be made when designing the base case fuel matrix dissolution model.

EFFECTS

The assumptions made will greatly impact the time function for release of Cs and I after canister failure. This FEP is modelled (in KBS-3) as given (assumed) fractions of Cs, I, C, Tc available for transport immediately after a breach of a canister.

SCREENING

Should be included in the PROCESS SYSTEM, probably by making conservative assumptions concerning fractions of the said species that are available for transport immediately after canister failure.

1.2.6 Solubility within fuel matrix

Lumping
Screening PROCESS SYSTEM

PROCESS

Solubility within the fuel matrix refers to the solubility of species contained in the fuel matrix in the water entering the canister after it has failed. Is highly dependent on water chemistry, redox potential and radiolysis.

EFFECTS

The solubility affects the release of radionuclides to the near field.

SCREENING

Should be included in the PROCESS SYSTEM.

1.2.7 Recrystallization

Lumping
Screening PROCESS SYSTEM

Recrystallization is linked to solubility phenomena and changes in water chemistry, in turn coupled to radiolysis.

Recrystallization may also refer to the long-term alteration of a cement matrix, i.e. crystallization of calcium silicate hydrates.

EFFECTS

The first effect may have to be taken into account close to the redox front. However, recrystallization is a non conservative assumption as it gives lower values of solubility.

SCREENING

The recrystallization should be included in the PROCESS SYSTEM.

1.2.8 Redox potential

Lumping 1.2.6
Screening OUT(Adm)

PROCESS

The redox potential is influenced by the natural composition of groundwater and, to a high extent, of possible radiolysis close to the fuel. The redox potential greatly influences the oxidation of materials and the solubility of species in the groundwater. It is thus an important intermediate parameter in calculating fuel dissolution, canister corrosion and radionuclide transport.

SCREENING

Redox potential is a parameter, not a process. Should be screened OUT on 'redundancy' (i.e. the ADM criterion). The parameter is handled within the far field chemistry and within the radiolysis effects in the near field.

1.2.9 Dissolution chemistry

Lumping 1.5
Screening PROCESS SYSTEM

PROCESS

Dissolution refers to dissolution of the fuel matrix. It is highly influenced by water chemistry and radiochemical reactions. The dissolution chemistry might be defined as those chemical conditions that influence the rate of fuel matrix oxidation (matrix conversion), reprecipitation and "leaching rate" of uranium. It includes chemical equilibria as well as reaction kinetics.

EFFECTS

The dissolution chemistry, together with solubility and groundwater exchange rate, decide the nearfield activity release.

SCREENING

Shall be included in the PROCESS SYSTEM.

1.3 Damaged or deviating fuel

Lumping
Screening PROCESS SYSTEM

PROCESS

The detailed composition of the stored fuel will vary, due to initial enrichment, possible Pu-enrichment, burn-up etc.

Damaged and possibly also extreme high burn-up fuel might have a greater surface exposed to the water penetrating the canister.

Codes to assess the nuclide inventory in different cases are available and sufficiently accurate; the difficulty is formulating representative input parameters for the calculations.

EFFECTS

For the single canister in question, this might be important for the release rate of radionuclides, but as long as it is light-water power reactor fuel, the overall impact will remain within general conservatism in assumptions.

SCREENING

Forms part of the PROCESS SYSTEM.

1.4 Sudden energy release

Lumping
Screening OUT (CONS) C3

PROCESS

Sudden energy release could occur by sabotage during the operational period.

Formerly, suspicions have been put forward on the possibility of sudden release of lattice energy stored in the fuel, similar to the Wigner effect. This has however, shown not to be possible.

EFFECTS

The storage is not very sensitive, canisters, backfill and excavations will not easily be damaged, the energy will spread elastically in the bedrock, consequences are like those from an earthquake.

REFERENCES

(See SKN-review of KBS-3).

SCREENING

Should be screened OUT for low consequence.

1.5 Release of radionuclides from the failured canister

Lumping
Screening PROCESS SYSTEM

PROCESS

Is linked to solubility of the fuel matrix, to the binding of soluble species in the matrix and to the access of water and its chemical properties. Examples of release resistance are Pb-I reactions, that could reduce the release of fission products to the groundwater.

EFFECTS

The effect of release resistance may be to reduce the release of fuel material to the nearfield.

SCREENING

Should be modelled in the nearfield chemical model and included in PROCESS SYSTEM. Chemical parameters subject to sensitivity analysis.

2.1.1 Chemical reactions (copper corrosion)

Lumping
Screening PROCESS SYSTEM

SCREENING

Naturally, chemical reactions is part of the PROCESS SYSTEM.

2.1.2 Coupled effects (electrophoresis)

Lumping
Screening OUT

Electrophoresis is the migration of ions in an electrical field. Probably this can only occur in connection with galvanic corrosion, i.e. after breach of the canister when migration of radionuclides is considered. The effect might possibly influence the rate of uranium dissolution. This can probably be calculated and/or tested by laboratory experiments.

SCREENING

May eventually be screened out after more careful analysis.

2.1.3 Internal corrosion due to waste

Lumping
Screening PROCESS SYSTEM

The only really aggressive components in the waste are the halogens (iodine and bromide) and possibly also Se and Te. It could easily be calculated how much copper these elements would consume if released from the fuel rods to the canister.

2.1.4 Role of the eventual channeling within the canister

Lumping
Screening PROCESS SYSTEM

This FEP only concerns the channels that may be formed in the canister itself. The effect on the canister of channeling in other parts of the repository (channeling in the buffer, in the nearby rock or in the geosphere are treated at these respective FEPs).

EFFECTS

Channelling within the canister can be ruled out within an intact buffer. Also, advective transport within the canister after failure of both canister and buffer has to be treated as a special case with no available models.

SCREENING

Should be in the PROCESS SYSTEM, but may at a later stage be screened out.

2.1.5 Role of chlorides in copper corrosion

Lumping
Screening PROCESS SYSTEM

During oxidizing conditions it has been shown in a Canadian work (MRS 88, Berlin) that the corrosion of copper is limited by the transport of reaction products in the presence of chloride ions.

During reducing conditions extremely low pH (about 2 or less) is necessary in order to cause copper corrosion (cf KBS-3). However, the pH interval where the copper is stable for corrosion may decrease as the salinity increases.

(This FEP is related to 5.1 Saline groundwater intrusion).

2.1.6.1 Repository induced Pb/Cu electrochemical reactions

Lumping
Screening PROCESS SYSTEM

This kind of reaction can only occur in a breached canister. Only of importance when coupled to (2.1.2) electrophoresis.

2.1.6.2 Natural telluric electrochemical reactions

Lumping
Screening PROCESS SYSTEM

PROCESS

Electric currents will have an effect on the corrosion on the canisters and possibly on the transport of elements through the bentonite buffer by electro-osmosis or electro-phoresis (the former for dissolved species the latter for particulates).

The first question is to find all possible sources of electric currents in the repository environment. The most obvious one is electrochemical reactions occurring at the canister boundary, or due to the presence of different metals in the repository.

Another source is the electrical field associated with radiolytic effects due to the waste; it has already been mentioned in some conferences. A third one is natural currents occurring in the ground, known as "telluric currents". These currents are generated be several processes; one is piezo-electricity which is being tested in Greece to predict earthquakes in the vicinity of faults where large stresses develop.

The major cause of telluric currents is related to the solar activity, which creates ionospheric currents around the earth, in relation to its magnetic field. These currents are random, and cover a large range of frequencies. The frequencies below 1 Hz have a penetration depth which exceeds the repository depth and therefore they need to be considered. Telluric currents also follow the solar activity (with the 11-year cycle) and have the same origin as the "polar lights".

At repository and since crystalline rocks are mostly resistors, the flow of the electric currents will take place in the water conducting fractures, and will be "channelised" by the conducting argillaceous material introduced into the repository as buffer and backfill. They will also use the long copper canisters as preferential pathways. It is thus necessary to study their role in corrosion studies, e.g. pit corrosion, since the circulation of the current in the water-conducting fractures will concentrate them to restricted areas of the canister, where they may increase the corrosion rate and the pitting factor; this effect may be one reason why the pitting factor of metal is a function of the size of the object (a small coin does not have the same pitting factor as a large bronze cannon).

It is also of interest to investigate the possible changes of these solar ionospheric currents in the future, e.g. if they have other cycles than the 11-year one, or what can happen when the magnetic pole of the earth vanishes and becomes inverted (a phenomenon that occurred several times in the past and is used as a geological clock; the next magnetic pole inversion is predicted to occur in approximately 200 000 years, i.e. within the time frame of a repository performance assessment).

If these currents are quantified, their potential impact on corrosion rates and transport enhancement by electro-osmosis could be assessed by a preliminary calculation, to see if they should be included in the scenarios.

SCREENING

Should be included in the PROCESS SYSTEM, although bases for quantification lack at the moment.

2.1.7 Pitting

Lumping
Screening PROCESS SYSTEM

Pitting is a corrosion phenomenon.

REFERENCES

Nielsen and Videm, Evaluation of the feasibility of carrying out a probilistic assessment of the life of the copper canister, Technical Report SKI 88:7, 1988.

2.1.8 Corrosive agents , Sulphides, oxygen etc

Lumping
Screening PROCESS SYSTEM

DESCRIPTION

The presence of corrodants, either naturally occurring or present initially in backfill materials, will give rise to corrosion of the copper canister, eventually leading to its failure and subsequent release of radionuclides. In the absence of oxygen, which is the expected condition at repository depth, copper may only corrode to cuprous sulphide. The source of sulphur is free sulphide (or possibly polysulphides) or sulphate. The latter is thought to be of little significance, however, due to very slow reaction kinetics; the supply of ferrous iron might also be limiting.

CAUSES

Sources of corrodants are substances originally present in backfill materials (oxygen, sulphides, sulphate) or in the groundwater. The content of corrodants in clay buffers etc can be controlled and is otherwise well known. In total they can contribute to general corrosion of some tens of kg of copper. The continuous inward transport of corrodants from the geological environment is probably dominated by diffusion from the tunnel system, giving rise to a localized attack at the top of the canister. This form of corrosion is then limiting for the canister life-time. The measured concentrations of total sulphide in groundwater is in general below 1 mg/l, which gives life-times on the order of tens of millions of years. A combination of very unfavourable conditions (concentrations, buffer failure, high groundwater flowrates etc) might lessen these figures by about one order of magnitude. In conclusion, a very early failure of canisters from corrosion attack, say within one million years, does not seem very probable.

EFFECTS

Extreme conditions (see above) might lead to failure of copper canisters from general corrosion in the timespan between one and ten millions of years. This assumption is based on a canister wall thickness of 100 mm. A smaller wall thickness will give correspondingly shorter life-times.

REFERENCES

Copper as a canister material for non-reprocessed nuclear fuel waste. Assessment from viewpoint of corrosion. (In Swedish.) KBS TR 90, KBS, Stockholm 1978.

Corrosion resistance of a copper canister for spent nuclear fuel. KBS TR 83-24, SKBF, Stockholm 1983.

Nielsen, P.-O. and Videm, K., Evaluation of the feasibility of carrying out a probabilistic assessment of the life of the copper canister. SKI TR 88:7, Stockholm 1988. (Translation of Scandpower Report 2.34.12-2, 1984.)

2.1.9 Backfill effects on Cu corrosion

Lumping
Screening PROCESS SYSTEM

DESCRIPTION

Backfill and buffer materials might influence the rate of copper corrosion in the following ways:

- initial content of oxidants, e.g. trapped oxygen, sulphides, sulphate, the transport of corrodants to the canister surface is limited by diffusion in the backfill and the transport resistance between the backfill and the flowing groundwater,
- the clay buffer influence localized corrosion, on the micro scale (pitting), and on the macro scale (in case of buffer failure).

CAUSES

Unfavorable conditions might result from inferior quality control and unexpected buffer failure.

EFFECTS

Poor backfill characteristics might shorten the expected canister life-time considerably. This is not thought to be a serious problem, however, see 2.1.8.

2.1.10 Microbes

Lumping
Screening PROCESS SYSTEM

PROCESS

Microorganisms exist in geologic environments. There are several different types. Anaerobic bacteria are the most likely species in deep groundwaters, e.g. methanogenic bacteria and sulphate reducers.

Microbial activity is likely both in the near- and far-field of a high-level waste repository but the biomass is constrained by nutrient availability. In the near-field the presence of microbes can not be excluded but the nutrical availability will generally be very low as compared to the biosphere.

Bacteria have been found in undisturbed deep groundwaters but again this is a heterotrophic environment with general unfavourable conditions for extensive microbial growth. The activity in the far-field is likely to depend on the supply of nutrients from the surrounding waters and host rock.

EFFECTS

Possible adverse consequences of microbial activities are production of corrosive agents and gases. Either the microbes themselves or substances produced by the microbes can be imagined to take up radionuclides by sorption or complex formation. These aggregates may act as mobile species of radionuclides which would otherwise have a low solubility or a strong tendency to sorb on the mineral surfaces. Bacteria driven geochemical reactions can also at least in principle cause generation of colloids e.g. ironhydroxide particles by oxidation of iron. Bacteria in a heterotrophic environment have themself a tendency to live sorbed on mineral surfaces. This may in fact add to the uptake of radionuclides on mineral surfaces but it also introduces an uncertainty vis-à-vis laboratory sorption measurements and the fact that dead bacteria or decomposition products of them may become released to the water phase.

In the near-field corrosive agents might be produced that could influence the corrosion rate of the canister and eventually also radionuclide migration. Resident microorganisms in the far-field could potentially act as colloids thus enhancing nuclide transport.

2.2 Creeping of copper

Lumping
Screening PROCESS SYSTEM

PROCESS

Movements in and deformation of the canister material.

CAUSES

If voids inside or outside of the canisters are present and internal or external pressure respectively is formed, the ductile copper material will creep into these voids. If tension stresses are formed at the outside of the copper material during manufacturing these stresses might be reliefed by creeping of the material.

EFFECTS

The canister barrier effect might be impaired. Coppers ductility for creep are yet not known to full extent but can be limited to deformations to a few percent. Especially the welding zone is sensitive for creep since this small area is subject to heavy heat changes during manufacturing of the canister.

2.3.1 Thermal cracking

Lumping
Screening PROCESS SYSTEM

PROCESS

Very high temperatures in a brittle material could cause stresses that could lead to cracks. The probability for such temperatures are judged to be negligible and copper is not a brittle material.

Cycling variances of temperatures could lead to fatigue in the material. The frequency in the temperature changes must then be rather high. Temperature changes with a high frequency are very unlikely in a repository environment.

2.3.2 Electro-chemical cracking

Lumping
Screening OUT(ADM)

Electrochemical cracking is covered by corrosion (2.1.1). Thus 2.3.3 may be screened out on the administrative (duplicate) criterion.

2.3.3 Stress corrosion cracking

Lumping 2.5.1
Screening KEPT

PROCESS

Stress corrosion refers to cracking of the copper material under stress.

CAUSES

In an aggressive environment and with tension stresses on the material corrosion might occur. The groundwater have to have a nitrogen concentration above 1 mmolar or 50-60 ppm before any corrosion reaction will occur. The probability for such an environment will be very low.

EFFECTS

Increased leakage of radionuclides.

SCREENING

Stress corrosion cracking could be lumped to random canister defects (2.5.1). One could view 2.3.3 being a special case of 2.3.3.

2.3.4 Loss of ductility

Lumping 2.5.1
Screening KEPT

PROCESS

Copper material looses some of its ductility for plastic and/or creeping deformations.

CAUSES

Loss of ductility may take place due to:

- Impurities in the copper material.
- Bad manufacturing methods.

EFFECTS

The material becomes more sensible for creep and/or plastic deformations.

2.3.5 Radiation effects on canister

Lumping 2.5.1
Screening KEPT

PROCESS

Radiation may lead to brittleness of the copper material.

CAUSES

A neutron flux will cause brittleness of the copper material. Since the neutron flux will be very low in the repository any severe brittleness will be very unlikely.

EFFECTS

May lead to canister failure (2.5.1) if combined with other effects.

2.3.6 Cracking along welds

Lumping 2.5.1
Screening KEPT

PROCESS

Cracking along the weld at the canister lid.

CAUSES

Bad manufacturing methods could lead to "cold cracks".

Late cracks:

Creep
Stress Corrosion Cracking
Loss of ductility

EFFECTS

Cracking implies a canister failure which may lead to leakage of radionuclides.

2.3.7.1 External stress

Lumping 4.2.1
Screening KEPT

External stress, caused e.g. by rock displacements, may lead to plastic deformations and creep in the canister and subsequent leakage of radionuclides.

2.3.7.2 Hydrostatic pressure on canister

Lumping
Screening OUT(CONS)

The hydrostatic load (5 MPa) on the canister must be a negligible stress compared to the swelling pressure of the buffer. The hydrostatic load could be screened out on low consequence on the canister integrity.

The canister is dimensioned for a hydrostatic load of 5 MPa and a swelling pressure of the buffer of 10 MPa (see KBS TR 83-20).

REFERENCE

KBS TR 83-20.

2.3.8 Internal pressure

Lumping
Screening PROCESS SYSTEM

PROCESS

After about 1 million years the He production in the spent fuel will have caused a higher internal pressure than the surrounding hydrostatic pressure and the swelling pressure from the bentonite. Design differences for fuel types as well as different burn-up history will, due to different internal pressure build up, cause a time spectrum for canister break down.

2.4 Voids in the lead filling

Lumping 2.5.1
Screening KEPT

PROCESS

If voids occurs in the filling material in the canister this might lead to creep phenomena in the surrounding copper material. Depending on the volume of the void this could lead to weak parts in the canister wall and thereby earlier breakdown of the canister than otherwise expected.

2.5.1 Random canister defects – quality control

Lumping
Screening KEPT

One or a few damaged canisters cannot be outruled despite careful quality control. There are a number of reasons why a canister may fail. FEPs influencing canister failures are lumped to 2.5.1.

2.5.2 Common cause canister defects – quality control

Lumping 2.5.1
Screening KEPT

Very unlikely but an important what-if situation (scenario). Common cause should be lumped to 2.5.1 (random defects) as common cause is a special case of 2.5.1. Evaluating the consequence of 2.5.2 knowing the consequence of 2.5.1 is probably straight forward.

3.1.1 Degradation of the bentonite by chemical reactions

Lumping
Screening PROCESS SYSTEM

PROCESS

The degradation could be caused either by material deficiencies, e.g. poor quality control, or by unexpected chemical composition of the ground water.

EFFECTS

The result of the bentonite chemical degradation could be twofold: firstly reduction of swelling capabilities and thus increased hydrological conductivity, secondly "cementation", reduction of plasticity and consequently a risk for channelling effects.

REFERENCES

Much information is available in the KBS-3 work on the features of bentonite, and also of the probabilities for chemical degradation.

SCREENING

Should be included in the PROCESS SYSTEM.

3.1.2 Saturation of sorption sites

Lumping
Screening PROCESS SYSTEM

There is an upper limit of the sorption capacity of a buffer material which may be described in terms of the cation exchange capacity (CEC) of the clay mineral component. (The clay mineral also has a minor anion exchange capacity which however is neglected here.) Most of the important nuclides will sorb on the

clay also for other reasons than ion-exchange mechanisms. It is probably the large specific surface of the clay that is of importance.

The risk that the amount of nuclides released from an eventually damaged canister exceeds the sorption capacity of a buffer may easily be avoided, provided that the nuclide content and CEC are known. It should also be noted that in the KBS-3 study no credit was taken from sorption in the buffer.

3.1.3 Effects of bentonite on groundwater chemistry

Lumping
Screening PROCESS SYSTEM

PROCESS

The ion-exchange properties of the bentonite and impurities such as sulphides, sulphates, organic compounds, carbonates and Fe(II), will influence the chemical composition of the groundwater. This will in turn have an impact on the aggressivity of the groundwater on the corrosion of the canister.

The ion-exchange capability may also affect the transport of radionuclides back through the bentonite to some extent.

This heading refers to the impact on ground water chemistry, which should be included in the base case description of the buffer material.

The ion exchange properties may also be beneficial and have a positive impact in cases, when the groundwater chemistry deviates from the standard composition.

SCREENING

The chemical properties of the bentonite should be included in the PROCESS SYSTEM.

3.1.4 Colloid generation – source

Lumping
Screening PROCESS SYSTEM

PROCESS

This heading refers to the possibility that the bentonite contains, or produces, particles small enough to follow the water in colloidal form, especially in case of non-filled cavities.

EFFECTS

The colloidal particles would bring with them radionuclides due to ion-exchange and other sorbing mechanisms. As long as the nuclides stick to the particles they would not be subject to sorption on the fracture surface along the groundwater flow path.

REFERENCES

The KBS-3 and later knowledge of bentonite properties should form the basis to set figures on probability and extent of colloid generation from the bentonite.

SCREENING

The existence of colloid particles should be included in the PROCESS SYSTEM.

3.1.5 Coagulation of bentonite

Lumping
Screening PROCESS SYSTEM

PROCESS

Coagulation or flocculation is the process by which dispersed clay particles begin to stick together in suspensions. The flocculation may take place due to the addition of a few percent of salt to the clay suspension. The flocculation gives rise to aggregates of clay particles. Large aggregates are influenced by gravity forces and will settle to a bottom sediment.

CAUSES

Flocculation is only expected to take place in a dilute clay-water system (e.g. gel, solution, or suspension). Flocculation is mainly favoured by high ion concentrations and by high cation valencies.

CONSEQUENCE

Although flocculation may change the properties of a bentonite-water system, the buffering capacity in the originally dense bentonite is expected to be damaged mainly by the dilution of the system and not by the subsequent flocculation. In fact, in order to avoid that the bentonite particles are dispersed from the buffer into the fractures, it is necessary that the bentonite in the buffer has a sufficient capacity for coagulation (the concentration of coagulating ions exceed the CCC (Critical Coagulation Concentration)).

3.1.6 Sedimentation of bentonite

Lumping
Screening PROCESS SYSTEM

PROCESS

Sedimentation is the process where large particles (on a molecular scale) in a suspension settles due to the gravity forces and form a sediment. After the sedimentation the suspension consists of the sediment and a clear, particle-free supernatant liquid.

CAUSES

Sedimentation in bentonite/water systems only occurs when the water content is so high that the properties of the system are similar to those of a liquid. If sedimentation occurs in the bentonite buffer it presupposes considerable dilution, caused by e.g. washing out of bentonite particles.

EFFECTS

In the vicinity of a canister, the effects of sedimentation may be considered as negligible in comparison to the processes which dilute the buffer. It should however be pointed out that sedimentation of water transported buffer material may play a significant role in the sealing of rock fissures.

3.1.7 Reactions with cement pore water

Lumping
Screening PROCESS SYSTEM

PROCESS

The cement pore water composition is determined by reactions with the solid phases. The flowing groundwater will deplete the pore water of initially dissolved sodium and potassium hydroxides. Then the $Ca(OH)_2$ cement component is dissolved and the pH-value rises to 12.4. When all calcium hydroxide is dissolved, then the aluminia silicate components are depleted from cement. The pH drops at the same time but is still above 10. When all silicate is dissolved, the pore water will be equal to the groundwater.

EFFECTS

See especially 3.1.1, 3.1.8, 3.2.1, 3.2.2, and 3.2.3.

REFERENCE

I Lunden & K Andersson: Modeling of the mixing of cement pore water and groundwater using the PHREEQE code. (1988).

3.1.8 Near field buffer chemistry

Lumping
Screening OUT (ADM)

Near field buffer chemistry is a heading and does not describe specific processes or events. This FEP is screened out on the administrative criterion.

3.1.9 Radiolysis

Lumping
Screening OUT(ADM)

Radiolysis is covered in 1.2.1. This FEP is screened out on the administrative criterion.

3.1.10 Interactions with corrosion products and waste

Lumping
Screening PROCESS SYSTEM

PROCESS

The heading refers to the ion-exchange and other interactions between corrosion products and waste and the bentonite material. These phenomena must be treated together with the interaction with groundwater, 3.1.3.

EFFECTS

The effects of interaction could be degradation of the bentonite material.

The probability of waste concentration in the bentonite to an extent that this degradation be of importance, is probably low.

SCREENING

The interactions should be modelled in the PROCESS SYSTEM.

3.1.11 Redox front

Lumping
Screening PROCESS SYSTEM

The redox front could refer to three different possible redox fronts:

1) The change of water chemistry when oxidizing surface water enters the far field and at the redox front changes to reducing conditions.
2) The transient after closing the storage, when the nearfield resumes the natural reducing conditions.
3) The possible establishment of oxidizing conditions, due to radiolysis in the close vicinity of the fuel, and the change to oxidizing conditions further out in the nearfield.

The effect of the first point (natural phenomenon) should be well known and taken into account in base case scenario. Alternative scenario could be caused e.g. by human induced change of surface water chemistry.

The second point should have negligible impact, as the transient will have ceased long before the canister failure.

The third point should be taken into account as a base case assumption, the extent of radiolysis being realistic and watched as the governing parameter.

The redox front is related to the following FEPs (6.3, 2.1.8, 1.2.1 and 4.1.1).

3.1.12 Perturbed buffer material chemistry

Lumping
Screening OUT (ADM)

This FEP is covered by 3.1.1 "Degradation of the bentonite by chemical reactions". Thus 3.1.12 may be screened out on the administrative criterion.

3.1.13 Radiation effects on bentonite

Lumping
Screening PROCESS SYSTEM

PROCESS

The bentonite could be influenced by the radiation from dissolved fuel passing or depositing in the bentonite clay.

SCREENING

Should be included in the PROCESS SYSTEM.

3.2.1.1 Swelling of bentonite into tunnels and cracks

Lumping
Screening PROCESS SYSTEM

PROCESS

The swelling of the buffer and backfill material is a basic property, represented in the nearfield model. Most of possible, and probable, swelling into cracks and surrounding tunnels will reduce the groundwater flow to the storage area, and thus, in this aspect, represent a conservatism in the model, as long as it is not taken credit for. However, the contact between the rock and the bentonite is usually assumed to be perfect which dramatically restricts the transport from the bentonite into the flowing groundwater. This restriction will be decreased if the bentonite does not fill all cracks intersecting the deposition hole.

EFFECTS

The negative aspect would include swelling into surrounding cavities to such an extent that the planned high density is not maintained, and thus not the planned, low hydraulic conductivity.

SCREENING

The swelling should be included in the PROCESS SYSTEM, using conservative assumptions concerning its impact on adjacent crack systems. The extreme swelling into cavities resulting in lack of bentonite pressure is handled under the heading poor quality control of backfill.

3.2.1.2 Uneven swelling of bentonite

Lumping 3.2.11
Screening KEPT

PROCESS

Uneven swelling probably represents a transient state, the time scale which should be experimentally verified and included in the PROCESS SYSTEM.

Deficiencies in material structure, cementing etc. could cause steady state imperfections.

EFFECTS

This could cause preferential pathways or even flow instead of diffusion. The probability is judged low, provided quality control is good.

SCREENING

This should be KEPT on the list of scenario events. The FEP is a subset of 3.2.11 Backfill material deficiencies.

3.2.2 Movement of canister in buffer/backfill

Lumping 3.2.11
Screening KEPT

PROCESS

This phenomenon is well known and calculations can be made on the extent of this type of movement. It is of no importance for base case calculation.

An accelerated movement could reduce the effect of the bentonite barrier. This would again probably be a consequence of material deficiencies or poor quality control.

EFFECTS

Canister movement in the buffer/backfill could bring the canister faster in contact or closer to the bedrock, thus reducing the effect of the buffer/backfill material.

SCREENING

Should be KEPT on the list as a subset of 'Backfill material deficiencies' 3.2.11.

3.2.3 Mechanical failure of buffer/backfill

Lumping 4.2.1
Screening KEPT

PROCESS

Mechanical failure of the buffer material here refers to disturbances of the buffer due to rock movements in fractures intersecting the canister deposition holes or intersecting the repository tunnels.

SCREENING

The causes for rock movements along fractures are covered in 4.2.1, Mechanical failure of the repository. Thus 3.2.3 may be lumped to 4.2.1.

3.2.4 Erosion of buffer/backfill

Lumping
Screening PROCESS SYSTEM

PROCESS

Solid material in buffer or backfill is carried away by flowing groundwater. This process should be distinguished from chemical dissolution, which of course can occur simultaneously.

CAUSES

Release of particulates in the "normal" situation is very unlikely indeed. For normal groundwater compositions this may only occur for very high flowrates. Flowrate criteria might be available. High flowrates may be caused by events such as earthquakes, glaciations etc, most of which are of a transient nature. The effect of temperature may be important.

Another cause for release of solid clay particles seems to be connected to change in water chemistry that gives abnormally low salt content (ionic strength); distilled water gives suspensions of bentonite. Criteria for groundwater can be developed.

Preceding or simultaneous chemical alteration of the clay might of course influence the situation.

EFFECTS

The barrier in question might be impaired. Redistribution of material in fractures. The eroding clay acts as an "engineered" source of colloids.

REFERENCES

Le Bel, KBS TR 97.

3.2.5 Thermal effects on the buffer material

Lumping
Screening PROCESS SYSTEM

PROCESS

The main thermal effects on bentonite may be associated with heat-induced conversion of montmorillonite to either beidellite or illite. The type of clay mineral formed depends on the K^+ concentration. A low K^+ concentration leads to the formation of beidellite, while a high K^+ concentration yields non-expanding illite.

Beidellite exhibits similar expansion properties as montmorillonite and does not collapse permanently with other cations than K^+ in the interlamellar spaces.

The thermodynamics of montmorillonite in polyelectrolyte solutions indicates that different cations are taken up in inter-lamellar positions at different degrees of water saturation. K^+ is preferred to Na^+ in very dense smectite clay while the opposite is valid for "soft" conditions.

Hydrothermal effects may also to some extent be associated with changes in the microstructural arrangement of clay particle and cementation caused by precipitation of silica and other components. Release of substantial amounts of silica has been documented for temperatures exceeding 150°C. Precipitation of amorphous silica has been observed on cooling after hydrothermal testing of Na montmorillonite.

EFFECTS

Thermal effects influence the hydraulic conductivity, rheology, and swelling capacity of the buffer material.

REFERENCES

R Pusch & O Karnlund: Hydrothermal effects on montmorillonite. A preliminary study, SKB TR 88-15 (1988).

3.2.6 Diffusion – surface diffusion

Lumping
Screening PROCESS SYSTEM

PROCESS

Diffusion as a fundamental transport process will certainly not require any comments. On the other hand, the underlying mechanisms must be understood in order that the beneficial and/or detrimental effects of diffusion processes can be judged. One of these proposed mechanisms is "surface diffusion" in clay materials, which seems to increase rate of transport for some radionuclides (Cs, Sr) through compacted clay layers. It is also anticipated to occur in connection with matrix diffusion.

CAUSES

The mechanism for the hitherto observed cases of "surface diffusion" is not yet fully understood. However, it seems unlikely that the observed phenomenon actually involves movement of ions or molecules that are really sorbed upon mineral surfaces. A more plausible explanation seems to be that cations which can take part in an ion exchange process are not "sorbed" at any specific sites at the mineral surface – they occupy the charged layer in the vicinity of the surface and are thus still highly mobile. The ion mobility in this layer is in fact lower than in ordinary water due to its higher viscosity. Also, the state of surface (or interlayer) water depends on the clay density, e.g. as described by the water sorption isotherm (which directly gives the swelling pressure). In order to more fully understand this mechanism the interpretation of diffusion data must also take into account the dependence of observed ("apparent") distribution coefficient on e.g ionic strength, the state of surface water and free water porosity. A multiphase model might be developed and tested.

EFFECTS

Surface diffusion gives rise to higher rates of diffusional mass transport than expected for cations that take part in ion exchange at mineral surfaces. The effect of this might possibly be accounted for by a judicious choice of transport parameters (diffusivities). However, in order to perform a logical analysis of the behaviour of certain barriers development e.g. during chemical and physical degradation it is necessary to use a model that more in detail describes all aspects of diffusion – including "surface diffusion". For bounding calculations the available information might well be sufficient.

3.2.7 Swelling of corrosion products

Lumping
Screening PROCESS SYSTEM

PROCESS

Corrosion products have a higher molar volume, even in the most dense state, than the corroded metal. All necessary data are easily available in literature.

CAUSES

This behaviour is an unescapable consequence of the fact that metals corrode.

EFFECTS

The detrimental effect of this swelling is that any surrounding material is compressed (clay buffers). It can also be the cause of cracking (cf corrosion of reinforcement bars in concrete) of such materials. In the present case it may also lead to mechanical stresses in the corroding metal canister that in turn might cause an even faster degradation. This effect is already accounted for in the performance assessment since the role of a canister as a barrier ends as soon as it has been breached by pitting corrosion.

The compression of surrounding buffer can easily be calculated. Most probably, in the case of a copper canister this effect is very minor. However, the chemical effects of corrosion products should also be discussed.

The swelling could also have positive effects as the void space and the transport of radionuclides may be decreased.

3.2.8 Preferential pathways in the buffer/backfill

Lumping 2.5.1 3.2.3 3.2.5 3.2.11
Screening KEPT

Transport through the near-field region may take place in possible continuous passages through the buffer (see 3.2.9), in possible spaces between buffer and rock, or in spaces between buffer and canister.

The second case is covered by the discussion in e.g. subsection 3.2.1.1. The third case is considered to be negligible in a bentonite buffer with high swelling capacity.

3.2.9 Flow through buffer/backfill

Lumping 3.2.8
Screening KEPT

Flow through buffer/backfill is highly dependent on the ability of the buffer/backfill to resist piping and subsequent erosion of ground water. Piping is more likely to occur in a sand/bentonite mixture than in a pure bentonite. In the former material piping may take place due to unproper grading of the sand or inhomogeneous mixing.

3.2.10 Soret effect

Lumping 3.2.6
Screening PROCESS SYSTEM

PROCESS

The Soret effect is a diffusion process caused by a thermal gradient. In liquids having both light and heavy molecules (or ions), the heavier molecules tend to concentrate in the cold region.

EVIDENCE

There is little or no experimentally obtained information about Soret effects in bentonite/water systems.

EFFECT

Soret effects may to some degree influence the ion concentrations in the water phase. Its importance is probably negligible but should be analyzed like other off-diagonal Onsager effects (e.g. 2.1.2).

REFERENCES

John H. Perry: Chemical Engineers Handbook. (1963)

3.2.11 Backfill material deficiencies

Lumping
Screening KEPT

PROCESS

This FEP concerns material properties that deviates from the design values. It is a heading for possible uneven swelling, unexpected movement of canisters in the buffer/backfill or the establishment of preferential pathways in the buffer/backfill material.

EFFECTS

It could cause substantial reduction of the buffer function and ultimately change the mode of water transport through the buffer from diffusion to a flow regime.

SCREENING

Should be KEPT on the list for composition of scenarios.

3.2.12 Gas transport in bentonite

Lumping 3.2.8
Screening

CAUSES

Potential sources for gas generation are discussed in 1.2.4.

EFFECTS

The gas transport may influence the stability of the buffer and the transport of radionuclides.

4.1.1 Oxidizing conditions

Lumping
Screening PROCESS SYSTEM

PROCESS

This is evidently a special case of redox conditions in general. It might be limited in space and time (eg when considering redox fronts), or it might apply to all of the migration path through the geosphere. The latter of these two possibilities should be covered in a separate scenario (design basis). Since the redox front concept is treated in a special FEP it is not necessary to lump this FEP.

CAUSES

The following FEPs may cause oxidizing conditions: (4.2.1, 4.2.3, 4.2.5, 5.2, 5.33, 5.34, 5.36, 5.37, 5.39, 5.41.

Oxidizing conditions all along the pathway from a breached canister to the biosphere is a highly unlikely feature for a properly sealed repository in Swedish bedrock. Still this possibility can not be excluded. Layers of ferric iron minerals have been found at great depths (ca 400 m) but it is not certain

that this is due to oxidizing conditions. Such perturbations of the otherwise very reducing geological environment might occur in connection with rock movements, fracturing and extreme channeling, leading to transients in high groundwater flow velocities. Drilling activities and other kinds of human intrusion in the accessible environment might be other causes.

Another possibility would be if extreme channelling occurs past an early breached canister and then past several others downstream. It could easily be checked whether the oxidant production from one canister is sufficient to cause penetration of others. Taken together the effect of such a "chain reaction" might also be reason for "oxidizing conditions" – or at least a strong elongation of the "redox front". (This situation should be treated under the FEP redox front.)

EFFECTS

Oxidizing conditions affect the following FEPs: (2.1.8, 4.1.4, 5.44, 6.3 and 6.6).

Most probably occurrences of oxidizing conditions will only be of short duration. Due to the presence of ferric iron many radionuclides in fact might be more retarded in an oxidized rock than in a reduced one. However, the source term for migration is greater by orders of magnitude for those radionuclides which in the normal case are precipitated at the redox front (notable examples are Tc and Np). This fact, coupled with the possible simultaneous occurrence of high flow rates, is reason enough to study this case more carefully. The probable short durations of these transients lead to the assumption that they might have only negligible effect on the integrated collective dose.

Another effect of oxidizing conditions is the increased rate of copper corrosion, although most oxygen should be consumed by ferrous iron and sulphur in reducing valency states and the copper in the canister itself. Even if the water surrounding the canister had an oxygen content equal to surface water (10 mg/l) there would not be more than 10 mg/canister of oxygen with a groundwater flow of 1 l/canister/year.

4.1.2 pH-deviations

Lumping
Screening PROCESS SYSTEM

PROCESS

First one must decide the meaning of this FEP. It is perfectly clear that the pH value might vary considerably due to "natural" reasons within a repository and the geosphere. In Swedish bedrock the outer limits of this variation is set by the buffering action of minerals and dissolved carbonates, e.g. about pH 6.5 – 10.5. The "natural" variation within these limits must of course be accounted for in any performance assessment. Thus, in this sense pH-deviations belong to the base case. Perturbances of the surface water chemistry might shift the general acidity level towards these limits, however. Even so, the limits will most probably not be exceeded. The effect of such perturbances can be treated in design basis scenario.

CAUSES

The following FEPs are related to causes for pH-deviations (5.27, 5.32, 6.8, 7.7, 7.11).

The only really credible impact of this kind would be intrusion of highly acidic surface waters (pH 4 – 4.5) into the bedrock. Possible causes are not exactly the same as for oxidizing conditions, i.e. in the latter case we already know that the rock has sufficient poising ability to reduce the atmospheric oxygen.

It is not certain that the bedrock has a similar buffering capacity for acid waters but the groundwater always experience a continuous supply of acids from the surface water (carbon dioxide originating from degradation of organic materials as well as humic and fulvic acids). Thus it appears that the buffering capacity of the rock is very large (the rock contains several percent of calcite and in addition also the feldspar reacts with acids).

EFFECTS

The following FEPs are related to effects of pH-deviations (1.2.4, 1.2.6, 1.2.8, 1.2.9, 1.5, 3.1.12, 5.44, 5.45, 5.46, 6.3).

An acidic recharge may increase the weathering in the upper layers of the geosphere. In turn this influences ground water chemistry in general – not only the acidity. Increase in colloid formation might also be a result. Sooner or later the perturbation might spread to the repository level and follow the migration pathways towards the decharge zone. Subsequently most chemical processes of any importance might be affected, although the consequences would be highly variable. Examples are: buffer/backfill chemistry, redox reactions, solubilities and sorption equilibria.

4.1.3 Colloids, complexing agents

Lumping
Screening OUT(ADM)

This FEP is split into two new ones 5.45 (Colloids and transport) and 4.1.9 (Complexing agents). 4.1.3 is screened out in the administrative criterion.

4.1.4 Sorption

Lumping
Screening PROCESS SYSTEM

PROCESS

Sorption is the collective term for adsorption of particles (molecules, ions, colloids) on outer or inner surfaces of solids. The forces responsible for sorption range from "physical" interactions (v d Waals' forces) to the formation of "chemical" bonds. Sorption retards the transient diffusion of radionuclides through buffer and backfill and the advective transport in the nearby rock and the far field. The effect is well established and included in the migration models. Sorption is element specific and depends both on radionuclide speciation (valency state, hydrolysis, complexation) and the solid phase composition and surface characteristics. At true thermodynamical equilibrium these two sets of conditions are linked together.

MODELLING

In most transport calculations sorption is accounted for by the simplistic method of letting the retardation be determined by constant distribution coefficients (Kd). This approach is sufficient only when truly conservative Kds are chosen. More elaborate and thermodynamically convincing models for sorption are available (surface complexation etc), but the amount of useful data is as yet very scarce. It should also be recognized that along a transport trajectory the chemical conditions might change significantly on a scale less than one mm. Other issues of importance for a proper modelling of sorption are the possibility of inclusion of radionuclides in fracture minerals, and the release of trapped (or sorbed) nuclides in connection with mineral dissolution. Phenomenologically it is difficult to distinguish between matrix diffusion on the microscale, surface sorption kinetics and weathering effects on mineral surfaces.

4.1.5 Matrix diffusion

Lumping
Screening PROCESS SYSTEM

PROCESS

Matrix diffusion is the process by which nuclides in the water flowing in the rock fissures migrates into the porous rock by diffusion. It is governed by the characteristics of fracture fillings and the rock mass (porosity and mineralogy).

EVIDENCE

There is considerable experimental evidence on matrix diffusion both from the laboratory and the field. For example KBS-3 or Abelin et. al. (1987) provide both models and references to experiments. However, the degree of matrix diffusion, i.e. the available transport length in the rock matrix, for any field situation is not yet known.

EFFECTS

Matrix diffusion is a very efficient retarding mechanism, especially for strongly sorbed radionuclides. It requires a special model, but it is not very difficult to account for. Conceptually, limited matrix diffusion is a more realistic alternative to sorption on fracture surfaces. In principle, matrix diffusion should be treated likewise both in the far field and the in rock close to the waste canisters. However, in the near field individual fractures may be considered, whereas for the far field a continuum model is probably sufficient.

REFERENCES

KBS-3, 1983.
Abelin et.al., Stripa TR 87-21, p 68. SKB, Stockholm 1987.

4.1.6 Reconcentration

Lumping
Screening PROCESS SYSTEM

PROCESS

The only interpretation of this process is the accumulation by precipitation or sorption of radionuclides within a rather confined volume along the path to the biosphere. Subsequent release by changed chemistry might then give a kind of pulse discharge to the environment. Such accumulation is a standard case in biosphere modelling (for sediments and biological accumulation). In the geosphere a similar situation is not very probable, however. Reconcentration might occur at the redox front, but this is treated under other headings. It is not very probable that any nuclide along its migration path (from the redox front) through the geosphere will encounter such conditions that precipitation can take place. On the other hand, drastic changes in flow directions and/or groundwater chemistry might give an significant release of originally strongly sorbed radionuclides.

4.1.7 Thermochemical changes

Lumping
Screening PROCESS SYSTEM

PROCESS

This FEP should be interpreted as the influence on all chemical equilibria (and reaction kinetics, for that matter) by changes in temperature.

CAUSES

Thermochemical changes may take place due to a temperature increase generated by the decay heat of spent fuel in the early times (up to about 10 000 y). A lowering of temperature will occur in connection with permafrost and glaciations.

EFFECTS

Temperature influences all chemical reactions of importance: weathering, bentonite degradation, solubilities, sorption etc. The early temperature gradient might cause increased weathering of silicate minerals and a subsequent precipitation of silica (colloid formation?) downstream the repository. On the other hand, precipitation of calcite within the near field will take place under these conditions.

4.1.8 Change of groundwater chemistry in nearby rock

Lumping
Screening PROCESS SYSTEM

DESCRIPTION

The presence of construction, backfill and other man-made materials will cause changes of the geochemistry in the nearfield. Another source of such changes is the formation of radiolysis products. In fact, the extension of these changes defines the nearfield in the chemical sense.

CAUSES

These changes are an unescapable consequence of the presence of "unnatural" materials in the repository.

EFFECTS

Clay materials such as sodium montmorillonite should have a very minor influence on the groundwater chemistry; the only effect is that they might act as sinks for cations other than sodium. Concrete will lead to weathering and subsequent formation of clay minerals (ref.), which in fact should be an beneficial effect. Corrosion products might only influence the conditions in the near vicinity of canisters.

MODELLING

The effects mentioned above can easily be calculated by available geochemical computer codes. Scooping calculations will probably show that the influence on the macro system is negligible.

REFERENCES

Emrén, A., Lundén, I., and Andersson, K., Geochemical Modelling. SKI TR 89:1, Swedish Nuclear Power Inspectorate, Stockholm 1989.

4.1.9 Complexing agents

Lumping
Screening PROCESS SYSTEM

PROCESS

The presence of naturally occurring complexing agents is well established even for deep groundwaters, e.g. those deriving from humic and fulvic acids. Thus, their effect on barrier performance should be included in the process system. However, it should be noted that surface waters has a very much larger content of humic and fulvic acids than the deep waters, which indicates that the transfer from the surface waters to the deep waters is restricted. Synthetic complexants due to human negligence and increased levels of humics resulting from geological disturbance of recharge pathways should be covered by the scenario analysis.

CAUSES

The primary causes for complexing agents in a repository are already mentioned above. The more immediate causes are almost the same as for "Oxidizing conditions" (4.1.1) with the addition of "Stray materials left" (5.3).

EFFECTS

The effect of humics etc on the macrochemistry is negligible (although the reverse is certainly not true). The only effects that need to be considered are radionuclide solubility and sorption, most probably only for the trivalent state. (The effect on tetravalent technetium is not well known, however.)

REFERENCES

Andersson, K., Complexation of actinides with phosphate and organic complex formers in deep groundwaters. SKI TR 88:10, Swedish Nuclear Power Inspectorate, Stockholm 1988.

4.2.1 Mechanical failure of repository

Lumping 4.2.6
Screening KEPT

CAUSES

One cause is the repository itself.

PROCESS

Mechanical rupture may occur due to sudden changes in stress e.g. earthquakes etc and due to slow motions (creep) in the rockmass e.g. loading-unloading and plate motions. The result is a fracture or a fault. Lack of QA during excavation of the vault can also result in an instant rupture of the surrounding rockmass (improper rock inforcement).

EFFECTS

A mechanical rupture of the repository may alter the rock permeability in the surrounding rockmass and alter the flow paths and flow distribution close to the repository and create new pathways through the repository. Displacements along flat lying fractures through deposition holes could if they exceed 1 cm in length result in a canister failure (KBS-3).2.3.7 Faults may cause mechanical damage on the buffer material (3.2.3).

4.2.2.1 Excavation/backfilling effects on nearby rock

Lumping
Screening PROCESS SYSTEM

A potentially seriously complicating factor for flow in crystalline rock is that the rock is deformable. Even small changes in the fracture openings cause large changes in permeability as the permeability is proportional to the aperture cubed. The rock deforms according to the rock stress field. Changes in the groundwater flow and changes in the temperature field will change the active stress acting on the rock which in turn will change the groundwater flow. Thus, the rock deformation, flow and heat transport are coupled processes. These couplings may be of great importance for the performance of a waste repository.

The coupled thermo-hydro-mechanical effects may be important in many scales. For example, the stress changes introduced by excavating the repository and the canister deposition holes combined with the heat from the waste will affect the permeability close to the repository. Furthermore, it is yet an unresolved matter if these changes may disturb the stability of the repository or cause more regional faulting.

The strong coupling between flow and rock stress/deformation have been observed in many field experiments. Still existing hydromechanical models are basically research tools expressing quantitative behaviors. A practical problem with coupled hydro-mechanical models is that they are so complex that only very simplified examples can be studied. Furthermore, the underlying constitutive relations for joint deformation has not yet been validated.

EVIDENCE

The skinzone development is observed on the tunnel scale at e.g. Stripa (Gale, 1982) or SFR 86-07 (also URL). The stress impact on fracture permeability has been verified in numerous laboratory experiments (e.g. Witherspoon and others at LBL).

EFFECT - MODEL

The skinzone due to excavation needs to be taken into account when evaluating flow and transport measurements in and close to the excavated repository. The stress redistribution occurring after backfilling/resaturation (see 3.2.1) may affect the flow distribution in the rock and thus have implications on the benefit of applying a deposition procedure where potential canister holes with large flow are avoided. The result of the skinzone (permeability change) may be modelled with the "standard" flow/and migration models by appropriate changes of the permeability. However, evaluation of the development of the skinzone, if at all possible, require specially coupled hydro-mechanical models (e.g. ROCMAS Noorishad and Tsang, 1987).

Modeling the skinzone development will be very difficult as the (generally unknown) undisturbed rock stress distribution is needed as input. Alternatively, rough estimates based on "field experience" may be used. Skinzone development and hydraulic conductivity redistributions are basically near-zone phenomena and need no special attention in the far field modelling except for eventual changes in the source term.

See also 4.2.7 Thermo-hydro-mechanical effects.

REFERENCES

Witherspoon et. al.
Gale 1982
SFR 86-07
Noorishad and Tsang (ROCMAS), LBL, 1987.

4.2.2.2 Hydraulic conductivity change – Excavation/backfilling effect

Lumping
Screening OUT (ADM)

This FEP is treated in Excavation/backfilling effects on nearby rock 4.2.2.1.

4.2.2.3 Mechanical effects – Excavation/backfilling effects

Lumping
Screening OUT (ADM)

This FEP is treated in Excavation backfilling effects on nearby rock 4.2.2.1.

4.2.3 Extreme channel flow of oxidants and nuclides

Lumping
Screening PROCESS SYSTEM

PROCESS

The water does not flow over the whole fracture plane. This fact is often noted by "channeling". However, within this term vastly different concepts on how flow occurs are possible.

One concept of channeling is that each fracture plane consist of open and closed parts – for this there also is experimental evidence i.e. Abelin et.al. (1987). This concept might only be viewed as an extension of the discrete fracture approach, at least if the closed part portion is not too large. There is little knowledge on how the fracture transmissivity is distributed on the fracture plane. It is clear that the flow distribution among the different fractures will depend very much on the shape of the open parts. To complicate matters further this shape depends upon the rock stress field. In fact, much basic research is needed to determine a proper way to attack this problem. Detailed mapping of tunnel or shaft walls, the use of statistical approach to hydraulic and fracture data in boreholes and tracer tests are some of the tools available to get improved knowledge of the channeling effect.

Another concept of "channels" is "extreme channeling" where there only are a few paths where most of the water flows in the rock mass. These paths are either caused by real physical conduits "wormholes" in the rock mass or the combined effect of a poorly percolating fracture network and the hydraulic boundary conditions.

The difference between "wormholes" and a poorly percolating network is that in the latter case the position and amounts of the important paths may change totally if the hydraulic boundary conditions are changed, whereas in the former case the flow is always confined to the "wormholes". The situation with a poorly percolating network would make it extremely difficult to characterize the flow and transport properties of the rock. Experiments performed on one scale then cannot be extrapolated to a larger scale. A poorly percolating fracture network could for example result if the transmissivity variance is large combined with large fracture size variance and a relatively low fracture density.

EFFECT – MODEL

Channeling will increase groundwater velocities but this is not the most important effect. More important is that the fracture surface "per volume flowing water" available for sorption and matrix diffusion decreases. (This effect may also enhance the flow of oxidants to the deposition hole). The specific fracture surface available for sorption/matrix diffusion is included in the "standard" migration models but a well understood treatment of channeling is still lacking.

In the near zone channeling will make the flow over some canister deposition holes much larger than the average flow (and v.v. much smaller at some holes). Channeling needs to be considered when evaluating the time distribution for canister failure and the when evaluating the source term (i.e. only a percentage of the canister holes will see the large flows).

REFERENCES

Abelin et.al., Stripa TR 87-21.

4.2.4 Thermal buoyancy

Lumping
Screening PROCESS SYSTEM

Both the water density and the viscosity depend upon the groundwater temperature. A temperature field will thus influence the flow as it changes the mobility of the water and as the density changes will create buoyancy forces. In reverse the groundwater flow affects the temperature field as the flowing water will transport the heat through advection. However, heat is also transported through conduction in both the water and the solid phase. In very low permeable media heat conduction is the dominant heat transport mechanism. In general, the temperature effects on groundwater flow are relatively well understood. However, special attention to the problem may be required in relation to coupled thermo-hydro-mechanical effects (see 4.2.7).

The spent nuclear fuel develops a certain amount of residual heat (see Tarandi SKB TR 83-22). This heat will initially rise the temperature at the repository but will later decline as the activity of the spent fuel declines and the heat is transported away (basically through conduction in the rock matrix). The temperature increase will produce an upward driving force for the flow. In calculations made for KBS-3 (Thunvik and Braester SKB TR 80-19) it was concluded that this flow was important up to the first 10000 years. A more thorough investigation of the temperature effects may still be motivated.

REFERENCES

KBS-3.

Thunvik R and C Braester, Hydrothermal conditions around a radioactive waste repository, SKB TR 80-19, 1980.

Tarandi T, Calculated temperature field in and around a repository for spent nuclear fuel, SKB TR 83-22.

4.2.5 Changes of groundwater flow

Lumping
Screening PROCESS SYSTEM

PROCESS

Many of the FEPs listed in the scenario database affect (or may change) the groundwater flow. The flow may be altered

– locally around the repository due to changes in the barriers or the nearby rock,
– in the far field due to changes in the rock,
– globally changes due to changes in the groundwater recharge.

LOCAL CHANGES

The following FEPs are examples of processes that may cause groundwater flow changes in the nearby rock:

3.1.1 Degradation of the bentonite
3.1.5 Coagulation of bentonite
3.2.1.1 Swelling of bentonite into tunnels and cracks
3.2.2.2 Uneven swelling of bentonite
3.2.3 Mechanical failure of buffer/backfill
3.2.4 Erosion of buffer/backfill
3.2.7 Swelling of corrosion products
3.2.9 Flow through the buffer backfill
4.2.2 Thermo-hydro-mechanical effects

CHANGES OF PROPERTIES IN THE FAR-FIELD ROCK

The following FEPs are examples of FEPs that may change the flow properties of the far-field rock:

4.2.6 Faulting
4.2.1 Mechanical rupture of repository
4.2.3 Extreme channel flow
4.2.4 Thermal buoyancy
4.2.8 Enhanced rock fracturing (Human induced actions)

5.2 Non-sealed repository
5.8 Poorly constructed repository
5.9 Unsealed bore-holes and/or shafts
5.27 Human induced actions on groundwater recharge
5.30 Underground test of nuclear devices
5.34 Geothermal energy production
5.36 Reuse of boreholes
5.38 Sabotage
5.41 Water producing well
5.14 Resaturation
5.11 Degradation of hole and shaft seals
5.21 Future boreholes and undetected past
5.15 Earthquake
5.16 Uplift
5.17 Permafrost

5.42 Glaciation
5.26 Surface sediment erosion
5.25 Stress changes on conductivity
6.13 Geothermally induced flow

GLOBAL CHANGES IN THE GROUNDWATER RECHARGE

The following FEPs are examples of what could cause global changes in the groundwater recharge:

5.42 Glaciation
5.31 Change in sea-level
5.32 Desert and unsaturation

In addition, earth tide can be observed in some aquifers, as a periodic small variation of the head with time. The deformation of the earth's crust with the tide is very small, but measurable. In fractured rocks earth tides can lead to small modifications of the fracture aperture, or perhaps to small periodic changes of the pressure in the medium. It is not clear wether or not these displacements are reversible; therefore, even if each cycle leads to a negligible displacement, it must be shown that the very large number of cycles (twice a day) does not change the picture significantly, and that earth tides can be neglected.

In principle, the boundaries of the flow domain considered for a groundwater flow calculation should be placed where the flow over these boundaries is known. In practice, this cannot be accomplished. Prescribing the groundwater table at the top surface is an indirect means of calculating the groundwater recharge which depends on e.g. the precipitation, soil moisture, vegetation cover, topography of the top surface and the permeability of the upper layers (Bear, 1979). The relation between the recharge and these quantities is complicated, but most of the local differences in recharge probably only results in flow at relatively shallow depth. In order to estimate the groundwater supply to deeper formations the method of prescribing a water table probably is defendable as the controlling factor there will be the effective hydraulic conductivity of the rock. However, it should be remembered that the method of prescribing a water table is questionable and the sensitivity of the flow at greater depths to the form of the prescribed head surface should be evaluated.

The external boundaries of a flow domain should be placed at a "safe" distance from the repository but contributions from regional flow may make this "safe" distance much longer than was assumed in KBS-3. In groundwater flow the influence distances are related to conductivity. If the region of interest intersects with (a) major horizontal feature(s) of high permeability these feat.

EFFECT

Groundwater flow models exist but there remain unsolved conceptual model problems. The groundwater flow affects the stability of the engineered barriers and the transport of eventually released nuclides. Present modeling can account for impact of groundwater flow. However, the cause for the change of the groundwater flow may affect other mechanisms of importance for transport and stability of the barriers.

4.2.6 Faulting

Lumping
Screening KEPT

PROCESS

Faulting may occur due to sudden changes in the stress situation e.g. earthquakes etc and due to slow motions (creep) in the rockmass e.g. orogenic events, loading- unloading of an ice load, and plate motions. The result is a fracture or if movement occurs along the fracture a fault.

EFFECT

Faulting may alter the rock permeability in the rockmass and alter or short-circuit the flow paths and flow distribution close to the repository and create new pathways through the repository. New or regenerated faults may enhance the groundwater flow and the stability of the barriers and the transport of eventually released radionuclides. (see also 4.2.5, 4.2.1,) New faults may, if they pass the deposition holes, cause mechanical damage on backfill (3.2.3) or canister (2.3.7, 4.2.1).

It has also been shown that fractures due to the iceloads may be affected not always by displacements along the fracture but through a variation of the opening of the fracture (Noorishad). The result in that case would be a modification of the permeability distribution in the affected rock mass.

4.2.7 Thermo-hydro-mechanical effects

Lumping
Screening PROCESS SYSTEM

A potentially seriously complicating factor for flow in crystalline rock is that the rock is deformable. Even small changes in the fracture openings cause large changes in permeability as the permeability is proportional to the aperture cubed. The rock deforms according to the rock stress field. Changes in the groundwater flow and changes in the temperature field will change the active stress acting on the rock which in turn will change the groundwater flow. Thus, the rock deformation, flow and heat transport are coupled processes. These couplings may be of great importance for the performance of a waste repository.

The coupled thermo-hydro-mechanical effects may be important in many scales. For example, the stress changes introduced by excavating the repository and the canister deposition holes combined with the heat from the waste will affect the permeability close to the repository. Furthermore, it is yet an unresolved matter if these changes may disturb the stability of the repository or cause more regional faulting.

The strong coupling between flow and rock stress/deformation have been observed in many field experiments. Still existing hydromechanical models are basically research tools expressing quantitative behaviors. A practical problem with coupled hydromechanical models is that they are so complex that only very simplified examples can be studied. Furthermore, the underlying constitutive relations for joint deformation has not yet been validated.

The validation exercises currently underway are related to block experiments with block sizes in the order of a few meters. Larger scale experiments are planned but the validation of the large scale effects are still in its infancy.

See also excavation backfilling effects on nearby rock (4.2.2.1) and thermochemical effects (4.1.7).

REFERENCES

Noorishad and Tsang (ROCMAS) Users guide.

4.2.8 Enhanced rock fracturing

Lumping
Screening **PROCESS SYSTEM**

Enhanced rock fracturing may be caused by excavation of repository through blasting and stress redistribution. (see also skinzone effects and loading effects of ice).

EFFECT

In the near zone the groundwater flow may increase(4.2.5,5.18). This is also valid for the surface area open to sorption/matrix diffusion (4.1.4,4.1.5).

4.2.9 Creeping of rock mass

Lumping
Screening **PROCESS SYSTEM**

Creeping of rock mass may occur in connection with excavation due to stress changes. These changes create an unstable situation in the rock mass close to the repository. However, this effect is probably of minor importance.

The ongoing plate motion induces creep in the rock to a certain extent. This creates rock stresses that are released through continuous or discontinuous movements (by sudden stress releases e.g earthquakes). The latter may be the end effect of creep. Creeping of rock mass is a continuously ongoing process. Creep should only be related to already formed discontinuities.

EFFECT

Change of groundwater flow through fractures. If channelling exists slow ongoing movements can change position of channeling flow. It may also affect the buffer material mechanically (3.2.3, 3.2.4, 3.2.8, 3.2.9) Creep may lead to 4.2.1.

4.2.10 Chemical effects of rock reinforcement

Lumping 5.3
Screening KEPT

During excavation the rock around the vault is reinforced. There is one main reason for reinforcement, that is to establish a secure environment during operation phase, which is in the short time perspective (50–200 years). In the longtime perspective one does not rely on rock inforcement. The question is instead to minimize foreign material which could endanger the function of the barriers (rockmass, bentonite etc.). By going through a QA procedure the choice of material of inforcement is selected.

EFFECT

Lack of QA of material of inforcement could in the long time span lead to an unsuitable chemical environment which might affect the technical or natural barriers. The chemical consequence of the inforcement material is similar to the consequence of left stray materials (5.3). Thus 4.2.10 is lumped to 5.3.

5.1 Saline (or fresh) groundwater intrusion

Lumping
Screening PROCESS SYSTEM

PROCESS

Saline water is often present at the repository depths. Change in groundwater salinity will influence chemical equilibria, and salinity gradients might be of importance for groundwater flow.

CAUSES

Saline water can be both of recent marine origin or it might occur as a result of release of salt from the rock itself. Intrusion of saline water in significant amounts is only expected in connection with prolonged glaciations and the subsequent subsidence.

EFFECTS

The importance for geochemistry in crystalline rock and canister corrosion is usually considered to be negligible. Up to now the presence of salinity gradients at or close to the repository has usually been neglected in flow calculations. This part of the problem is not a potential scenario but part of a modelling uncertainty/approximation. However, one might consider events when salt (or fresh) water intrude in the repository area (especially during the resaturation phase).

It should also be considered the case of saline groundwater with a sharp boundary to fresh groundwater. According to present knowledge (SKB) there is a only a small groundwater flow over the boundary layer. The intermixing of fluids is according to preliminary data not very large.

REFERENCES

Svensson, U., and Hemström, B., Modelling of saline water intrusion.

5.2 Non-sealed repository

Lumping
Screening ISOLATED SCENARIO

This belongs to man-made causes but lies in the near (and thus fairly predictable future). The probability of a society that cannot afford (or lacks technology) to close the repository in 2050 is by some not judged to be so small.

A non-closed repository could be screened out on the "non planned options" criterion. If to be included, which we recommend, it requires a specially designed scenario. It will shortcut most of the far field barriers and possibly also include thermally driven groundwater circulation in boreholes and shafts. The consequences of such a scenario may be much reluctant to the detailed design of the repository.

Open or partially open boreholes and shafts will enhance disruption of the mechanical barriers, increase the groundwater flow and produce paths from the repository with practically no sorption or matrix diffusion.

The evaluation of the scenario should be done not only by comparison to the closed repository scenarios, but also with the scenario that the fuel is left in intermediate storages, which probabilistically is close to this one, at least for part of the spent fuel in question.

REFERENCES

KBS-3 p 21:8.

5.3 Stray materials left

Lumping
Screening KEPT

PROCESS

During construction and operation there might be possibilities for leaving unwanted material in the vicinity of the radioactive waste. The materials can be of many different kinds and can to some extent affect many of the important longterm processes in the repository from canister corrosion to transport mechanisms of radionuclides.

5.4 Decontamination materials left

Lumping 5.3
Screening KEPT

PROCESS

The same process occurs as in 5.3. Since the decontamination materials are specially made to release radionuclides and make them transportable this event is worse than to leave any other kind of material in the repository.

5.5 Chemical sabotage

Lumping 5.3
Screening KEPT

PROCESS

Intentional sabotage actions to impair the barrier functions of the repository may be planned (and planted) during the operation stage. Internal security actions must be taken to prevent this type of sabotage.

5.6 Co-storage of other waste

Lumping
Screening OUT (NON PLANNED)

This scenario should be screened out based on the "non planned options" criterion.

Anyone suggesting co-storage should have to prove the non-negative impact on the source term.

5.7 Poorly designed repository

Lumping
Screening OUT (ADM)

This belongs to the group man-made causes in the near (and fairly predictable) future. However, the design should be known in the safety analysis, the possible impact of poor design or construction on barrier function represented by more detailed FEPS on the list. Thus this FEP should not need to be considered and is screened out on the ADM criterion.

5.8 Poorly constructed repository

Lumping
Screening OUT (ADM)

PROCESS

A poor execution of (a good design of) a repository may cause enhanced degradation of the engineered barriers and unwanted alterations in the nearby rock.

SCREENING

This FEP is too general to be of any value in scenario development. In a way it includes all aspects of unwanted characteristics of the engineered system that are already covered by other and more specific FEPs.

5.9 Unsealed boreholes and/or shafts

Lumping
Screening KEPT

PROCESS

This is a variant of 5.2 non-closed repository, even if a non closed repository may include more than unsealed boreholes and shafts. Unsealed boreholes and shafts affect the stability of the technical barriers, the transport in the nearby rock and the transport in the geosphere.

Just unsealed boreholes should be treated separately, also as they are connected with the water producing well 5.41 and geothermal energy production 5.34.

SCREENING

One of the reasons for not lumping this FEP to 5.2 is that 5.9 needs to be included in the DESIGN BASIS, whereas 5.2 may be accepted to lead to higher source terms. This FEP may be used as a primary FEP for all different well problems.

5.10 Accidents during operation

Lumping
Screening OUT(ADM)

This FEP falls out of the scope of this analysis since it only deals with the operational part of the time scale.

As a comment this problem is discussed in KBS-3 where it is stated that "such mistakes are avoided by the use of a carefully planned and executed quality assurance programme. It should be rather simple to execute, since the activities connected with the actual final disposal procedure are uncomplicated and easy to oversee."

The most severe consequence of an accident during the operational phase would be if the accident leads to an inability to close the repository. The probability for such an event is judged to be extremely low.

5.11 Degradation of hole- and shaft seals

Lumping 5.9
Screening KEPT

PROCESS

In this context degradation is a physical or chemical process leading to reduced or completely lost sealing capacity of the buffer material.

CAUSES

Degradation of hole and shaft seals is probably mainly associated with the following FEPs: Coagulation of bentonite (3.1.5), Sedimentation of bentonite (3.1.6), Erosion (3.2.4), and Heat-induced conversion of montmorillonite (3.2.5).

The causes and effects associated with each FEP are discussed in the above mentioned subsections.

EFFECT

see unsealed boreholes and shafts 5.9.

5.12 Near storage of other waste

Lumping
Screening OUT (PROB)

PROCESS

If other types of waste is placed in the vicinity of a final repository for HLW this might affect the chemical composition of the groundwater as well as the transport mechanisms for radionuclides.

The probability for unintentional siting of repositories for other types of waste in the absolute vicinity of the HLW repository must for geometrical reasons be negligible. Intentional siting of such a repository must also have an extremely low possibility since the adverse effects then would be known. The overall judgement is that this FEP could be neglected.

5.13 Volcanism

Lumping
Screening OUT (PROB)

Is primary cause for 6.11 Intruding dykes, which could be lumped into Volcanism 5.13. However, probability of volcanism is very low. 6.11 (and 5.13) may be screened out on low probability (C1) in the time frame of interest to consider.

SCREENING

Screen out.

5.14 Resaturation

Lumping
Screening PROCESS SYSTEM

During the resaturation (and sealing) of the repository flow directions are different and the hydraulic conductivity is different (see 4.2.2.1 and also due to partially saturated fractures). Furthermore, (or especially) the groundwater chemistry is very different (oxidizing conditions etc.). The special problems (but also simplifications) associated with the resaturation phase should be noted.

5.15 Earthquakes

Lumping 4.2.6
Screening KEPT

PROCESS

Earthquakes occur in Sweden. They are usually small, magnitude 0-4, but there are historic examples with earthquakes up to magnitude 6 (1904 Oslo graben). There are also indications of even larger earthquakes occurring in connection with the last iceage due to an uneven distribution of the overburden (ice load). Magnitudes up to 8 and even 9 has been mentioned, but this is under dispute.

Earthquakes in Sweden are generally generated by the build up of stresses in the rockmass, which are suddenly released. The mechanism behind this phenomena might be the ongoing plate movements (5.19) with a ridge push,or due to the ongoing land uplift (creep) after the last glaciation (5.16) or a combination of both. The stress is released by a movement along a preexisting fault or by a new fracture.

EFFECT

In the general case earthquakes do not create any substantial damage especially if it is an underground opening. There are examples of large earthquakes which had catastrophic impact on buildings on the surface but which weren't felt especially much in mines at depth (Japan,South America). This can be explained by the fact that the ground motions and interference waves at the surface are transmitted through buildings and amplified. At repository depth the waves propagate through the area without being amplified and without any damage.

In the case with an earthquake activated fracture zone passing through the repository there could be movements along the fracture zone. This movement might damage a canister if the QA of canister emplacement is bad or if the process of earthquake generation creates an entirely new zone hitting one or a few canisters. The geometrical distribution of canister positions versus known fracture zones are important to consider in this case. (Considered in KBS-3)

5.16 Uplift and subsidence

Lumping
Screening KEPT

PROCESS

There is a continuous ongoing land uplift in Sweden. The maximum rate of uplift in northern Sweden is 9 mm per year, in Stockholm 5 mm and in Scania about 0 mm. Geological studies show that the greatest uplift was shortly after the retreat of the ice and has declined since then. The maximum total cumulative land uplift since deglaciation is estimated at about 850 m. The remaining future uplift is estimated to lie between 20 m and 200 m. The ongoing land uplift is mainly due to compression of the rockmass under the ice load during the last glaciation. This is a similar movement that the bedrock has undergone repeatedly in connection with previous glaciations. There is also proof of several uplifts in the earlier history during the formation and denudation of the basement more than 650 million years ago. In the last case the mechanism has been associated with orogenies and ongoing crustal movements rather than by glaciation periods.

EFFECT

It is under discussion wether disturbances in the state of equilibrium of the crust due to iceloading would affect the repository at depth. In KBS 3 it was argued that it would not affect the repository at 500 m depth, it is only one more repetition of crustal movements that have already taken place before . There is an ongoing project, Stephansson et al, trying to model the impact of the load of an icesheet. The results will soon be published. It is believed that most of the movements will take place in the major fracture zones, in which the repository will not be built.

The work by Noorishad at LBL and also the above mentioned ongoing work by Stephansson show that minor cracks will also be affected by such movements, not necessarily by displacement, but by a variation of their opening. The result could be a modification of the permeability distribution in the rock mass. According to de Marsily this process should possibly be included in the central scenario since we have no way of showing that the present distribution of the fracture opening is the most probable one for the future.

SCREENING

Uplift is a presently ongoing process. However, the future development of uplift (and subsidence) is very dependent on the future climatic evolution which is uncertain. Thus it is not practical to include uplift in the PROCESS SYSTEM).

5.17 Permafrost

Lumping
Screening KEPT

PROCESS

There are lot of evidences that Sweden has gone through several cycles of permafrost during the quarternary period (last 2 m.y.) At present, in the Spitzberg area, the permafrost depth is 450 m, and in Siberia, depths exceeding 1500 m have been reported. Although these latter examples are possibly permafrost of older ages than the last ice age. With todays present knowledge however it is not possible to exclude a deep permafrost situation in Sweden. It is therefore necessary to consider the potential of permafrost at repository depth as well as on the surface.

As a gross generalization it is assumed that the limit of permafrost shows a strong relationship to the mean annual air temperature isotherm of -1 to -2 degrees C. The depth of frost penetration is affected by the topography and the thickness of the snow cover. The geothermal gradient is in general in Sweden today in crystalline rock about 3 degrees C per 100 m with some local variations. This is also a controlling factor, the lower limit to permafrost approaches an equilibrium depth, at which the temperature increase due to earth heat just offsets the amount by which the freezing point exceeds the mean surface temperature.

EFFECT

Possible potential effects of permafrost are for instance fracturing or opening of fractures because of water freezing; compression of backfill and opening of voids at melting; increasing water flow in the temperature gradient and potential rapid flow paths; accumulation (concentration) of gas and radionuclides below the lower surface of the permafrost frozen rockmass giving rise to a pulse of radionuclides when melting occurs.

5.18 Enhanced groundwater flow

Lumping
Screening OUT (ADM)

Enhanced groundwater flow is almost identical to 4.2.5 Changes of groundwater flow. Thus 5.18 is screened out on the ADM criterion.

5.19 Effect of plate movements

Lumping
Screening OUT (ADM)

This is an ongoing process which is one of the causes for 4.2.6, 4.2.8, 4.2.9, 5.15, 5.16. The heading as such (plate movements) is too general to be of any value in the analysis. Thus 5.19 is screened out on the ADM criterion.

5.20 Changes of the magnetic field

Lumping
Screening OUT (CONS)

PROCESS

Even if there would be a change in the magnetic field it is hard to find any process that would impact the structure and function of the repository barriers. The working group has judged this FEP to have extremely low consequences for the repository.

5.21 Future boreholes and undetected past boreholes

Lumping 5.9
Screening KEPT

This FEP is similar to 5.9, 5.11, 5.34, 5.36 and 5.41.

5.22 Accumulation of gases under permafrost

Lumping 5.17
Screening KEPT

PROCESS

Gases from deeper geological layers might accumulate in the repository during permafrost, especially during the early phase when the nearby rock is still kept at higher temperatures.

CAUSES

Nitrogen and light hydrocarbons, notably methane, are known to penetrate from deep geological formations to the surface.

EFFECTS

Gas accumulation will lead to enforced outflow of groundwater from the repository. This will take place at a very slow rate, and the consequence must be regarded as negligible. The influence of a gas cushion on the flow field might be of some importance, however.

Clathrates are methane hydrates that occur as solids in certain conditions of temperature and pressure and are also associated with permafrost. They are found underground e.g. in the Spitzbergen, in sediment areas with methane production and in the seabed at greater depth. Their potential role can be included within the general framework of gas production in the repository, its effect on migration, or on explosion in connection with radiolytic gases. As a result of the heating by the waste, existing clathrates could produce methane.

Note that their presence is extremely difficult to detect since solid samples are sublimated when brought to room temperature and pressure. However, crystalline rocks are not known to contain large amounts of methane. However, for an intermediate level repository methane generation can be a problem and the potential formation of clathrates should be considered. This issue needs to be carefully considered and documented, but probably not included in the initial list of scenarios.

5.23 Changed hydrostatic pressure on canister

Lumping 2.3.7.2
Screening

EFFECT

See hydrostatic pressure 2.3.7.2.

5.24 Stress changes of conductivity

Lumping OUT(ADM)
Screening

This FEP is treated in EXCAVATION/BACKFILLING EFFECTS ON NEARBY ROCK 4.2.2.1 and in thermo-hydro-mechanical effects 4.2.7. This FEP is screened out on the ADM criterion.

5.25 Dissolution of fracture fillings/precipitations

Lumping
Screening OUT(ADM)

This FEP is treated in 6.6 Weathering of flow paths.

5.26 Erosion on surface/sediments

Lumping 5.46
Screening PROCESS SYSTEM

PROCESS

Erosion of surface sediments (and crystalline bedrock) is a continuously ongoing process due to weathering. Erosion is balanced by deposition of eroded sediments at other localities. The material is redistributed by e.g. water flow. Due to frequent glaciation periods in Sweden the sediment cover is relatively thin, as the surface of the rock is eroded to the greatest extent during glaciation periods.(formation of eskers etc). Calculations (KBS-3) showed that in the normally type of flat terrain that characterizes most of Sweden, the cumulative erosion of the crystalline basement caused by the glaciers has normally been limited to a few tens of meters. In a hilly terrain the erosion might be deeper.

EFFECT

Affect groundwater recharge/discharge and thus gw flow (i.e affects release) and geosphere transport. However, the impact on (the distribution) of the groundwater recharge is minor relative to the general uncertainty of the (distribution of) the groundwater recharge. The (sure) occurrence of sediment erosion should be considered when estimating the recharge/discharge uncertainty but may otherwise be screened out.

Groundwater recharge/discharge should perhaps be entered as a special phenomenon into which one may lump 5.26 (this phen.), human induced actions on g.w. recharge (5.27), change in sealevel (5.31), river meandering 6.9...

5.27 Human induced actions on groundwater recharge

Lumping
Screening KEPT

PROCESS

Examples of human induced actions that directly will cause alterations on the groundwater recharge are changes in agriculture, changes in vegetation, wells (5.41), dams, polders or cities (7.11). Human action causing climate changes will indirectly affect the groundwater recharge.

EVIDENCE

Some changes are likely but it is open issue whether the important ones are likely.

EFFECT

The modelling consequence is easily taken care of once the amount of the change is determined (change g.w. head or force flux at some boundaries.) Evaluation of the g.w consequence of the human action may be a different manner.

See also comment on erosion in surface sediments (5.26).

5.28 Underground dwellings

Lumping 5.33
Screening KEPT

PROCESS

There is a possibility that future generations might use relatively easy accessible underground facilities as dwellings. The use of a repository site would of course only come in question if the knowledge of the repository is lost. If a future generation has the ability to excavate down to repository depth it is also probable that they have the ability and knowledge to measure and monitor radioactivity.

5.29 Meteorite

Lumping
Screening OUT (PROB)

In Doe UK report DOE/RW/85/036 "Modeling of time dependent effects" on page 13 it is stated:

"A review of probable meteorite impact craters in Europe was made and a total of 17 were found – including probable and possible occurrences. The probability of a large scale impact on the British mainland is approximately 0.006 per million years (based on the ratio between the land of Britain and the area of Europe as a whole). If the area in which a meteorite impact would have to occur in order to damage a repository is conservatively defined as that of a circle with a 150 km radius then the probability of such an impact is 0.002 per million years."

SCREENING

Thus the probability appear to be less than 0.01 per million years (screening criteria 1) and meteorite impact may be screened out.

5.30 Underground test of nuclear devices

Lumping
Screening OUT (RESP)

This FEP is much connected to 6.7 nuclear war and the intended intrusion events (5.5, 5.33, 5.34, 5.35, 5.37). It is obvious that an underground test of a nuclear device close to the repository may seriously disturb both the engineered and the geological barrier. However, the situation will only occur if the future generation either

i) knows how to construct nuclear devices but have lost the records (7.9) on the repository location or does not realize the potential radiological risks involved in testing the bomb at that location.

ii) does not care that the repository may be damaged.

The first situation is not very likely, the second situation may be discarded on the principle formulated in KBS-3 that "each generation must take the responsibility for its own conscious actions".

REFERENCES

KBS-3 p 21:6.

5.31 Change in sealevel

Lumping
Screening KEPT

PROCESS

In the future the sea level will change both up and down due to glaciation and warmer periods (polar ice melting). How much , when and in what direction is not well known. The terms transgression and regression are directly coupled to this phenomena but they also include the change in thickness and distribution of sediments and changes of facies. (5.26)

It has been estimated that during the last ice age the sea level of the oceans dropped about 120 m. The exposed seabottom suffered extensive erosion especially close to the ice rim during the inter glacial periods (warmer periods) due to a warm period. Figures mentioned of the amount of sealevel rise varies, 80 m has been mentioned.

Processes that may cause sea level changes are (5.16, 5.42, 6.8, 6.10).

EFFECT

Changes in sea level will affect groundwater flow (4.2.5) and possibilities for saline groundwater intrusion (5.1) and may enhance groundwater flow (5.18).

MODEL

Far field: Change in hydrological boundary conditions.

Near zone: Eventual change in flow.

Biosphere: Change in recipient. This is especially important if the repository is situated close to the sea, where it is foreseen major changes in the recipient situation.

5.32 Desert and unsaturation

Lumping
Screening OUT (PROB)

CAUSES

(Human induced) climatic change 6.8. It seems hard to believe that the climate will change so drastically even within a million year time scale. Perhaps 6.1 may be screened out on low probability.

EFFECT – MODEL

The well (5.41) becomes more important. The probability of very deep wells is large.

Unsaturated flow needs special models (which are available but complicated to use.

If the rock becomes unsaturated most of the models and assumptions both regarding the technical barriers and the situation in the far field need to be altered.

5.33 Waste retrieval, mining

Lumping
Screening ISOLATED SCENARIO

This phenomenon may be screened out on the KBS-3 principle "each generation must take responsibility for its own conscious actions" and "in order to rediscover the repository from the ground surface, for example by means of geophysical methods, such a future civilization must have access to advanced technology. They should then also have the ability to detect and handle the radioactive materials that are stored in the repository..."

REFERENCES

KBS-3 p 21:6-7.

5.34 Geothermal energy production

Lumping 5.9
Screening KEPT

Geothermal production is an intrusion problem similar to the well (5.41), active pumping will affect flow paths severely. Geothermal energy sources in the "classical" sense require volcanism (5.13). However, the general geothermal gradient may be used. This is practiced in a few sites in Sweden today (Sven Jonasson Chalmers, pers. comm.) and may involve deep boreholes and recirculating flows (also causing substantial alteration of groundwater chemistry).

Geothermal energy production is lumped to 5.9 "Unsealed bore-holes and shafts". The motivation for this lumping is that the geothermal energy production is one (eventually serious) example of how the geosphere barrier may be short circuited. Unsealed boreholes and shafts is perhaps the most serious example of a short circuited geosphere.

5.35 Other future uses of crystalline rock

Lumping
Screening OUT (PROB)

Granite may certainly be a useful raw material in the future. However, why mine it at the repository depth and location? The (geometrical) probability for this must be very small.

Need not to be further considered.

5.36 Reuse of boreholes

Lumping 5.9
Screening KEPT

The boreholes (drilled in the preinvestigation or construction phases or for postclosure monitoring (5.39)) are probably cheaper and less complicated to reopen than to drill new holes.

This phenomenon needs perhaps to be considered so that the boreholes are not placed at unfavorable locations. Special care may be motivated when designing a post-closure monitoring scheme.

The evaluation of the consequence of using the boreholes is similar to evaluation of wells (5.41). All types of short circuited geosperes are lumped to 5.9 "Unsealed boreholes and/or shafts".

5.37 Archeological intrusion

Lumping 5.33
Screening KEPT

Cannot be outruled especially after loss of records (or lost real understanding of records). Warning messages would probably only encourage an ambitious researcher!

5.38 Explosions

Lumping
Screening ISOLATED SCENARIO

This FEP concerns explosions coupled to sabotage.

This FEP could be treated as an ISOLATED SCENARIO.

5.39 Postclosure monitoring

Lumping
Screening ISOLATED SCENARIO

Postclosure monitoring schemes must be designed with care. A monitoring well represent a short path to the biosphere and may also be used for water supply. Thus this phenomenon puts demands on monitoring schemes but not necessarily on the repository design. The consequence of monitoring wells may be analyzed as a special case of 5.41 (water producing wells).

Also cables through the buffer/backfill to probes close to the canister need to be evaluated.

5.40 Unsuccessful attempt of site improvement

Lumping
Screening OUT (RESP)

An effort intended for improving the site and/or the technical barriers (also post closure) may in fact worsen the situation. However, it may be justified to screen out this FEP based on the principle that each generation must be responsible for its own conscious actions.

5.41 Water producing well

Lumping 5.9
Screening KEPT

A (many) water well(s) may be drilled in a fracture zone in the vicinity of the repository. Water from this well may be used as drinking water for a small community, by cattle or used for irrigation. Such wells are common in crystalline rock and it is difficult to assume that the location of the repository always will be remembered. Drilling wells does not depend on very advanced technology.

CONSEQUENCE

The well will to some (or a large) extent remove the function of the geological barrier. Evaluation of the well may be performed with flow and transport calculations.

The well is lumped to 5.9 "Unsealed bore holes and/or shafts" as the well represent a special case of a short circuited (or partially "damaged") geosphere.

5.42 Glaciation

Lumping
Screening KEPT

PROCESS

During the past earth history there are many evidences for repeated glaciation periods. Glacial and interglacial periods have followed each other. Numerous hypotheses have been put forward in order to account for the appearance of ice ages in the geological past. It is however acknowledged as stated by Bjelm (1989) that the ultimate cause of the Pleistocene glacial and interglacial cycles are the Milankovitch orbital forcing parameters. These involve the three cycles of earth/sun geometry that controls the distribution of solar radiation on earth, the tilt (obliquity) of the earth's axis, the eccentricity of the earth's orbit around the sun, and the precession of the equinoxes. These are continuously ongoing processes.

There are no reasons which exclude that these processes will not happen also in the future, though human induced effects like the "greenhouse effect" might have an impact on the rate and on the starting point of the next glaciation period. As a fact there are scientists arguing that we already have left the "true" inter – glacial conditions behind us and that we have entered the glacial part of such a cycle. Full glacial conditions may perhaps according to them lie 40 000 – 80 000 years ahead of us or even longer. Today there is a general consensus that within the next one million years Sweden will most probably be affected by one or more new glaciation periods.

CONSEQUENCE

During full glacial conditions in a region like Scandinavia the weight of the inland ice sheet (3000 m ice thickness) depresses the earth's surface by several hundr :ds of metres, or perhaps even thousand metres. This affects the regional stress field, fracture zones, induces movements along old and perhaps new fractures. The movements might be associated with seismic events or not. The above mentioned processes will also affect the groundwater flow at depth and at the surface. It may also cause extreme groundwater heads at he ice edge, change the position of the inflow and outflow areas and cause sea level changes.

5.43 Methane intrusion

Lumping 5.22
Screening

The potential sources might be clathrates in combination with permafrost or deep earth gases in general. This problem is mainly covered in 5.22 (Accumulation of gases under permafrost).

5.44 Solubility and precipitation

Lumping
Screening PROCESS SYSTEM

PROCESS

These processes should be limited to radionuclides for description of the FEP. In that case they relate to the two source terms: spent fuel and the redox front.

CAUSES

It is possible to list a lot of factors that govern solubility. In our case it can all be reduced to these two: aqueous phase composition and temperature. (Since, in fact, we are interested in the concentration of a radionuclide, sorption should also be added to the list. This is believed to be accounted for by appropriate modelling, however.) In turn the composition of the aqueous phase is determined by groundwater chemistry in general, n.b. the gw chemistry and temperature that applies to a certain location (e.g. within the buffer or at the redox front) and time (i.e. the "chemical history" at that location).

5.45 Colloid generation and transport

Lumping
Screening PROCESS SYSTEM

DESCRIPTION

Colloids are particles in the size range between 1 and 100 nm. They might sorb or otherwise include radionuclides in the groundwater system.

CAUSES

Colloids are always present in deep groundwaters; measured concentrations are generally less than 1 mg/l. They are of both inorganic and organic origin. Possible sources of specific significance for a deep geological repository in crystalline rock are the presence of gradients in groundwater composition leading to precipitation (e.g. as a result of changes in redox potential and pH), and erosion (dispersion) of clay minerals. Under extreme external conditions (e.g. glaciations, faulting) transients in colloid concentration might occur.

EFFECTS

Depending on composition and physico-chemical characteristics (e.g. size distribution, surface potential, etc.) colloids are transported more or less with the same velocity as the groundwater. Reversible sorption of radionuclides on particles in the larger size range is of less importance, and this probably also holds for colloids in the smallest size range (the formation of such colloids should be reversible and sorption of them considerable). "Irreversible" sorption on and transport with colloids in the intermediate range might be of some importance for certain radionuclides. Until this problem has been further studied these statements are to be regarded as speculations, however.

5.46 Groundwater recharge/discharge

Lumping
Screening OUT (ADM)

This is a heading for a primary FEP and is thus screened out on the ADM criterion.

6.1 Undetected fracture zones

Lumping 6.12
Screening KEPT

Fracture zones are part of our conceptual model. It is not clear that possibly undetected features are dealt with in the "standard" sensitivity/uncertainty analysis. Undetected features can be analyzed by using the frequency of fracture zones from other sites. It is possible to evaluate the probability that there exist an undetected fracture zone at a given location using the expected frequency of fracture zones and the observation range of the performed measurements.

6.2 Gas transport

Lumping
Screening PROCESS SYSTEM

There may be different sources of gas production. It could be produced by the waste or by materials left in the repository. Alternatively, earth gases may later intrude. Perhaps the gases are solved in the groundwater but they may be dissolved as the pressure decreases in the rising groundwater flow. The gases may be a fast transport mechanism.

6.3 Far field hydrochemistry – acids, oxidants, nitrate

Lumping
Screening PROCESS SYSTEM

DESCRIPTION

The geochemistry might be changed by inflow of chemicals from the surface.

CAUSES

Extreme events, such as faulting, might lead to inflow of groundwater in the repository with other properties than the "natural" at these depths. Most probably such events are of comparatively short duration. More serious cases of chemical intrusion can occur due to human actions (see 7.8).

EFFECTS

See 4.1.1, 4.1.2 and 4.1.9.

6.4 Dispersion

Lumping
Screening PROCESS SYSTEM

PROCESS

More or less regardless of the level of detail used in the description of the flow field there will always remain velocity variations that cannot be described explicitly in an advection term. The spreading of radionuclides by means of diffusion and these unresolved velocity variations could generally be denoted by the term dispersion. Dispersion is especially important in connection with radionuclide transport (KBS-3). Even a small fraction of early arriving nuclides will carry a considerable amount of radioactivity as the time for radioactive decay has been very limited for these nuclides.

Obviously, the actual definition of dispersion is directly related to the used definition of the advection. In some instances it is possible to relate the dispersion to a given statistical structure of the permeability field (see e.g. Gelhar and Axness, 1983 or Neuman et.al. 1987). However, the great uncertainty with regard to the spatial structure of crystalline rocks also implies great uncertainty on the dispersion.

For extreme channeling dispersion cannot be described as a Fickian process (see e.g. Rasmuson WRR 8, 1247, 1986) not even for one-dimensional flow. It has been suggested (in KBS-3) that channeling could be described with a constant Peclet number implying that the dispersivity will increase with travel distance. However, transport with extreme channeling is not at all dispersive, it is skewed to the fast flow paths. Using a constant Peclet number is correct only for the first two moments of a breakthrough curve whereas higher order moments will differ. Again the portion of nuclides that will arrive in the very fast channels will carry most of the radioactivity due to their limited time for radioactive decay.

Dispersion in a two or three dimensional flow field of a strongly heterogeneous spatial structure is even more complicated. In particular Tsang (1989) notes that it is impossible to make accurate predictions of tracer arrivals at a given point in space and time. Multiple point or areal averages are needed. However, the actual formulation of appropriate measures of this kind is still a research problem.

SCREENING

Dispersion is a process that needs to be included in the PROCESS SYSTEM.

6.5 Dilution

Lumping
Screening PROCESS SYSTEM

In this context "dilution" refers to the dilution of radionuclides in the groundwater. In e.g. transport modelling there is sometimes a need to distinguish between "dilution" and "dispersion". However in this work these concepts are regarded as synonyms (see also 6.4).

6.6 Weathering of flow paths

Lumping
Screening PROCESS SYSTEM

PROCESS

Ongoing chemical reactions between groundwater and rock- and fracture minerals lead to more or less continuous changes of the solid phases along the flowpaths from a repository. Thus, not only weathering of rock minerals take place but also healing of existing and newly formed fractures. The latter process is thought to take on the order of 10 000 years. Special cases of weathering are when silicate minerals dissolve during the first initial stage of temperature increase in the repository. In principle, rather subtile changes of groundwater chemistry can dissolve minerals where already radionuclides have been sorbed, thereby causing some sort of pulse release. The consequences will be small provided that dissolution is preceded by matrix diffusion.

CAUSES

Natural and human induced perturbations of groundwater chemistry and temperature.

EFFECTS

Increased groundwater flow and channelling. Release of sorbed radionuclides.

6.7 Nuclear war

Lumping 5.2
Screening OUT

You could argue, as did KBS-3, that the consequence of the war is graver than the damage on the repository but damage on the repository may persist much longer time than the other consequences of the nuclear war. However, nuclear war implies unintended actions (bomb explosions) against the repository. Intended actions (e.g. sabotage with nuclear device) are more harmful and would create similar (but worse) type of damage.

Effect similar to unclosed repository 5.2 Nuclear war increase probability for 5.2.

6.8 Human induced climate change

Lumping 5.31 5.32 7.7 7.8
Screening KEPT

Lump into human induced changes of surface water hydrology (7.7) and altered surface water chemistry by humans (7.8).

6.9 River meandering

Lumping
Screening OUT (CONS)

There are examples in Sweden where major rivers have changed their position permanently and naturally , e.g. Klarälven. This process is in the more extreme cases connected to glaciation periods, but there are examples in historic time where the position is changed through pure river meandering. In the local scale it is an natural process for an old river to meander and change its position. The effect on the hydrology is local and mainly near surface and may to a certain degree be predicted (topography). In the future a possible source for change of river flow might be human induced (7.7).

CONSEQUENCE

Meandering is probably of minor importance.

6.10 No ice age

Lumping 5.42
Screening KEPT

This is a variation of ice age (not a specific feature, event or process on the merged list). However, no ice age puts special demands on how to treat the biosphere not to be confused with the base case scenario which assumes a steady biosphere.

6.11 Intruding dykes

Lumping
Screening OUT (PROB)

Could be lumped into Volcanism (5.13). However, probability of volcanism is very low. 6.11 (and 5.13) may be screened out on low probability.

SCREENING

Screened out on low probability.

6.12 Undetected discontinuities

Lumping
Screening PROCESS SYSTEM

See discussion on undetected fracture zone 6.1.

6.13 Geothermally induced flow

Lumping
Screening PROCESS SYSTEM

There can be natural geothermal flows due for example to variations in thermal conductivity. Also thermally induced flows can be induced by heat output from the repository. Simple estimates should be made from these effects, and compared with the anticipated natural head gradients for the various scenarios. It may then be possible to eliminate this phenomena using the consequence criterion.

6.14 Tectonic activity – large scale

Lumping
Screening OUT (CONS)

At the Kolmården meeting this phenomenon was screened out as "the effect is probably of negligible impact on repository and site characteristics.

7.1 Accumulation in sediments

Lumping
Screening OUT (OTHER)

This is only related to the BIOSPHERE.

7.2 Accumulation in peat

Lumping
Screening OUT (OTHER)

This is only related to the BIOSPHERE.

7.3 Intrusion into accumulation zone in the biosphere

Lumping
Screening OUT (OTHER)

This is only related to the BIOSPHERE.

7.4 Chemical toxicity of wastes

Lumping
Screening OUT (OTHER)

Chemical toxicity of the wastes may be an issue. However, this question falls outside the scope of SKI/SKB scenario project.

7.5 Isotopic dilution

Lumping
Screening PROCESS SYSTEM

DESCRIPTION

In an assessment of the behaviour of radionuclides the presence of stable and/or naturally occurring isotopes of the same elements must be taken into account. For transport paths through the geosphere and biosphere to man, mixing or dilution of the radioactive species from the waste with species of the same element from other sources will lead to a reduction of the radiological consequences. The following viewpoints mainly concern the processes in the geosphere.

MODELLING

The presence of several isotopes of the same element are included in models that describe e.g. dissolution and precipitation reactions in the nearfield. However, these effects are not limited to isotopes of the same element. Coprecipitation of similar elements is a wellknown phenomenon that might lead to significant reduction of the release to the geosphere. Similar elements of this kind are the trivalent actinides and lanthanides.

Another important aspect is the naturally occurring decay series. For example, Swedish granitic bedrocks are often saturated with respect to uranium and thorium. This means that in calculation of the outflow of radionuclides to the biosphere there should be no contribution from the spent fuel to the dose consequences for these radionuclides above the natural background.

7.7 Human induced changes in surface hydrology

Lumping
Screening KEPT

May alter groundwater recharge (e.g. see 6.6 and other related phenomena).

Dams
Polders
Cities (7.11)
Irrigation
Overuse of surface aquifers
.....

Most of these changes may be covered within a general uncertainty of groundwater recharge/discharge.

7.8 Altered surface water chemistry by humans

Lumping
Screening KEPT

The industry pollution could give rise to considerable change in surface water chemistry by acidic rain, increased atmosphere carbon dioxide content, complexing agents in the surface waters etc. The risk of such a scenario will probably be neglectable, provided the bedrock groundwater flow is undisturbed, i.e. the groundwater transport time is long and the bedrock buffering capacity can be taken credit for. The scenario should however be kept on the list, although only combined with scenarios, containing groundwater flow to the repository through unsealed boreholes or shafts. This combination could probably be outscreened at a later stage.

7.9 Loss of records

Lumping
Screening PROCESS SYSTEM

KBS-3 states (p 21:7) "Knowledge of the final repository could conceivably have been lost at some point in time in the future, either as a result of some catastrophic event such as a global war of extermination" (6.7) "or as a consequence of human life being rendered impossible during a given era due to a new glaciation" (5.42) "If the country is thereafter repopulated, it is conceivable that certain activities might violate the barriers of the final repository".

7.10 Diagenesis

Lumping
Screening OUT (PROB)

TNC 86: Chemical, physical and biological processes that takes place in sediments or sedimentary rock after formation but before eventual metamorphism or weathering.

SCREENING

Screened out as there are no sedimentary rocks at the repository.

7.11 City on the site

Lumping 7.8 5.46 5.27
Screening KEPT

A city on the site may change the groundwater recharge/discharge (see 7.7). A city will also have a tunneling system which likely can reach depths of 100 m or more.

The most probable direct consequence seems to be a lowering of the water table, i.e. a decrease in recharge. A city might also be situated within, or enclose, the recharge area. Lumping to 5.27 in the first place.

Appendix

B:2 LIST OF OUTSCREENED FEPs

1.1.1 Criticality

Lumping
Screening OUT (Cons)

1.2.2 H_2/O_2 explosions

Lumping
Screening OUT (CONS)

1.2.8 Redox potential

Lumping 1.2.6
Screening OUT(Adm)

1.4 Sudden energy release

Lumping
Screening OUT (CONS)

2.1.2 Coupled effects (electrophoresis)

Lumping
Screening OUT

2.3.2 Electro-chemical cracking

Lumping
Screening OUT(ADM)

2.3.7.2 Hydrostatic pressure on canister

Lumping
Screening OUT(CONS)

3.1.8 Near field buffer chemistry

Lumping
Screening OUT (ADM)

3.1.9 Radiolysis

Lumping
Screening OUT(ADM)

3.1.12 Perturbed buffer material chemistry

Lumping
Screening OUT (ADM)

4.1.3 Colloids, complexing agents

Lumping
Screening OUT(ADM)

4.2.2.2 Hydraulic conductivity change – Excavation/backfilling effect

Lumping
Screening OUT (ADM)

4.2.2.3 Mechanical effects – Excavation/backfilling effects

Lumping
Screening OUT (ADM)

5.6 Co-storage of other waste

Lumping
Screening OUT (NON PLANNED)

5.7 Poorly designed repository

Lumping
Screening OUT (ADM)

5.8 Poorly constructed repository

Lumping
Screening OUT (ADM)

5.10 Accidents during operation

Lumping
Screening OUT(ADM)

5.12 Near storage of other waste

Lumping
Screening OUT (PROB)

5.13 Volcanism

Lumping
Screening OUT (PROB)

5.18 Enhanced groundwater flow

Lumping
Screening OUT (ADM)

5.19 Effect of plate movements

Lumping
Screening OUT (ADM)

5.20 Changes of the magnetic field

Lumping
Screening OUT (CONS)

5.25 Dissolution of fracture fillings/precipitations

Lumping
Screening OUT(ADM)

5.29 Meteorite

Lumping
Screening OUT (PROB)

5.30 Underground test of nuclear devices

Lumping
Screening OUT (RESP)

5.32 Desert and unsaturation

Lumping
Screening OUT (PROB)

5.35 Other future uses of crystalline rock

Lumping
Screening OUT (PROB)

5.40 Unsuccessful attempt of site improvement

Lumping
Screening OUT (RESP)

5.46 Groundwater recharge/discharge

Lumping
Screening OUT (ADM)

6.9 River meandering

Lumping
Screening OUT (CONS)

6.11 Intruding dykes

Lumping
Screening OUT (PROB)

6.14 Tectonic activity – large scale

Lumping
Screening OUT (CONS)

7.1 Accumulation in sediments

Lumping
Screening OUT (OTHER)

7.2 Accumulation in peat

Lumping
Screening OUT (OTHER)

7.3 Intrusion into accumulation zone in the biosphere

Lumping
Screening OUT (OTHER)

7.4 Chemical toxicity of wastes

Lumping
Screening OUT (OTHER)

7.10 Diagenesis

Lumping
Screening OUT (PROB)

Appendix

B:3 FEPs IN THE PROCESS SYSTEM

1.1.2 Radioactive decay; heat

Lumping
Screening PROCESS SYSTEM

1.1.3 Recoil of alpha-decay

Lumping 1.2.6
Screening PROCESS SYSTEM

1.1.4 Gas generation: He production

Lumping 2.3.8
Screening PROCESS SYSTEM

1.2.1 Radiolysis

Lumping
Screening PROCESS SYSTEM

1.2.3 Pb-I reactions

Lumping 1.5
Screening PROCESS SYSTEM

1.2.4 Gas generation

Lumping
Screening PROCESS SYSTEM

1.2.5 I, Cs-migration to fuel surface

Lumping
Screening PROCESS SYSTEM

1.2.6 Solubility within fuel matrix

Lumping
Screening PROCESS SYSTEM

1.2.7 Recrystallization

Lumping
Screening PROCESS SYSTEM

1.2.9 Dissolution chemistry

Lumping 1.5
Screening PROCESS SYSTEM

1.3 Damaged or deviating fuel

Lumping
Screening PROCESS SYSTEM

1.5 Release of radionuclides from the failured canister

Lumping
Screening PROCESS SYSTEM

2.1.1 Chemical reactions (copper corrosion)

Lumping
Screening PROCESS SYSTEM

2.1.3 Internal corrosion due to waste

Lumping
Screening PROCESS SYSTEM

2.1.4 Role of the eventual channeling within the canister

Lumping
Screening PROCESS SYSTEM

2.1.5 Role of chlorides in copper corrosion

Lumping
Screening PROCESS SYSTEM

2.1.6.1 Repository induced Pb/Cu electrochemical reactions

Lumping
Screening PROCESS SYSTEM

2.1.6.2 Natural telluric electrochemical reactions

Lumping
Screening PROCESS SYSTEM

2.1.7 Pitting

Lumping
Screening PROCESS SYSTEM

2.1.8 Corrosive agents, Sulphides, oxygen etc

Lumping
Screening PROCESS SYSTEM

2.1.9 Backfill effects on Cu corrosion

Lumping
Screening PROCESS SYSTEM

2.1.10 Microbes

Lumping
Screening PROCESS SYSTEM

2.2 Creeping of copper

Lumping
Screening PROCESS SYSTEM

2.3.1 Thermal cracking

Lumping
Screening PROCESS SYSTEM

2.3.8 Internal pressure

Lumping
Screening PROCESS SYSTEM

3.1.1 Degradation of the bentonite by chemical reactions

Lumping
Screening PROCESS SYSTEM

3.1.2 Saturation of sorption sites

Lumping
Screening PROCESS SYSTEM

3.1.3 Effects of bentonite on groundwater chemistry

Lumping
Screening PROCESS SYSTEM

3.1.4 Colloid generation – source

Lumping
Screening PROCESS SYSTEM

3.1.5 Coagulation of bentonite

Lumping
Screening PROCESS SYSTEM

3.1.6 Sedimentation of bentonite

Lumping
Screening PROCESS SYSTEM

3.1.7 Reactions with cement pore water

Lumping
Screening PROCESS SYSTEM

3.1.10 Interactions with corrosion products and waste

Lumping
Screening PROCESS SYSTEM

3.1.11 Redox front

Lumping
Screening PROCESS SYSTEM

3.1.13 Radiation effects on bentonite

Lumping
Screening PROCESS SYSTEM

3.2.1.1 Swelling of bentonite into tunnels and cracks

Lumping
Screening PROCESS SYSTEM

3.2.4 Erosion of buffer/backfill

Lumping
Screening PROCESS SYSTEM

3.2.5 Thermal effects on the buffer material

Lumping
Screening PROCESS SYSTEM

3.2.6 Diffusion – surface diffusion

Lumping
Screening PROCESS SYSTEM

3.2.7 Swelling of corrosion products

Lumping
Screening PROCESS SYSTEM

3.2.10 Soret effect

Lumping 3.2.6
Screening PROCESS SYSTEM

4.1.1 Oxidizing conditions

Lumping
Screening PROCESS SYSTEM

4.1.2 pH-deviations

Lumping
Screening PROCESS SYSTEM

4.1.4 Sorption

Lumping
Screening PROCESS SYSTEM

4.1.5 Matrix diffusion

Lumping
Screening PROCESS SYSTEM

4.1.6 Reconcentration

Lumping
Screening PROCESS SYSTEM

4.1.7 Thermochemical changes

Lumping
Screening PROCESS SYSTEM

4.1.8 Change of groundwater chemistry in nearby rock

Lumping
Screening PROCESS SYSTEM

4.1.9 Complexing agents

Lumping
Screening PROCESS SYSTEM

4.2.2.1 Excavation/backfilling effects on nearby rock

Lumping
Screening PROCESS SYSTEM

4.2.3 Extreme channel flow of oxidants and nuclides

Lumping
Screening PROCESS SYSTEM

4.2.4 Thermal buoyancy

Lumping
Screening PROCESS SYSTEM

4.2.5 Changes of groundwater flow

Lumping
Screening PROCESS SYSTEM

4.2.7 Thermo-hydro-mechanical effects

Lumping
Screening PROCESS SYSTEM

4.2.8 Enhanced rock fracturing

Lumping
Screening PROCESS SYSTEM

4.2.9 Creeping of rock mass

Lumping
Screening PROCESS SYSTEM

5.1 Saline (or fresh) groundwater intrusion

Lumping
Screening PROCESS SYSTEM

5.14 Resaturation

Lumping
Screening PROCESS SYSTEM

5.26 Erosion on surface/sediments

Lumping 5.46
Screening PROCESS SYSTEM

5.44 Solubility and precipitation

Lumping
Screening PROCESS SYSTEM

5.45 Colloid generation and transport

Lumping
Screening PROCESS SYSTEM

6.2 Gas transport

Lumping
Screening PROCESS SYSTEM

6.3 Far field hydrochemistry – acids, oxidants, nitrate

Lumping
Screening PROCESS SYSTEM

6.4 Dispersion

Lumping
Screening PROCESS SYSTEM

6.5 Dilution

Lumping
Screening PROCESS SYSTEM

6.6 Weathering of flow paths

Lumping
Screening PROCESS SYSTEM

6.12 Undetected discontinuities

Lumping
Screening PROCESS SYSTEM

6.13 Geothermally induced flow

Lumping
Screening PROCESS SYSTEM

7.5 Isotopic dilution

Lumping
Screening PROCESS SYSTEM

7.9 Loss of records

Lumping
Screening PROCESS SYSTEM

Appendix

B:4 LIST OF FEPs LUMPED TO FEPs OUTSIDERS

2.5.1 Random canister defects – quality control

Lumping
Screening KEPT

Lumping from

2.3.3 Stress corrosion cracking
2.3.4 Loss of ductility
2.3.5 Radiation effects on canister
2.3.6 Cracking along welds
2.4 Voids in the lead filling
2.5.2 Common cause canister defects – quality control
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[1] The Royal Institute of Technology, Department of Chemical Engineering, Stockholm
[2] Studsvik Nuclear, Nyköping
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[1] Swedish Geological Co, Uppsala
[2] EMX-system AB, Luleå
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[1] SKB, Stockholm
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[1] Kemakta Konsult AB
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