NUMO
原子力発電環境整備機構

NUMO-TR-09-04

Study on strategy and methodology for repository concept development for the Japanese geological disposal project

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Nagra

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1 Introduction

1.1 Background of this study

NUMO has selected an open solicitation approach for the site selection process in Japan, both for the high-level waste repository (open call in 2002) and the TRU repository (open call in 2008). Such an approach, albeit flexible, poses a special challenge for NUMO's repository design.

A detailed repository design must be tailored to the given geological and surface environment, not least to take advantage of the potential for optimization. The repository design must fulfill a broad range of requirements resulting, for example, from the long-term and operational safety goals, engineering practicality and socio-economic issues. The special challenge for NUMO's design team is to be able to specify a number of different designs for different geological and geographical sites and, moreover, to be able to finalize specific designs within a very limited time period (see Figure 1.1. NUMO plans to select site through the literature survey (LS) stage, the preliminary investigation (PI) stage and the detailed investigation (DI) stage; the site should be selected by around 2028).

For the Swiss radioactive waste disposal program, Nagra has experience drawn from looking at a wide range of geological environments for both the HLW and L/ILW projects. It was thus agreed to set up a collaborative study aimed at transferring relevant knowledge from the Swiss geological disposal program to the Japanese one.

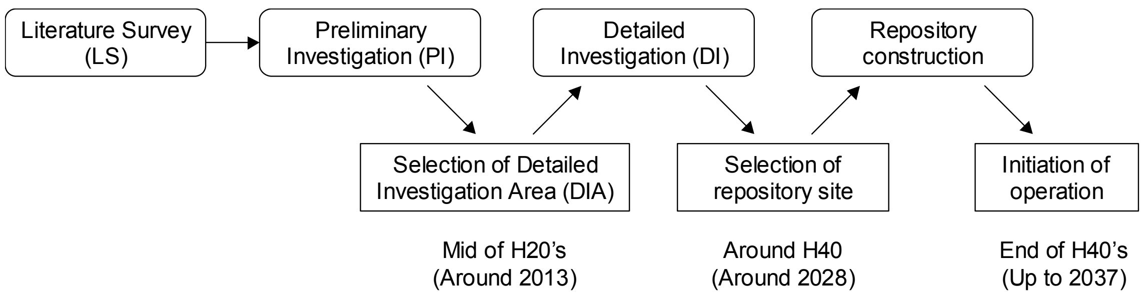

Figure 1.1 Schedule of geological disposal program in Japan.

1.2 Overview of the collaborative study on repository concept development

The repository concept (RC) collaborative study was initiated in 2001, mainly as a technical knowledge transfer between the implementing organizations of Japan and Switzerland. The focus was on developing a methodology for tailoring repository concepts to a broad range of site environments. The outcome of the study between 2001 and 2003 (phase 1) is summarized in NUMO (2004a).

The RC collaborative study was further continued and expanded to cover a wide range of topics from the strategic to the technical level. Every year, two main meetings were organized, one in Switzerland and one in Japan. These meetings were supplemented by a number of working meetings both in Switzerland and Japan. These working meetings allowed the members of the NUMO-Nagra team to exchange discuss and further develop ideas and concepts applicable to the Japanese environment. The main meetings also discussed work performed by contractors and guided future developments.

The 2nd phase of the RC study was completed in FY 2007. The goal of this report is to summarize the main results of the study between FY 2004 and FY 2007, as a complement to NUMO (2004a).

For each of the fiscal years covered in this report, the main topics investigated as part of the RC collaborative study are as outlined below.

FY 2004

- Multiple attribute analysis (MAA) of different repository designs
- Preliminary ideas for application of a prototype requirements management system (RMS) to an integrated repository project
- Identifying future requirements for PA models and databases.

FY 2005

- Structured approach for tailoring repository concepts to specific sites
- Further development and implementation of a requirements management system (RMS)
- Establishing a performance assessment code and database development program.

FY 2006

- Structured approach for tailoring repository concepts to specific sites, to include:
  - Completion of the NUMO Structured Approach (NSA) policy report
  - Development of ideas for NSA implementation
- Further development and implementation of a requirements management system, including review of the RM structure of NUMO's operational safety study
- Establishing performance assessment strategies and methods, including:

- Development of the PA strategy in the three investigation stages
- A study of scenario development
- Identification of topics related to the PA methodologies.

FY 2007

- Interaction between repository concept (RC) development and site characterization
- Study on structure and contents of the RMS
- Study on development and evaluation of performance assessment (PA) scenarios
- Survey on specific issues for RC development
- Summary report on RC collaboration (draft).

1.3 Structure of this report

From the extensive list of topics covered under the collaboration, three topics are selected here and described in more detail.

Chapter 2 summarizes the roadmap for the preliminary investigation (PI) stage. The main focus in developing the PI roadmap was to identify potential interactions among different disciplines, e.g. site characterization, repository design and safety assessment.

Chapter 3 covers the methodology for scenario development for safety assessment. The scenario development method used in the H12 report is reviewed and more recent methodologies used in European programs are presented. NUMO's strategy for scenario development is also described.

Chapter 4 is dedicated to the development of NUMO's Requirements Management System (RMS). As case studies, the ongoing developments at SKB and Nagra are briefly summarized. NUMO's idea for RMS development is also summarized in Chapter 4.

Chapter 5 contains the conclusions of the collaborative study.

2 Development of NUMO's PA/RD roadmap at the PI stage

2.1 Premises for the roadmap

The aim of the PA/RD (performance assessment/repository design) roadmap is to establish a guideline for implementing site characterization, repository design and safety assessment activities at the preliminary investigation (PI) stage. Because such efforts are multidisciplinary, one of the focal points of the PA/RD roadmap was to identify the interactions among the disciplines throughout activities during the PI stage.

The time horizon assumed is the one considered in the current framework for the PI stage, i.e. that the activities for the PI stage must be implemented within 5 years. This time constraint was one of the boundary conditions in setting up the overall site investigation program for the roadmap. As is shown below, within this period the project team assumed that two, more or less sequential field investigation campaigns can be organized, executed and completed.

As noted in Chapter 1, the site and, consequently, the site conditions have not been specified in Japan to date. Thus, the roadmap was developed in a generic manner without going into detailed technical specifications. Once the site conditions are better defined, the processes in the roadmap can be further optimized.

2.2 Interaction with site characterisation activities

Site characterization (SC), repository design (RD) and performance assessment (PA) activities are closely interlinked. This is particularly true if the time available is limited and the activities within these disciplines need to be optimized. The interaction and integration of these disciplines is illustrated in Figure 2.1. Typically, PA and RD provide input to SC on what site data should be collected during the PI, based on an idealized preliminary conceptualization (from literature data for example) of the site from SC.

It is expected that the results of the SC will result in refinement (or, if necessary, revision) of the initial thoughts on the proposed repository concept (or concepts) for a site and, consequently, on the demonstration of the safety of the disposal system. This in turn may make it necessary to revise the initial PI SC plan and proceed, in a phased approach, with investigations aimed at answering the newly posed questions.

For this reason, NUMO has developed a staged roadmap for planning the PI (that mainly focuses on site characterization) [Preliminary Investigation Phase Planning Manual (PIPM). Koike, 2008]. This plan foresees the need for input from the RD/PA group on identifying and prioritizing the issues and focusing of the SC at different steps of the PI stage.

A similar roadmap was also developed for the RD/PA work, showing the links and feedbacks between RD/PA and SC. Thus, the ultimate goal is to consolidate the PI SC and RD/PA roadmaps into one comprehensive roadmap covering the entire scientific and technical work processes of PI stage.

The current version focuses on RD/PA during the PI stage; the interactions with SC activities are included and highlighted. A basic structure for such a roadmap has been developed and is illustrated in Figure 2.2. In the subsequent sections, each step of the roadmap is outlined in more detail. A common structure was adopted for each task, which includes the following information:

- Task of SC, RD or PA
- Issues to be considered in the task
- Required input from RD/PA group
- Main outcome from the task.

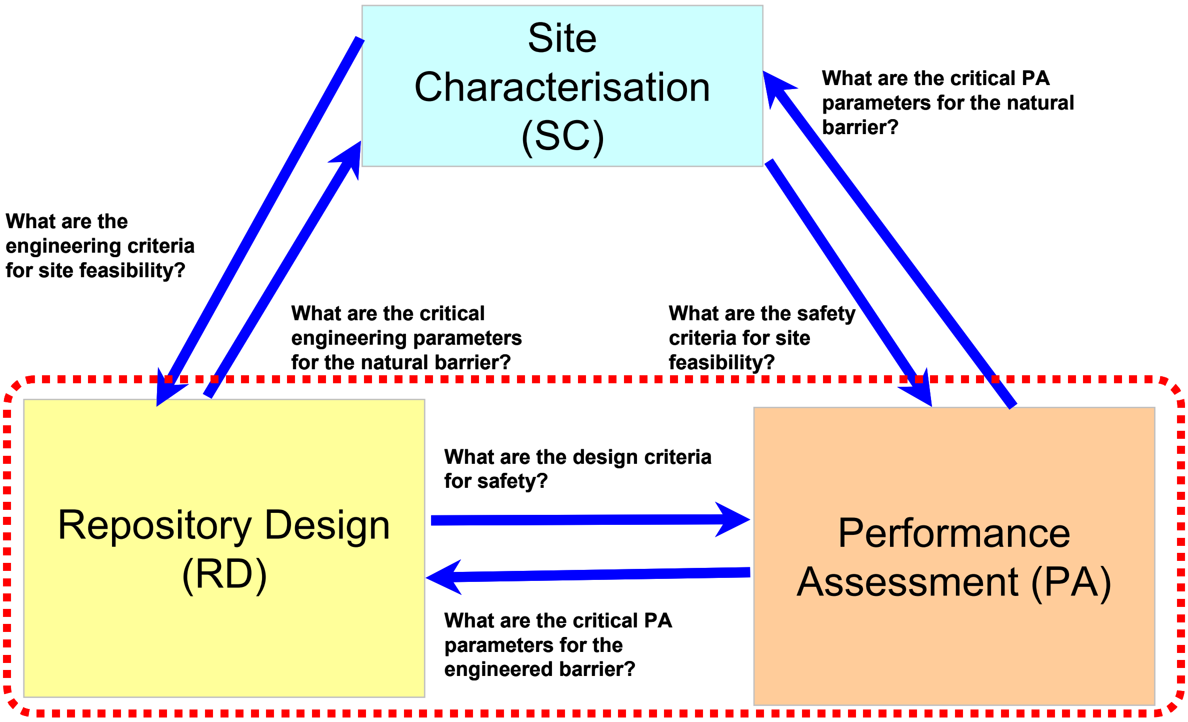

Figure 2.1 Interactions between SC, RD and PA.

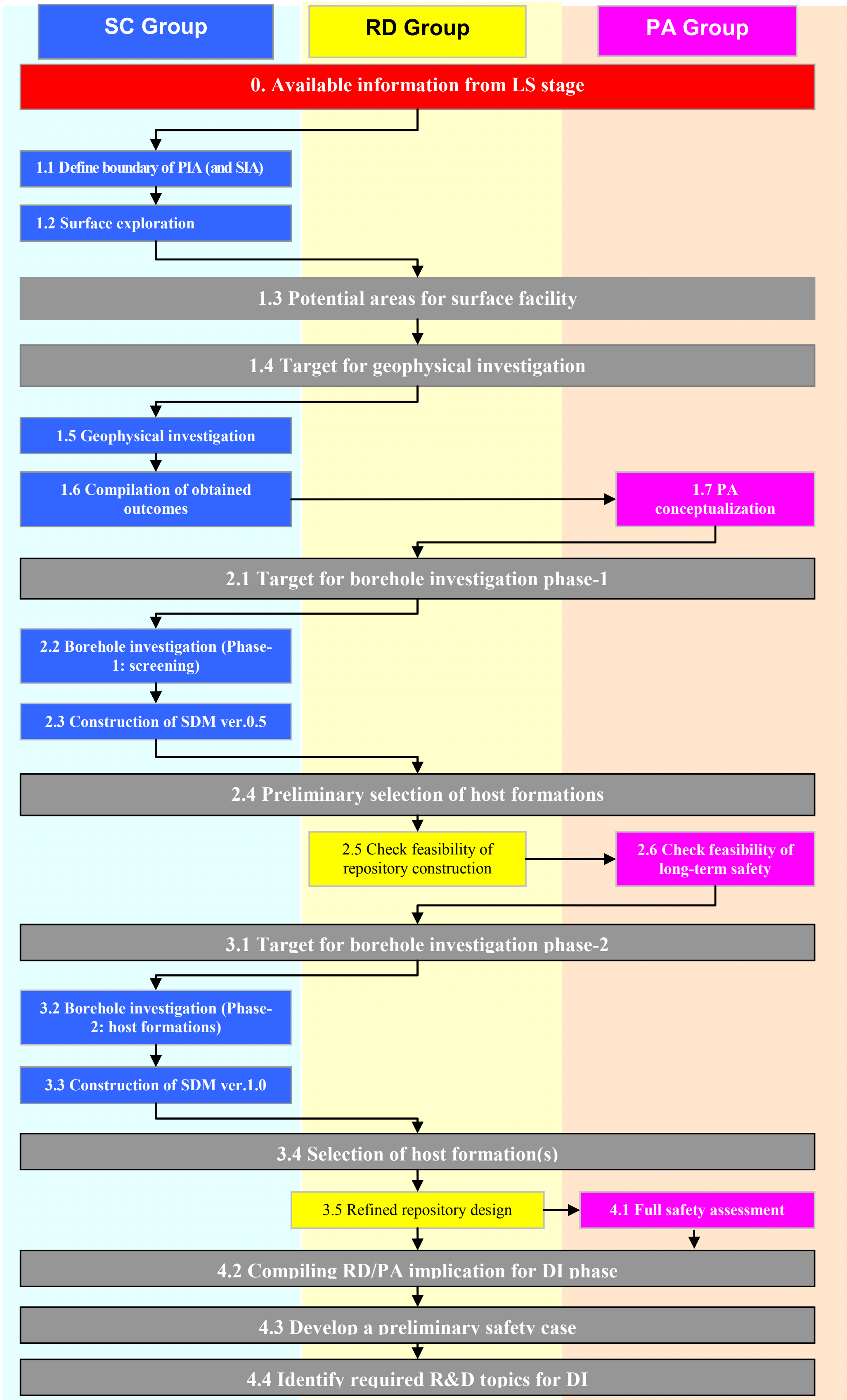

Figure 2.2 Outline of the proposed PA/RD roadmap for the PI stage.

2.3 Roadmap at the PI stage

2.3.1 Task 0: Available information from the LS stage

The detailed planning of activities during the PI stage rests on the findings of the assessments made during the literature survey (LS) stage. The roadmap outlined here assumes that the following information has been compiled and decided upon:

Boundary of volunteered area

This is expected to be defined by the volunteer municipality, but NUMO may need to negotiate to ensure that it will be large enough for the expected footprint. This may be the case particularly if the potential repository host rock is in an offshore area.

Confirmation of non-violation of the exclusion criteria

Using the available information, NUMO will check whether there are areas that could violate the exclusion criteria. Such areas will be excluded from the proposed PIA.

Site Descriptive Model (SDM) version 0

Based on literature data, a version 0 conceptual and Site Descriptive Model (SDM) is developed by NUMO. Among other things, this model identifies (hypotheses of) the main geological features such as topography, main rock type boundaries and regional faults and puts the area into its regional geological setting based on an overall understanding of Japan's geology. It should be noted that the SDM version 0 contains a high level of uncertainty and clear identification of uncertainties is critical for PI planning.

Provisional selection of host rock(s)

Using the SDM version 0, potential host rock(s) in the area are identified by NUMO, e.g. by applying the procedures described in the PIPM (see Figure 2.3).

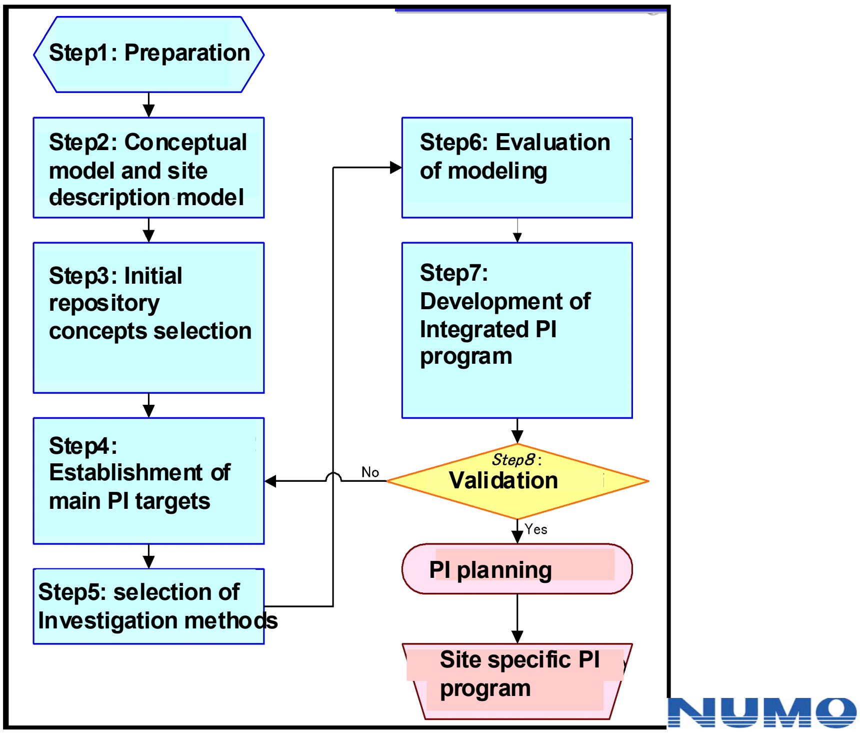

Figure 2.3 Planning of the site characterization activities at the PI stage – Flow chart (Koike, 2008).

Range of RCs suitable for the potential host rocks

Repository concepts judged to be suitable for the identified potential host rocks are proposed, e.g. by applying the procedures discussed in NUMO(2004a).

Regional groundwater flow model

A regional groundwater flow model will be developed by NUMO based on the SDM version 0. This model will establish groundwater flow in the regional setting and will, at least, provide a good indication of groundwater divides and regional recharge and discharge areas. Such a groundwater flow model will be developed by the SC group.

Draft PI SC plan

A first PI site characterization plan needs to be developed. It should identify the PI targets and priorities, the steps in the PI, plans for the investigations and plans for further site descriptive modeling, e.g. by applying the PI roadmap (Koike, 2008).

Draft PA plan for the PI stage with safety assessment version 0

A PA plan needs to be developed for the PI stage. Such a plan should identify the main activities in future PAs, identify potential site- and RC-specific critical issues and outline the structure of the site-specific "safety case" – to indicate how it is conceived that safety will eventually be argued. The plan should also confirm the feasibility of constructing a safe repository at the site (safety assessment version 0) – but there is no need for formal compliance (further aspects of the PA plan are discussed in the RC report for FY 2006, Kitayama et al., 2007). One of the obvious exercises at this stage is to compare the expected performance of the disposal system with H12 or preliminary PA studies by NUMO.

2.3.2 PI - introductory and geophysical investigation phase

It is foreseen that the PI will start with surface-based mapping and geophysical investigations. The results of these investigations will be important for the detailed planning of borehole investigations and may also result in a need to revise some of the targets for these.

(1) Task 1.1: Define the boundary of the PIA (and SIA)

According to the Final Disposal Act, a PIA must not contain any of the features specified by the national exclusion factors and should be large enough to provide sufficient understanding of the host rock. However, as is pointed out in NUMO(2004b), there could be cases where supplementary investigation areas (SIA), i.e. areas outside the PIA, would be needed for providing additional information as shown in Figure 2.4. In selecting the PIA, both the PIA itself and the SIA(s) should be identified (if needed).

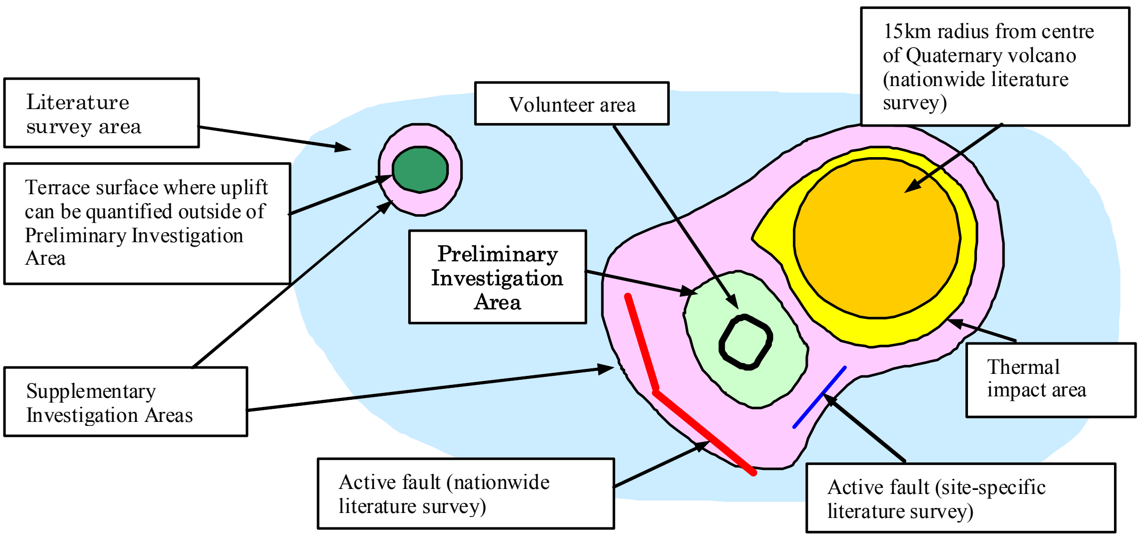

Figure 2.4 Schematic illustration showing how the legally defined Evaluation Factors for Qualification affect the identification of the location and geometry of a Preliminary Investigation Area (after NUMO, 2004b).

Responsibility for the task

The definition of the PIA (and SIA) is primarily the task of the SC group.

Issues to be considered for this task

The following issues needs to be considered for this task:

- Main features defining the regional geological setting should be available from SDM version 0 in Section 2.3.1 (Task 0). Examples of such features include topography, main rock type boundaries and regional faults.
- Location of features to be excluded from a PIA as found during the LS stage
- Potential repository footprint and potential depth range considering the provisional host rock and range of potential repository concepts
- In the case of a coastal site, how extensive an area of sea will be included in the PIA or SIA.
- Potential discharge area of regional groundwater to at least be included in the SIA (based on the regional groundwater flow model based on SDM version 0)
- Since there is no flexibility for expanding the PIA at a later stage, the PIA should be defined as extensively as possible
- Socio-economic factors have to be considered in defining PIAs (and SIAs). Current and future land use in the relevant region needs to be considered. Political boundaries will also be carefully analyzed and considered in defining the PIA.

General guidelines for PIA selection are included in NUMO(2004c), but it is worth expanding these to include more comprehensive issues.

Required input from the RD/PA group for this task

The RD/PA group needs to provide information on the potential repository footprint considering the provisional host rock(s) and range of potential repository concepts identified during the LS stage. It is important to carefully investigate existing tunnels or underground facilities constructed in the potential host formation and to include such areas in PIAs or SIAs.

Main outcome

The outcome of this step is a clear boundary for the PIA (and SIA if needed).

(2) Task 1.2: Surface explorations

Surface explorations are carried out to provide a two-dimensional SDM and - early on - input to the three-dimensional SDM. Features included in the SDM version 0 can be checked in cases where they are visible at the surface. Surface explorations also provide input for identifying suitable locations for geophysical explorations and borehole campaigns.

Responsibility for the task

Surface explorations are carried out by the SC group supported by contractors, e.g. field geologists.

Issues to be considered for this task

The surface exploration task focuses on key features of the SDM version 0 that can be detected using surface-based methods. Examples of such features are:

- Thickness and characteristics of the rock formations (mainly at outcrops)
- Characteristics and properties of the overburden
- Estimation of uplift and erosion rates or subsidence/sedimentation rates (e.g. terrace surfaces)
- Presence of faults or lineaments
- Monitoring of seismic activity
- Presence of natural resources that could attract future human intrusion (confirmation of LS results)
- Early assessment of surface hydrology – streams, springs.

Required input from the RD/PA group for this task

The RD/PA group should help in identifying key issues in the site characterization plan. However, this should already have been done in the LS stage (task 0).

Main outcome

The main output from this step are the results of the surface explorations. This information can be used for modifying the location and size of potentially usable host rock formations and their main geometric constraints, later to be used for updating the SDM version 0. If the potential host rock is exposed at the surface (outcrop), the properties of rock can be provisionally analyzed.

(3) Task 1.3: Identification of potential areas for the surface facilities

From a land use planning viewpoint and in the interactions with the local municipality, there is generally a need at an early stage to establish potential locations for the surface facilities. However, the optimum location is not only a function of the surface conditions; it also has to be suitable for the underground facilities. This means that the location of the surface facilities may not always be clearly defined in the early stages of the PI – but potential locations could be identified. In reality, socio-economic factors for locating the surface facilities may be a dominant factor and the siting of the underground facilities may need to accommodate such considerations.

Responsibility for the task

Identification of potential areas for the surface facilities needs to be done jointly by the SC/RD/PA groups as well as with the groups within NUMO that deal directly with interactions with the municipalities.

Issues to be considered for this task

The following issues should be considered:

- Socio-economic factors (e.g. land use, land prices, surrounding environment)
- Routes for material transportation at the surface (logistics)
- Topographic conditions
- Whether all of the facilities will be located at the surface or partly subsurface
- Potential discharge point (e.g. river) of the groundwater pumped up during construction and operation
- Potential discharge area of deep (potential repository level) groundwater
- RD/PA input regarding suitable or less suitable locations, with regard to the subsurface conditions (see below).

Required input from the RD/PA group for this task

The RD/PA input at this early (i.e. SDM version 0) stage can only be relatively generic. This means that the likely input from RD/PA would be aimed at maintaining sufficient flexibility in the surface location until a better understanding of the volume is achieved. This means that the location of the surface facilities should preferably be reconsidered both after SDM version 0.5 and after SDM version 1.0. Making a decision too early could lead to non-optimized solutions. Typical input from RD/PA (at any stage) is given below.

- Any constraints in location given the potential host rock and repository concept. Such constraints could include complex geotechnical conditions (e.g. very weak rock, highly transmissive and difficult to grout, etc.) in some areas of the PIA, being too far away from the potential host rock or a limited volume of host rock that should not be disturbed by access routes from the surface
- Potentially suitable areas for the surface facilities and where to locate subsurface access, i.e.

those locations that would not unduly disturb the host rock.

Main outcome

The main outcome of this step is identification of potential area(s) for the surface facilities. However, the suitability of these areas needs to be further explored by the RD/PA team once they have more information from the subsurface.

(4) Task 1.4: Define targets for geophysical investigations

Targets and priorities for the PI could be developed using the methodology outlined in Step 2 of the PI roadmap (Koike, 2008). The targets for the geophysical investigations are generally a subset of the overall targets of the PI. Based on the general targets, specific targets for the geophysical campaign are identified. The geophysical investigations are generally suitable for identifying different geological formations and gently dipping features such as faults.

It should be noted that geophysical investigations usually need to be followed up by a borehole campaign. This means that the planning of the geophysical campaign also needs to consider the potential borehole campaign – even if the outcome of the geophysics will be used to modify the borehole campaign. Furthermore, complementary geophysical investigations may be considered throughout the PI and even during the DI stage.

Responsibility for the task

Defining the targets is a joint task of the SC/RD/PA groups.

Issues to be considered for this task

The investigation issues will be site-specific and should be based on hypotheses made during LS and formulated in the SDM version 0. Clear targets will help in detailed planning of the geophysical investigations (e.g. required resolution and investigation area). Typical issues would include:

- Extent (vertical and horizontal) of the potential host formations, locations of large faults and displacements
- Additional information obtained from surface explorations, e.g. revised ideas about formation boundaries or potential faults
- Suitable locations for boreholes (i.e. considering surface constraints) for following up the geophysical campaign. This may affect the exact location of seismic profiles
- Identifying the key volume of interest, although at this early stage the investigations should, in principle, cover the entire PIA.

Required input from the RD/PA group for this task

The RD/PA group should help to identify the key issues in the site characterization plan, although this should already have been done in the LS stage (task 0). Examples of important input include:

- Key volume of interest (i.e. potential host rock and potential depth range)
- Feedback on priorities for the planned investigations. For the given site and concept is there a potential volume problem – or are hidden active faults the main issue – or both?
- Safety constraints regarding the density and location of boreholes.

Main outcome

The main outcome of this stage are revised and refined targets for the PI and a revised PI plan.

(5) Task 1.5: Geophysical investigations

This step concerns the detailed planning and execution of the geophysical investigations, based on the targets defined in the previous step.

Responsibility for the task

Performing the geophysical investigations should be the responsibility of the SC group, with contractors for carrying out the actual field investigations.

Issues to be considered for this task

Detailed planning is required prior to the execution of the geophysical investigations, e.g. selection of applied methods, horizontal extent of the investigation area, density of seismic sources and receivers. Depending on the depth of the host formation and required investigation area, the investigation area may extend beyond the PIA (but it must be within SIA). Specific issues to be considered include:

- Meeting appropriate targets according to plan
- Handling unexpected findings.

Required input from the RD/PA group for this task

No, or very little, input from the RD/PA group is required for this step. A possible exception would be if the SC group needs additional feedback on priorities during the actual investigations in the case where there are problems completing the original plan or if unexpected findings are made. The SC team may then need some feedback from RD/PA on the RD/PA significance of these findings or deviations.

Main outcome

The findings from the investigations are used for revising the SDM version 0 (see next step – task 1.6). It is not expected, nor desirable, for the RD/PA team to interpret the geophysical data themselves.

(6) Task 1.6: Compilation of obtained results

A full update of the SDM is not considered necessary for this step (unless there are significant unexpected findings). However, the geophysical data need to be interpreted and put into the context of SDM version 0, such that the data can be used as input for the borehole campaign. This interpretation, as well as the interpretation of the surface exploration data, could also be seen as the early stages of development of SDM version 0.5, but the results are intermediate and should not be formally published. It therefore needs to be considered how the results can be communicated among the disciplines and how they will be utilized in the subsequent phases.

Responsibility for the task

Compilation of obtained results is the task of the SC group supported by contractors.

Issues to be considered for this task

The following issues are to be considered for this task:

- Have the surface and geophysical data addressed key uncertainties in SDM version 0 and have new uncertainties been identified, specifically regarding the dimensions of the host formation and potentially layout-determining features?
- Is there any reason to seriously question the conceptual model of SDM version 0?
- Have any critical risks been identified which could potentially cause significant problems for RD or PA?
- Are the proposed borehole locations identified in the planning of the geophysical investigations still appropriate?

Required input from the RD/PA group for this task

There is essentially no new input required from the RD/PA group for this task. However, the compilation/evaluation should be done considering the RD/PA input to the PI program, i.e. on what issues are of relevance.

Main outcome

The main outcome of this task is a summary of the results from surface and geophysical investigations. This summary should include:

- Updated information on the extent (vertical and horizontal) of the potential host formations and the locations of large faults and displacements. However, it would be too early to make any extensive assessments of the implications of this information. This can wait until SDM version 0.5
- Geometric issues/hypotheses to be tested in the borehole campaign.

It has to be considered in advance how (and in what form) the complied results can be communicated to the PA/RD group without formal updating of the SDM.

(7) Task 1.7: PA conceptualization

In order to allow an efficient assessment of site suitability after the first borehole campaign, it is important for the PA groups to assess the information obtained during the surface and geophysical investigations.

Responsibility for the task

PA conceptualization is the task of the PA group.

Issues to be considered for this task

The following issues are to be considered for this task:

- Is the previous conceptualization for PA use still valid?
- Updating of safety assessment modeling needs (based on the plan prepared during LS)
- Scoping safety calculations
- Planning numerical groundwater flow modeling addressing a selection of scales, features and required resolution.

It should be remembered that migration and flow are not the only safety-relevant site issues. The need for extensive groundwater flow modeling depends on the host rock and repository concept. There may be other issues, e.g. geochemical or geomechanical ones, that could also be important and where planning of the modeling needs and approaches would be necessary.

Required input from the SC group for this task

Required input from the SC group to the PA conceptualization includes:

- Geometry of the main features suggested to be of hydraulic significance and information about their characteristics (e.g. porous or fractured medium)
- Help in selection of the modeling domain for the groundwater flow numerical model
- Features/characteristics that may have an impact on long-term safety (potential for

aggressive groundwater, potential rock stability problems).

Main outcome

The main outcome of the PA conceptualization is a modified perspective of the features/characteristics that may have an impact on long-term safety (if relevant), hypotheses that could impact the further characterization and an updated safety assessment modeling plan. Such a modified perspective and identified potentially critical uncertainties should be accommodated in the borehole campaign planning.

2.3.3 PI - borehole investigation phase 1

It is expected that the borehole investigations will be divided into two phases, with an assessment of targets and objectives after the first stage. However, the actual PI plan may indicate that further phasing of the investigations is more appropriate. Nevertheless, the planning, execution and assessment of the findings would essentially follow the same pattern and a need for integration between the SC/RD/PA groups, regardless of the details of the PI phases.

(1) Task 2.1: Targets for borehole investigation phase 1

Targets and priorities for the PI could be developed using the methodology outlined in Step 2 of the PI roadmap (Koike, 2008; see Figure 2.3). The targets for the borehole investigations are generally a subset of the overall targets of the PI. Based on the general targets and the additional hypotheses formed during the surface and geophysical investigations, as well as on additional feedback from the RD/PA group, specific borehole targets are defined.

Responsibility for the task

Defining the targets is a joint task of the SC/RD/PA groups.

Issues to be considered for this task

The main aim of the borehole investigation phase 1 is to determine the general geological conditions of the site and to guide the further characterization work during borehole investigation phase 2. In defining targets and priorities, the following issues should be considered:

- Critical features for which early information is needed
- Deciding whether there is a need (i.e. if the PIA is large) to obtain information to aid in focusing on a promising volume for more detailed investigations during borehole investigation phase 2

- Checking relevant hypotheses by assessing the surface and geophysical information
- Obtaining basic properties of the potential host rock formations (e.g. hydraulic, mechanical, geochemical properties)
- If the borehole campaign is performed under time pressure or under tight budget constraints, it is important to set clear priorities for the targets.

Required input from the RD/PA group for this task

The RD/PA input for this task would be a reassessment of the RD/PA significance of the key issues already identified in the site characterization plan developed at the end of the LS. More specifically, the RD/PA groups should suggest what properties are of key interest given the type of formations considered. The answer may be quite different depending on the type of host formation and what is already known about it. They could concern:

- Dimensions (or thickness) of the rock formations
- Properties of the host formation (e.g. permeability, thermal properties, rock mechanical properties)
- Groundwater composition (key factors such as salinity, Eh, pH or "aggressive water" could have a large impact on what are potentially suitable RCs)
- Role of water-conducting features (WCFs) in mass transport (modeled as porous or fractured media)
- More accurate determination of the host rock volume, i.e. confirm potential faults, layer thickness, etc.

Considering this, the RD/PA group should provide feedback on what hypotheses suggested by the geophysical data interpretation need to be explored.

Main outcome

The main outcome of this task are detailed prioritized targets for borehole phase 1.

(2) Task 2.2: Borehole investigation (phase 1 - screening)

This task involves the detailed planning and execution of the phase 1 borehole investigations.

Responsibility for the task

The detailed planning and execution of the borehole investigations is the task of the SC group supported by contractors for borehole drilling and investigation.

Issues to be considered for this task

A detailed plan of borehole drilling and investigations has to be prepared considering the targets identified in task 2.1. It will be necessary to consider constraints and wishes regarding borehole locations, including:

- Optimum location for meeting targets, e.g. to ensure encountering of a typical section of the host rock volume, to drill through as many potential formations as possible or located such that it will hit other features of interest
- Location of the borehole could be outside the volunteer area but must be within the PIA – surface conditions need to be suitable
- Consideration of whether boreholes can be drilled through the potential repository area (based on feedback from the RD/PA group).

Although this is a single step in this roadmap, it will represent major work for the SC group to select contractors and specify drilling and investigation plans and to implement the borehole investigations.

Required input from the RD/PA group for this task

The key input to this task from the RD/PA group is set by the targets of task 2.1. In addition, the following input is needed:

- Whether boreholes can be drilled through the potential repository area. The answer will depend on the repository concept, the size of footprint in relation to the potentially available host rock volume and on perceived problems in later sealing of boreholes
- Whether there is a possibility that the borehole might be used for other purpose, e.g. monitoring or additional testing
- Feedback during the borehole investigations in case there is a need to modify the investigations.

Main outcome

The main outcome are the data from the investigations with assessment of measurement uncertainty. These data, which form the input to SDM version 0.5 (see next section) would potentially include information on:

- Confirmation of the geological setting
- Typical hydraulic, thermal and mechanical properties of potential host rock formations
- Hydraulic properties of WCFs in the host rock and surrounding rock
- Mineralogy of the rock matrix, small-scale structure of fractures and the mineralogy/thickness/extent of fracture coatings, infill, etc. from borecores

- Typical groundwater composition in the host rock
- Initial stress (e.g. orientation and magnitude).

(3) Task 2.3: Construction of SDM version 0.5

The investigations during the PI provide primary data (measurement values and directly calculated values), which are compiled in a database. In order to make use of the compiled (measured) information, it must be interpreted and presented in a geoscientific Site Descriptive Model (SDM); see step 5 of the PI roadmap (Koike, 2008). After borehole investigation phase 1, there are sufficient data to warrant an update of SDM version 0 into SDM version 0.5. This SDM in turn is key component for planning the completion of the PI stage. More specifically, it provides a geo-dataset for use in preliminary PA and design.

Responsibility for the task

Site descriptive modeling is the task of the SC group, but it has to address the needs of the RD/PA groups.

Issues to be considered

Issues to be considered in the construction of SDM version 0.5 include:

- Identification of layout-determining features (large faults)
- Dimensions of the host formation
- Typical properties of the host formation (and other formations if they are judged to be of importance)
- Expected variability of properties with time (particularly groundwater flow and composition)
- Identification of key uncertainties related to PI targets
- Surface hydrology - dilution and evolution.

Required input from the RD/PA group

The RD/PA group should already have provided their main input to the targets and plans for surface and geophysical investigations and to the borehole investigation plan. However, the RD/PA groups also need to provide feedback on the derivation of the geo-dataset for use in PA and design.

Main outcome

The main outcome of this task is the SDM version 0.5 with its description of:

- Identification of layout-determining features (large faults)
- Dimensions of the host formation

- Typical properties of the host formation and surrounding formations: hydraulic, thermal and mechanical, groundwater composition, mineralogy and initial stress (e.g. orientation and magnitude)
- Identification and assessment of key uncertainties related to PI targets
- A geo-dataset for use in PA and design.

(4) Task 2.4: Preliminary selection of host formations

SDM version 0.5 will allow a much more informed, although still preliminary, selection of potential host formations for the repository. This selection in turn affects selection of repository concepts.

Responsibility for the task

The preliminary selection of host formation(s) is a joint task of the SC/RD/PA groups.

Issues to be considered for this task

The selection should be based on NUMO's "Guideline for host rock selection". Issues to be considered include:

- Identification of options – are there any – or is the selection evident?
- Volume and properties of the different formations
- Assessment of the potential for exploring different options.

Required input from the RD/PA group for this task

The RD/PA group needs to provide the following input:

- RCs suitable for the potential host rock(s) considered
- Footprint needed for different RCs in different host rocks
- An overall, qualitative assessment of the potential for success of different options.

Main outcome

The main outcome of this task is the preliminary selection of host formations.

(5) Task 2.5: Checking the feasibility of repository construction

A key element for the further planning of the PI is to check the feasibility of repository construction for the proposed RC in the suggested host rock(s). This assessment, together with the long-term safety feasibility check (see next step) is essential for guiding further work and decisions in the PI.

Responsibility for the task

Checking the feasibility of repository construction is the task of the RD group.

Issues to be considered for this task

The following issues are to be considered for this task:

- Extent of the host formations within the volunteer area
- If one formation cannot accommodate the planned waste volume (40,000 canisters), consider the possibility of using two or more rock formations
- If the potential rock formation has a small horizontal extent but is very thick, a multi-layer repository layout can also be considered
- Stress conditions and strength of the rock formation
- Thermal properties of the host formation (from core sample tests)
- Potential risks and measures for mitigating them (through design modification), e.g. smaller host rock extent, formation at much greater depth, higher permeability, etc. and consequences of such risks will be analyzed
- Complex groundwater composition (salinity, corrosive, redox – affects potential for selection of the EBS and its longevity).

Input needed from the SC group

The main input would be the SDM version 0.5 and the selection of the host rock made in the previous task. In addition, close discussion with the SC group will be required to identify the level of uncertainty involved in SDM version 0.5.

Main outcome

The main outcome of this task is:

- An outline repository layout identifying areas for repository panels and accesses
- An assessment of whether there are constructability issues and, if so, how they would affect RC selection
- Identification of further PI (and DI) targets related to constructability and more detailed design work.

(6) Task 2.6: Checking the feasibility of long-term safety

Based on SDM version 0.5 and the preliminary repository design assessments of task 2.5, it is possible to update the assessment of the feasibility of assuring long-term safety. This feasibility check is essential for deciding whether to continue the PI and for planning how they should be completed. Additional aspects of the performance of this task are discussed in the RC report for FY 2006 and in Kitayama et al. (2007).

Responsibility for the task

Checking the feasibility of long-term safety is the task of the PA group.

Issues to be considered for this task

Checking the feasibility of assuring long-term safety will involve a systematic evaluation of all (potential) critical issues identified during the LS on the basis of the understanding obtained in SDM version 0.5. At this stage, the evaluation would go further and may also involve (simple) quantitative analyses; it should also assess whether there are additional critical issues. The following can be considered:

- Updating the groundwater flow model (based on the hydraulic description in SDM version 0.5)
- Assessing conditions that could impair the functioning of the EBS for the intended RC(s).
- Retention properties of the host rock and the "near" far-field (hydraulic conductivity, flow distribution, potential for sorption) and variation with time.
- Exploitable resources and other issues related to human intrusion.

One possibility for judging the feasibility of long-term safety would be to compare the site conditions as described in SDM version 0.5 with the conditions assumed for H12 (if relevant).

It should also be noted that regional migration, or the length of the radionuclide transport path, is generally of very little significance for assuring the long-term safety of a RC. Generally, most RCs depend on containment or excellent retention in a relatively restricted (e.g. 100s of meters) volume of rock, while migration in the far-field adds little to safety. These aspects need only be considered in the later preparation of the safety case.

Main outcome

The main outcome of this task would be:

- Confirmation of the feasibility of long-term safety and a judgment whether there is good reason to continue to borehole investigation phase 2
- Feedback on what uncertainties in the SDM version 0.5 appear to be most important to resolve – as well as whether there are additional critical issues (will provide a revised list of issues and targets for borehole investigation phase 2)
- Evaluation of the PI program: are the critical issues properly addressed – or is there a need for re-focusing?

- Key aspects of groundwater flow (e.g. overall groundwater flow regime, dominant flow path, residence time (indication for groundwater dating), prediction of dominant discharge area)
- Feedback on potential repository concepts – if a selection is to be made.

2.3.4 PI - borehole investigation phase 2

Borehole investigation phase 2 is an extension of phase 1 and should generally follow the overall targets of the PI. However, selection of host formation(s) and the RD/PA assessment made using SDM version 0.5 should allow this phase to be focused on the potential host formation and on issues/targets judged to be particularly important after assessing the results of phase 1. It should also be noted that borehole investigation phase 2 need not necessarily be restricted to boreholes – depending on targets and site conditions there may be a justification for carrying out additional complementary geophysical investigations (particularly if borehole investigations call into question hypotheses made on the basis of geophysical investigations or are in apparent contradiction to them).

(1) Task 3.1: Define PI targets for borehole investigation phase 2

The hypotheses and uncertainties identified in SDM version 0.5, the repository construction issues identified in task 2.5 and the issues relating to long-term safety (task 2.6) are used to define detailed targets for the completion of the PI. These targets are usually resolved by drilling additional boreholes, but complementary geophysical investigations may also be important.

Responsibility for the task

Defining PI targets for borehole investigation phase 2 is a joint task of the SC/RD/PA groups.

Issues to be considered for this task:

The main objective of the phase 2 investigations is to obtain information on selected host formations. Refined target and priorities will be selected based on SDM version 0.5 and the assessments made by RD and PA.

Required input from the RD/PA group for this task

Refined targets and priorities are based on the outcome of task 2.4 "Pre-selection of host formations", task 2.5 "Checking the feasibility of repository construction" and task 2.6 "Checking the feasibility of long-term safety". The RD/PA groups should address the need for additional refined information from the site considering:

- Reassessment of RD/PA significance of the key issues already identified in the site characterization plan

- Potentially interesting host formations where investigations can be focused, considering both the properties of the host formations and the required footprint of the RC in these formations.
- Identification of further PI (and DI) targets related to constructability and more detailed design work (output from "Checking the feasibility of repository construction")
- Feedback on what uncertainties in the SDM version 0.5 appear to be most important to resolve – as well as whether there are additional critical issues (output from "Checking the feasibility of long-term safety" and "Checking the feasibility of repository construction").

Main outcome

The main outcome is an agreed set of prioritized targets and an outline of borehole investigation program phase 2.

(2) Task 3.2: Borehole investigation phase 2 – characterization of host formations

This task includes the detailed planning and execution of the phase 2 investigations.

Responsibility for the task

Investigation phase 2 is the task of the SC group supported by contractors for borehole drilling and investigations.

Issues to be considered for this task

The main issue to be considered for this task is the detailed planning of the phase 2 investigations and executing this program. Among others, the following issues should be considered:

- Optimum locations of boreholes for meeting targets, e.g. crossing crucial features and penetrating as many rock formations of interest as possible
- In the case where the critical features are sub-vertical, inclined or controlled boring will be considered
- Constraints regarding borehole locations, including legal and practical restrictions, and reconsideration of whether boreholes can be drilled through the potential repository area (based on feedback from the RD/PA group)
- Investigations need not necessarily be restricted to boreholes – depending on targets and site conditions there may be a justification for carrying out complementary geophysical investigations.

When performing the program, it is also necessary to be prepared to redirect efforts in the event that investigations are not fulfilling the specified goals.

Required input from the RD/PA group for this task

The key input for this task from the RD/PA group is determined by the targets of task 3.1 (see Section 2.5.1). In addition, the following input is needed:

- Whether boreholes can be drilled through the potential repository area. The answer will depend on the repository concept, the size of footprint in relation to potentially available host rock volume and on perceived problems in later sealing of boreholes
- Feedback during the borehole investigations in case there is a need to modify the investigations.

Main outcome

The main results are the data from the investigations with assessed measurement uncertainty. These data, which form the input to SDM version 1.0 (see next section) would potentially include:

- Data on the geometry of the host formation and on the location of layout-determining features potentially affecting the size of the host formation
- Additional data on key host formation properties (mechanical, thermal, hydraulic)
- Detailed hydrogeochemical data sufficient for understanding hydrogeochemical processes of importance for the long-term evolution of the EBS (a reasonable set of data on current groundwater composition and on fracture and rock mineralogy along flow paths where groundwater composition changes)
- Data of importance for assessing migration properties (flow distribution, potential for sorption and diffusion, etc.) of the potential host formations and surrounding rock judged to be important for radionuclide retention
- Data on rock engineering properties – issues of concern for access (e.g. depth of overburden, occurrence of weak rock, water problems).

(3) Task 3.3: Construction of SDM version 1.0

After completion of the PI phase, SDM version 0.5 is updated into SDM version 1.0. This SDM is important for concluding the PI stage. More specifically, it provides a geo-dataset for use in design, PA, a preliminary safety case and in planning the DI stage.

Responsibility for the task

Site descriptive modeling is the task of the SC group, but it has to address the needs of the RD/PA groups.

Issues to be considered

Issues to be considered in constructing SDM version 1.0 include:

- Addressing the targets set out for the PI phase (see task 3.1)
- More focused information on the potential host formations will be included
- Compiling the input needed for RD and PA
- Addressing overall confidence and uncertainty.

Required input from the RD/PA group

The RD/PA group should already have provided their main input to the targets and plans for surface and geophysical investigations and to the borehole investigation plan. However, the RD/PA group also needs to provide feedback on the derivation of the geo-dataset for use in PA and design.

Main outcome

The main outcome of this task is the SDM version 1.0. Its focus will need to be related to the targets set out by RD and PA, but would likely include:

- Refined geometry of the host formation – confirmed location of layout-determining features potentially affecting the size of the host formation
- At least a statistical description of the spatial variability of key host formation properties (mechanical, thermal, hydraulic)
- Current distribution of groundwater composition and a reasonable understanding of geochemical processes of importance for long-term evolution of the EBS
- At least a statistical description of the spatial variability of the migration properties of the potential host formations and surrounding rock considered important for radionuclide retention
- Engineering properties of host rock and potential access routes
- Likely evolution of the site (particularly groundwater flow and composition) and associated uncertainties
- Information of relevance for assessing dilution in aquifers/surface waters and evolution thereof
- Quantification (as well as alternative hypotheses if needed) of key uncertainties related to PI targets.

(4) Task 3.4: Preliminary selection of host formation(s)

Generally, this task will be similar to the pre-selection made after SDM version 0.5, but with the added knowledge provided by SDM version 1.0. An overriding question is whether SDM version 1.0 has altered any of the facts considered when selecting formations after SDM version 0.5.

Responsibility for the task

The preliminary selection of host formations is a joint task of the SC/RD/PA groups.

Issues to be considered for this task

The selection should be based on NUMO's "Guideline for host rock selection". Issues would be similar to those for the preliminary selection made after SDM version 0.5, i.e.:

- Relation to potential surface facilities
- Identification of options – are there any – or is the selection evident?
- Volume and properties of the different formations
- Assessment of the potential for exploring different options.

Required input from the RD/PA group for this task

Input would be similar to that provided after SDM version 0.5, but considering the new information, and would generally be a qualitative assessment of the potential success of different RCs in the different potential host formations. This assessment would include:

- Footprint needed
- Potential strength of the safety case to be made
- Engineering challenges.

Main outcome

The main outcome of this task are the selected host formation(s) – as well as the arguments made for their selection (important part of the safety case). Given the selection of the host formation, it also has to be considered whether it is necessary to renegotiate the location of the surface facilities.

(5) Task 3.5: Refined repository design

Even if a repository will only be constructed after the detailed investigation stage, a refined repository design in three dimensions is needed both for assessing the potential for constructing a safe repository at the site and to provide input for planning of the DI. Evidently, the DI need to be focused in the repository volume and it is also likely that the underground access routes used for the DI will be part of the access routes to the final repository.

Responsibility for the task

Clearly it is the task of the RD group to refine the repository design.

Issues to be considered

There are several issues to be considered in developing a refined repository design, including:

- Safety-related requirements (restrictions on materials to be used, thermal requirements, respect distances, acceptance criteria, etc.)
- Tunnel/cavern stability requirements (e.g. disposal and access tunnels, cavern for working area)
- Environmental issues
- Minimization of footprint (consistent with other requirements)
- Operational safety (both related to underground construction work and radiation protection during operation)
- Efficiency and practicability of construction and operation
- Cost (probably not a key issue at this stage, but still an element of engineering feasibility).

Input needed from SC and PA

Refining design obviously requires SDM version 1.0 as input. However, the PA group also needs to provide input on the basis for setting requirements on the host rock and the EBS. Such requirements may include:

- Thermal (e.g. bentonite temperature < 100 degrees C) and mechanical and chemical loads that the design should be able to handle
- Respect distances to layout-determining features
- Avoidance criteria for disposal tunnels if judged necessary.

These requirements would need to be developed from the PA work based on SDM version 0.5. The requirements may be modified after the full safety assessment (see below). In practice, this input tends to be developed as an iterative exercise between RD and PA, since requirements will change depending on the details of the design (e.g. depending on the thickness of the buffer, it may be acceptable for some of the buffer to experience temperatures above 100 degrees C).

Main outcome

The main outcome of this task includes:

- A refined repository layout including access routes and the location of the underground excavations needed for the DI
- A first version of "production line reports", defining the initial state for PA and identifying issues of concern for further assessment
- Feedback to DI on key uncertainties that would require additional site data to be sufficiently resolved
- Feedback to PA on requirements that pose design problems – can they be modified?

2.3.5 Assessment of PI findings and developing input to the DI stage

The main results of the PI are the SDM version 1.0 and the refined repository layout. This information is then to be analyzed in a full safety assessment made to support a decision to continue with a DI stage as well as for planning the DI stage if this is decided.

(1) Task 4.1: Full safety assessment

Given the mass of information obtained in the PI and the substantial commitment to continuing to the DI stage, it is essential to assess the long-term safety of proposed repository concepts at the site.

Responsibility for the task

Conducting a safety assessment is the task of the PA group.

Issues to be considered

The full safety assessment should apply a state-of-the-art PA methodology covering all aspects expected to be part of a full PA (see Kitayama et al., 2007). However, since this is not part of a license application a formal comparison with regulatory criteria may still be unnecessary. The assessment should thus include:

- Repository evolution (groundwater flow, hydrogeochemistry, mechanical, thermal)
- Resulting performance (dose/risk, etc.) for assessed RCs at the studied sites
- Identification of remaining outstanding issues of key importance for safety (i.e. affecting long-term stability of the EBS and/or radionuclide migration) and assessment of their importance
- Identification of the main safety features (safety arguments)
- Assessment of the long-term safety implications of the remaining uncertainties regarding the

site as identified and quantified in SDM version 1.0

- Implications for repository EBS design at the different sites (e.g. need for special containers, buffer material, dimensions, etc.). Assessment whether all requirements set out for the detailed design are necessary or if they could be relaxed
- Implications for repository excavation design and layout at the sites – rock excavation: Are there site-specific design constraints that need to be observed in order to ensure safety
- Assessment of whether additional requirements may be necessary.

Main outcome

The main outcome of this task is the safety assessment report version 1.0.

(2) Task 4.2: Compiling RD/PA implications for the DI stage

The uncertainties and key remaining issues identified in SDM version 1.0, in the refined layout and in the safety assessment report version 1.0 form input for planning the RD/PA activities of the DI phase.

Responsibility for the task

This is a joint task of the RD/PA/SC groups

Issues to be considered

The following issues should be considered:

- Key remaining issues as identified in the full safety assessment (see task 4.1)
- Safety-related restrictions on underground access (location of access, groundwater control, chemicals that can be used, etc.)
- Plans for verification of assumptions made on rock conditions and engineering feasibility (to be executed during the DI phase)
- Characterization targets for the DI phase.

Main outcome

The main outcome of this task is a report or memo compiling the RD/PA implications for the DI stage.

(3) Task 4.3: Developing a preliminary safety case

Even if not formally required for proceeding to the DI stage, it would be good to develop a preliminary safety case based on the findings during the PI stage. This preliminary safety case would be based primarily on the safety assessment version 1.0, but would also consider other aspects that are part of a safety case. Furthermore, an outline for the preliminary safety case should be developed at an early stage (first version already at the LS stage), since this will provide considerable guidance on what to consider during the PI.

Responsibility for the task

Developing the safety case is a joint task of the PA, RD and SC groups.

Issues to be considered

The preliminary safety case should at least consider the following:

- The full safety assessment and its list of safety arguments and remaining issues is a key component of the safety case
- How the host rock, repository depth and repository design were arrived at (information to be found in the detailed design work)
- Summarize what makes the repository design at the site safe
- Address engineering feasibility (as further described in "production line reports")
- Summarize confidence in SDM version 1.0 – is there anything else to consider in addition to the input given to PA (i.e. is the degree of understanding robust)?
- List remaining issues and address whether they concern optimization. If remaining issues fundamentally concern feasibility, a decision to go underground is probably premature
- Outline plan for resolving remaining issues
- Make it reasonable for the remaining issues to be resolved by the data obtained during the DI or from other planned R&D
- List complementary safety arguments
- Make a final statement on safety.

Main outcome

The main outcome of this task is a documented preliminary safety case.

(4) Task 4.4: Identify R&D topics required for DI

The preliminary safety case and its supporting documentation is the main source for identifying R&D topics that need to be addressed during the DI stage. It should be noted that such R&D need not necessarily be restricted to underground investigations. There may be many issues that would require further technical development (i.e. in the laboratory) and it may also be worthwhile to continue with some surface-based borehole investigations.

Responsibility for the task

Identifying R&D topics required for DI is a joint task of the SC/RD/PA groups.

Issues to be considered

The main issues to be considered are those remaining from long-term safety, engineering design and site understanding as identified when developing the preliminary safety case (see above). It should be assessed whether further resolution of these issues is needed (input from the preliminary safety case).

Input needed from RD/PA

The main input needed from RD/PA is a list of remaining critical issues from the design work, the safety assessment version 1.0 and from the preliminary safety case.

Main outcome

The main outcome of this stage will be an R&D program for the DI stage.

3 Scenario development

3.1 Background

Scenario development is a key stage in any PA. Scenarios define the sequences of events and processes to be considered in determining, as a function of time, the possible ways in which a geological repository will perform (or fail to perform) its fundamental roles of isolating the waste from the human environment and containing its radionuclides.

The IAEA's Radioactive Waste Management Glossary (IAEA, 2003) defines a scenario as:

"A postulated or assumed set of conditions and/or events. They are most commonly used in analysis or assessment to represent possible future conditions and/or events to be modelled, such as possible accidents at a nuclear facility, or the possible future evolution of a repository and its surroundings".

As explained, for example, in SKI's SITE-94 PA (SKI, 1997):

"Scenarios are not predictive devices, but are means of stimulating and disciplining the imagination so as to provide an organised way of illustrating possible future behaviour of the system and defining how such behaviour might arise".

A specific set of objectives for scenario development was identified at an OECD/NEA workshop on scenario development in 1999 (NEA, 2001):

(1) "To demonstrate or try to ensure completeness or sufficiency in the scope of a PA".
It should, for example, be ensured in scenario development that all relevant scientific knowledge is taken into account.
(2) "To decide which FEPs to include in a PA and how to treat them".
A clear rationale should be provided for excluding FEPs, e.g. on the basis of irrelevance to assessment scope, low probability, etc.
(3) "To provide traceability from data and information to the PA scenarios, models, parameter values, and calculation cases".
Scenario development should provide a documented link between scientific understanding (including uncertainties) and the assessment cases chosen for analysis.
(4) "To promote transparency and improve comprehensibility of the PA and the PA results".
Thus, the above link should be clear and understandable.
(5) "To guide decisions concerning future work".

Scenario development should provide a systematic way of identifying (and prioritizing) critical uncertainties and unresolved issues.

Since H12, progress has been made in developing methodologies that satisfy these various objectives. The aim of this Chapter is to indicate some particular areas of progress that NUMO could consider when evaluating the applicability of the H12 methodology (or revised methodologies provided by JAEA) in future Japanese PAs.

Scenario development in H12 is summarized and reviewed in Section 3.2. Some aspects of scenario development in more recent PAs are discussed in Section 3.3, focusing on the methodologies applied in the Swiss Project Opalinus Clay (Nagra, 2002a) and the Swedish SR Can project (SKB, 2006). The focus is on: (i) the link between scientific understanding (including uncertainties) and the assessment cases chosen for analysis – including the recognition that this is a "top down" rather than "bottom up" process and (ii) the issue of completeness (i.e. objectives 1 and 3 above), since these are identified as areas where the H12 methodology could particularly be enhanced.

The use of some aspects of scenario development to guide decisions concerning future work (objective 5 above), which may be of more immediate relevance to NUMO, is discussed in Section 3.2.3.

3.2 Scenario development in H12

3.2.1 Classification of scenarios in H12

As illustrated in Figure 3.1, two groups of scenarios were defined in H12 (JAEA, 2000), as required by the Atomic Energy Commission of Japan (AEC) guidelines:

- Groundwater scenarios
- Isolation failure scenarios.

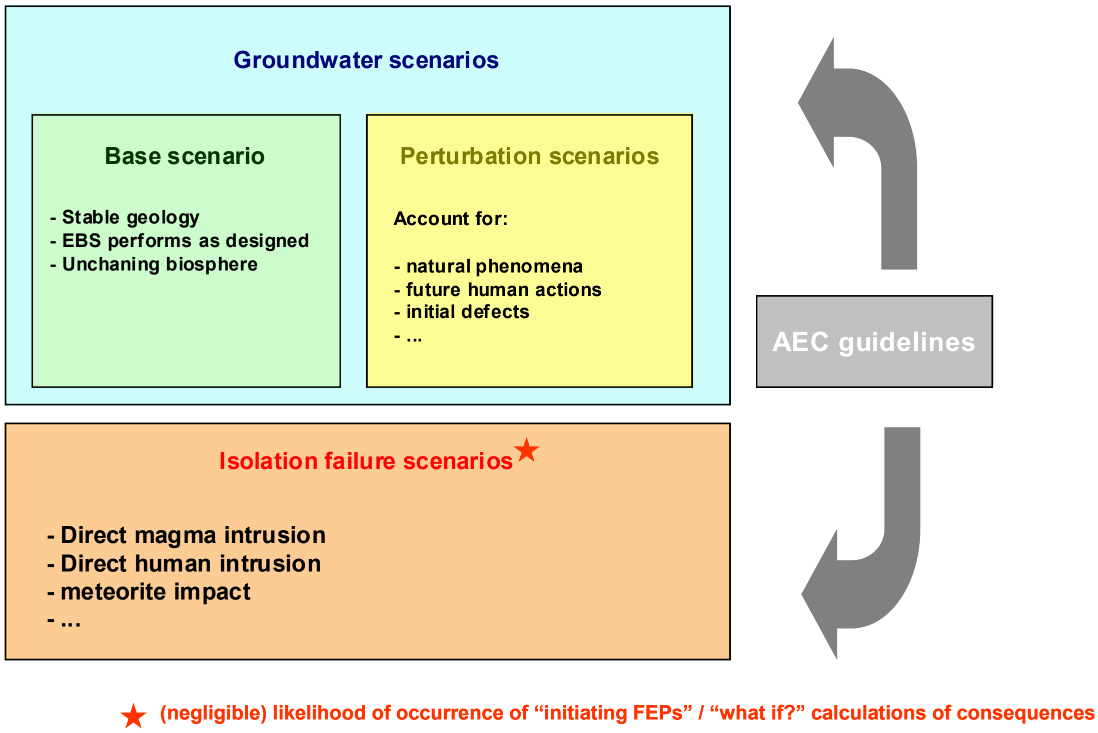

Figure 3.1 Classes of scenarios in H12.

Groundwater scenarios are those in which groundwater provides the principal pathways by which radionuclides could reach the human environment. These were further subdivided into:

- A base scenario, in which the repository was assumed to be implemented according to design specifications, the EBS was assumed to evolve broadly as expected, the geological environment was assumed to be stable and the biosphere was hypothetically assumed to remain unchanged over the entire timeframe addressed in the PA
- Perturbation scenarios, in which one or more of the above assumptions was changed as a result, for example, of some postulated natural phenomena or future human actions.

The groundwater scenarios were considered to have a non-negligible likelihood of occurrence and were analyzed in detail in the main part of the PA. The isolation failure scenarios, on the other hand, which included scenarios such as direct magma intrusion into the repository, could be excluded from the main part of the PA, for example on the grounds that siting criteria would render them impossible or of negligible likelihood. Their consequences were nonetheless evaluated in additional "what-if?" calculations in order to illustrate the robustness of the H12 concept.

3.2.2 Scenario development procedure in H12

The scenario development procedure adopted in H12 is illustrated in Figure 3.2.

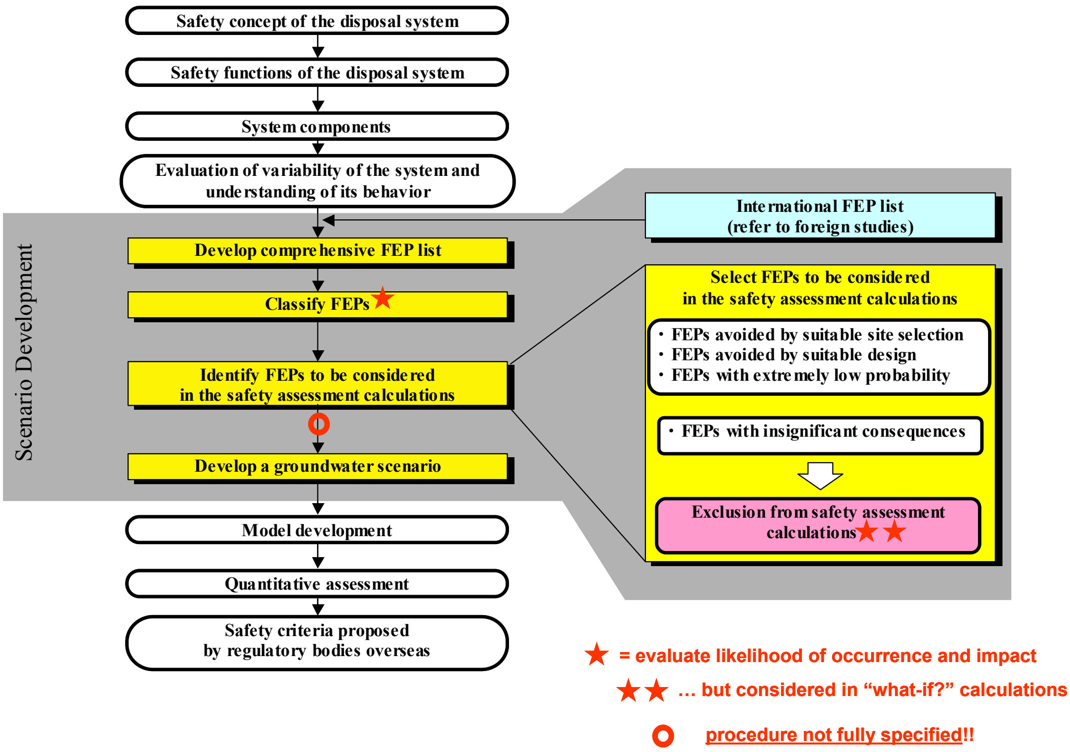

Figure 3.2 H12 scenario development procedure.

The procedure consists of the following steps:

Step 1: On the basis of the available scientific understanding of the characteristics and evolution of the repository and its environment, a comprehensive list of concept-specific features, events and processes (FEPs) is developed and checked for completeness against international FEP lists.

Step 2: The FEPs are classified according to their likelihood of occurrence and possible impact on system evolution.

Step 3: On the basis of this classification, a decision is made as to which FEPs to carry forward in the main part of the PA (either as part of the base scenario or as part of one or more perturbation scenarios) and which FEPs to exclude (though possibly considering them in "what-if?" calculations).

Step 4: Groundwater scenarios are developed from the FEPs carried forward, but the procedure used is not fully specified (Section 3.2.3, below).

3.2.3 Limitations of the H12 methodology

In H12, in common with most descriptions of PA methodologies at the time, it is stated or implied that PA scenarios are synthesized from collections of individual FEPs. The procedure by which this is achieved is, however, not clearly specified.

The base scenario is said to emerge "bottom-up" from the constituent FEPs and this base scenario is used to generate an influence diagram. The influence diagram shows which FEPs influence (or are influenced by) other FEPs in this scenario. It is then stated that the base scenario influence diagram is used to evaluate the impact of events and processes on safety functions. Again, how these events and processes are selected and how the influence of the safety functions is assessed is unclear in the H12 documentation.

More recent PAs have sought to address these limitations, as described in the following sections.

3.3 Scenario development in more recent PAs

3.3.1 Recognition that scenario development is a “top-down” process

Although several PAs at the time of H12, including H12 itself, state or imply that scenarios are synthesized in a "bottom-up" fashion from individual FEPs, none outline an explicit procedure describing how this synthesis is achieved. Nagra recognized at the time of Project Opalinus Clay that the actual procedure by which assessment cases (scenarios and the models and datasets used to assess them) are identified is rather a series of judgements based on a description of the characteristics and evolution of the system that is as full and accurate as possible, including a description of uncertainties and resulting possible deviations from expected evolution.

According to the safety report of Project Opalinus Clay (Nagra, 2002a):
"The identification of individual assessment cases is a matter of expert judgement, guided by:
Understanding of the system and its evolution ...; and
Understanding of the fate of radionuclides in the Reference Case, and sensitivity to various conceptual assumptions and parameter variations ..."

The process is thus a "top-down" one, in which the starting-point is not a fragmented set of FEPs, but rather a comprehensive system description. This is almost certainly the process that was, in reality, also adopted in H12, in which case the H12 scenario development methodology would perhaps more accurately be represented as shown in Figure 3.3, in which there is a direct link from the "evaluation of variability of the system and understanding of its behavior" to "developing a groundwater scenario". In this description of the approach, the role of FEP lists is to support "completeness checking", i.e. to ensure that no important phenomena have been overlooked in the scenarios and assessment cases, as described in Section 3.3.3.

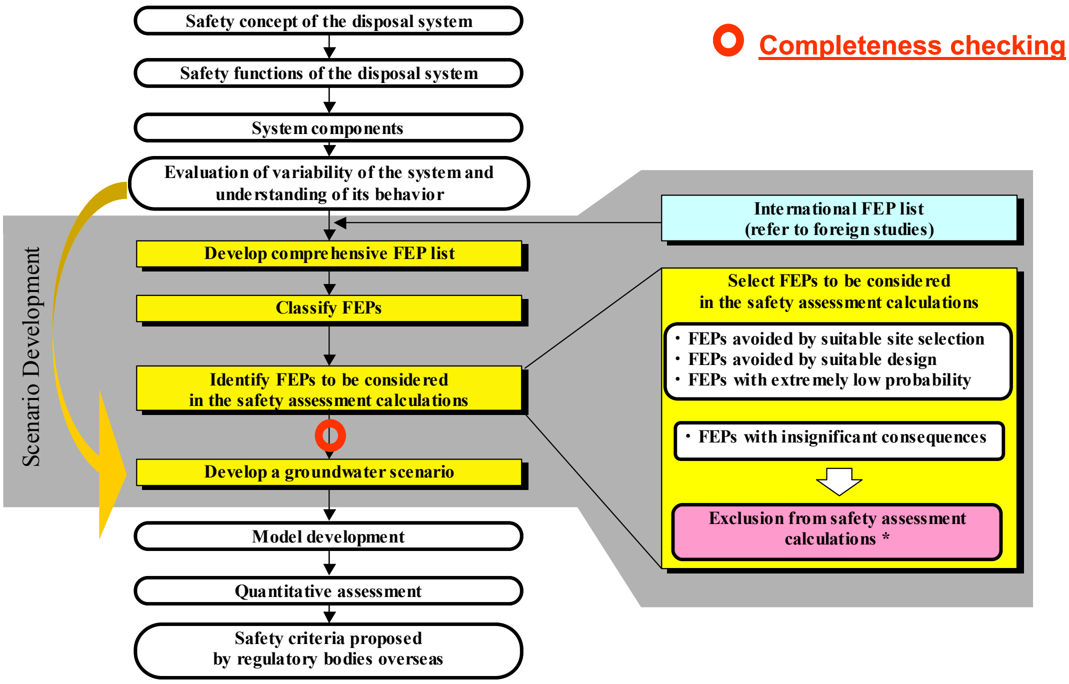

Figure 3.3　Alternative view of the H12 scenario development procedure.

3.3.2 Identification of individual scenarios

The identification of scenarios in PA is part of the wider task of uncertainty analysis. Safety assessments treat uncertainties primarily by defining and analyzing a wide range of assessment cases – i.e. specific model realizations of different possibilities or illustrations of how a system might evolve and perform. Each of the cases, which may be analyzed deterministically, probabilistically or by some combination of these approaches, addresses the impact of some particular uncertainty or combination of uncertainties.

Most PAs define a base, or reference, scenario, generally representing the expected or more likely evolutionary paths of the disposal system, and a set of alternative scenarios representing substantially different and generally less likely evolutions compared to the base or reference scenario. They also generally define a number of individual assessment cases representing more minor variants within each scenario.

Organization of assessment cases

The organization of assessment cases within scenarios is an operational matter that can vary substantially between different PAs. One approach is to categorize uncertainties as, for example, scenario uncertainties, model uncertainties and parameter uncertainties (see Box 1); it should however be noted that, in any such scheme, categorization is always somewhat subjective and dependent on the chosen models and assessment approach. A scenario is then represented by a group of individually analyzed cases. Within each scenario group, sub-groups of cases address alternative possibilities arising from conceptual model uncertainties. Finally, individual cases within each sub-group address alternative possibilities arising from parameter uncertainties. This is the approach used in the Swiss Project Opalinus Clay. The resulting hierarchy of assessment case groupings is illustrated schematically in Figure 3.4.

Box 1: **Example of a categorization scheme for different classes of uncertainty (after NEA, 1997)**

A scenario represents a set of FEPs and interactions. *Scenario uncertainty* results from difficulties in identification of a complete set of scenarios, a complete set of FEPs for each scenario and correctly identifying which interactions between significant FEPs must be considered in a PA.

Conceptual model uncertainty refers to uncertainty about the model used to represent a given set of FEPs and interactions, or choice of models. Simplifications introduced, for example by applying one- or two- dimensional PA-models is part of the conceptual model uncertainty, as is the uncertainty introduced by selecting a scale of spatial/temporal representation.

Parameter uncertainty refers to uncertainty in the parameter values to be used in a (given) conceptual model.

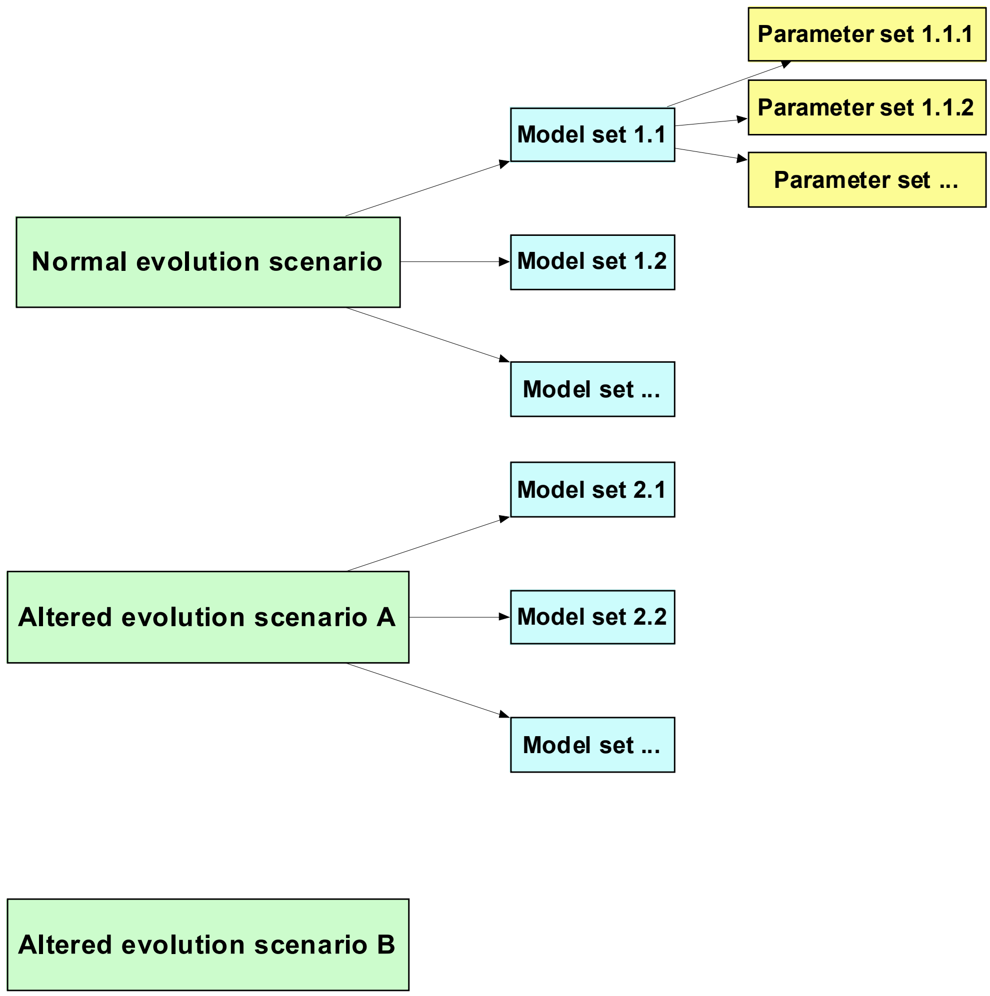

Figure 3.4 Schematic illustration of the structuring of assessment cases, with each case consisting of a scenario, a model set and a parameter set.

In Project Opalinus Clay, alternative scenarios and assessment cases were selected by considering the range of influence of the possible deviations from the expected evolution of the disposal system, as illustrated in Figure 3.5. The expected evolution scenario is represented by the green box across the top of the diagram. In this scenario, the clay barrier (i.e. the bentonite and Opalinus Clay together) is largely undisturbed by the phenomena occurring and provides effective isolation of the waste by limiting mass transport of radionuclides over very long periods of time. The possible deviations from the expected evolution for all significant phenomena that influence repository performance are listed in the column on the left. For each phenomenon, the bar represents the domain over which there may be an influence. For example, alternative climates influence only the biosphere, thus the bar extends through this domain only. The color coding represents transport through the host rock (black) and the tunnel and seal system (grey), with red bars representing "what if?" cases.

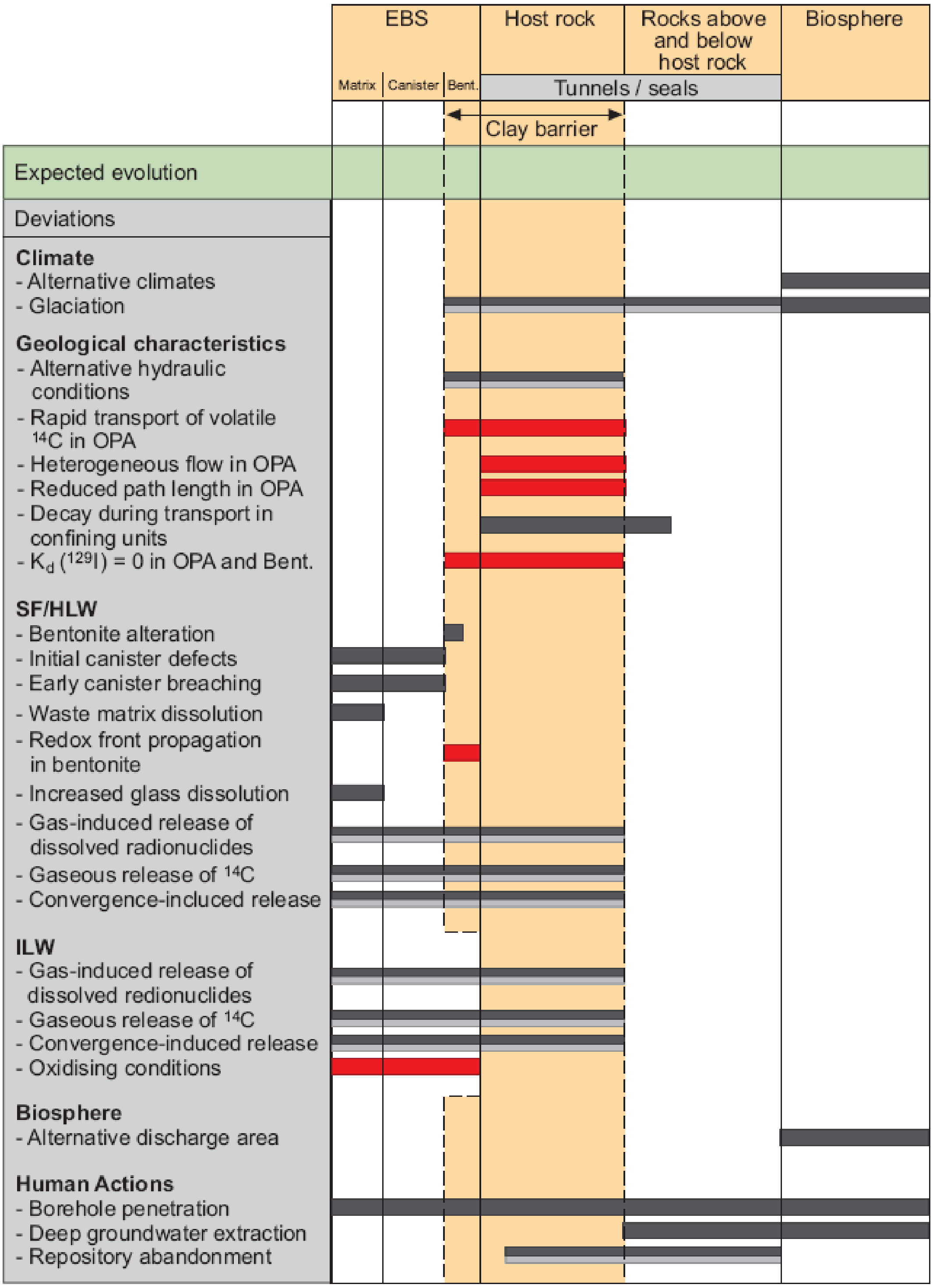

Figure 3.5 Range of influence of possible deviations from the expected evolution of the Project Opalinus Clay disposal system (after Figure 5.7-1 in Nagra, 2002a).

Safety functions and pillars of safety

The NEA review of Project Opalinus found that there was clear linkage from uncertainties to PA assessment cases (NEA, 2004). It also noted, however, that concepts such as safety functions and pillars of safety, which are central to the safety case, were not linked to scenario development. This linkage has received much attention in the recent Swedish SR-Can PA (SKB, 2006).

The methodology used to identify variant scenarios is based on that developed for SR-Can. It consists of the following steps:

- **Step 1: Consider the main safety functions of each of the main components of the disposal system**
  These main components are essentially the overpack, the buffer and the host rock. The safety functions of the host rock include, for example, the protection of the EBS and providing a transport barrier to any radionuclides released following overpack failure.
- **Step 2: For each safety function, identify one or more "safety function indicators"**
  A safety function indicator is a measurable or calculable property of the system that is critical to a safety function being fulfilled. For example, an adequate buffer density is critical to colloid filtration, which is (whether explicitly stated or not) one of the buffer safety functions in all repository concepts employing a clay buffer.
- **Step 3: For each safety function indicator, derive "safety function indicator criteria"**
  Safety function indicator criteria specify the range of values that the safety function indicators should have if it is to be assumed in PA that the corresponding safety functions are fulfilled. Examples of safety function indicators and criteria for the SR-Can canister and buffer are given in Figure 3.6. It should be noted that overall system safety does not depend on all criteria being met at all times – i.e. they are not "safety requirements". Rather, if a situation (scenario) can be envisaged in which a criterion is not fulfilled, then the consequences of the loss of the corresponding safety function need to be assessed in the PA.
- **Step 4: Build a model of the system and assess its evolution – with focus on the fate of the safety functions**
  A major effort is needed in building a model of how the system, and especially the safety functions, would evolve. This system model is used as input to the next step.
- **Step 5: Identify the failure modes that could occur in the course of system evolution**
  Use the system model to consider what would have to happen for a particular component to cease to fulfill its various safety function indicators – and hence to fulfill its various safety functions. For example, processes leading to a loss or redistribution of buffer mass could lead to a violation of the buffer density criterion and hence to a loss in the capacity of the

buffer to filter colloids (as well as other consequences, such as advective solute transport and microbial activity in the buffer).

- **Step 6: Consider if and when the occurrence of such failure modes is plausible**
  For example, based on system understanding, could groundwater flows or changes in composition arise over the course of time that could lead to significant buffer erosion?

- **Step 7: Consider the implications of loss of one safety function on the others**
  For example, would a loss of buffer mass affect not only the safety functions of the buffer, but also canister integrity (via an increased transfer of corrosive agents to the canister surface).

- **Step 8: Identify plausible descriptions of the evolution of safety functions over time**
  These would be defined in many programs as "scenarios", although in SR-Can, because of the way in which regulatory guidance is formulated, all those that are considered "probable" are classified as variants within the "main scenario". Scenarios outside the scope of the main scenario are those that are judged less likely to occur (see Section 11.3 of SKB, 2006).

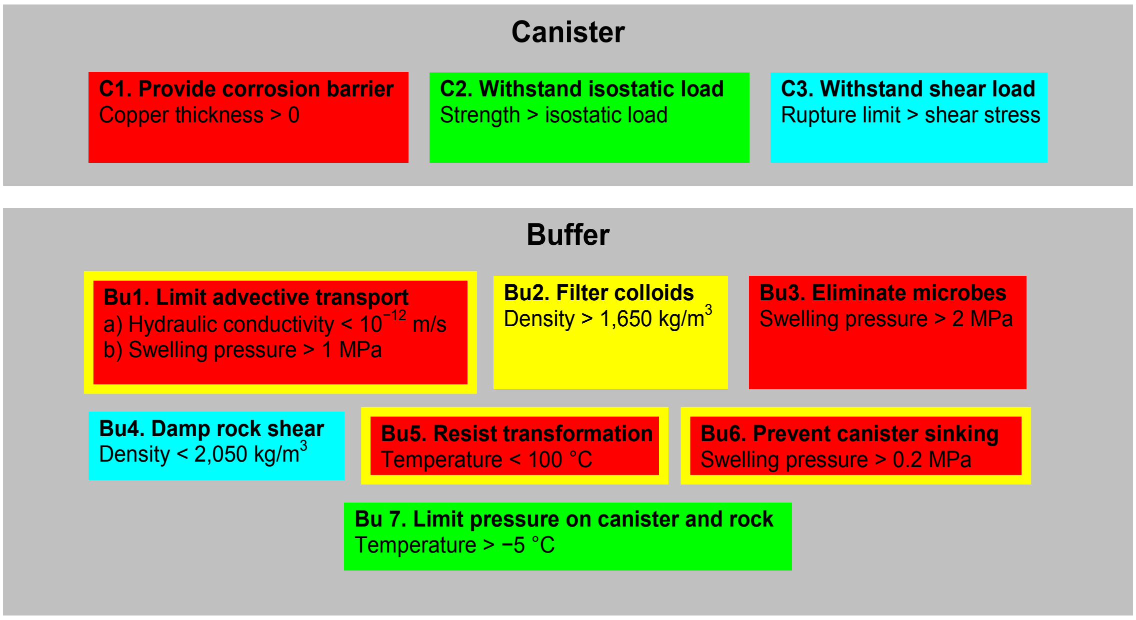

Figure 3.6 Safety function indicators and criteria for the SR-Can canister and buffer (after SKB, 2006).

3.3.3 The issue of completeness

In some recent PAs (e.g. the Swiss Project Opalinus Clay – Nagra 2002a), a distinction is made between (i) phenomenological uncertainty in how FEPs influence the evolution and performance of a disposal system and (ii) what is called in the Swiss case "completeness uncertainty", which is uncertainty as to whether all relevant features, events and processes (FEPs) and all relevant scientific understanding of these FEPs have been taken into account in the assessment. Scenario, model and parameter uncertainties, as defined in Box 1, are all phenomenological uncertainties and are the focus of the uncertainty analysis within PA. In addition, however, whether or not it is classified as a type of uncertainty, all PAs must address the issue of completeness.

It is generally recognized that completeness uncertainty cannot be eliminated. It can, however, be reduced by certain practices within PA and by certain principles in siting and design (e.g. designing for simplicity). The insensitivity of system evolution and performance to some types of completeness uncertainty can also be tested by means of "what-if?" assessment cases (see e.g. Figure 3.5).

Specific measures to reduce completeness uncertainties in recent PAs include:

- The use of international FEP lists, tailored to the system under consideration, as checklists against which to compare the assessment basis, assessment cases and the models used for their evaluation
  The use of international FEP lists as checklists is a feature of all recent PAs, including H12, Project Opalinus Clay and SR-Can. In Project Opalinus Clay, it formed part of a wider process of FEP management or "bias audit". In carrying out the project, a bias audit group was established that was responsible for ensuring that all relevant scientific understanding was taken into account in the PA and that the information and computer codes used in the PA were appropriate. The FEP management tasks of the bias audit group are shown in relation to assessment methodology as a whole in Figure 3.7 and are also summarized in Table 3.1.
- The issuing of appropriate guidelines to experts involved in the project
  In Project Opalinus Clay, for example, the experts chosen were asked (i) to take account of the views of the scientific and technical community as a whole and not simply to present their own personal opinions and (ii) to interact with others in their own field and in other relevant fields. Experts were also made aware of all available information (and its limitations) that was relevant to the judgment they were being asked to make, by giving them access, for example, to the documentation structure and centralized catalogue of all relevant documents.
- The use of structured documentation with prescribed formats
  In SR-Can, for example, the scientific understanding of each process was documented according to the structure shown in Box 2. Through the structuring of the process documents in this way, the responsible experts are obliged to consider, for example, any natural analogue studies that may be relevant to a particular process.

Box 2: **Process documentation in SR-Can**

For each process, the process reports give:

- Overview / general description
- Boundary conditions
- Model studies / experimental studies
- Natural analogues/observations in nature
- Time perspective
- Handling in the safety assessment SR-Can
- Uncertainties

- Iterative development of the system description
  In all PAs, the system description used as a basis for scenario development and analysis is likely to undergo iterative development and repeated internal and external reviews (including reviews of earlier PAs) over many years, gradually building confidence in the completeness of the description.

Table 3.1 Tasks of the bias audit group in Project Opalinus Clay.

Task	Description	Products
Develop a project-specific FEP database and check for completeness against international FEP databases	The project-specific FEP (feature, event and process) database is a structured, comprehensive list of FEPs that are potentially relevant to the disposal system under consideration, with accompanying FEP descriptions, based on international experience and the scientific understanding of the disposal system. The scope of the list is constrained by a set of assessment bounding rules. These define the bounds of the SA and exclude classes of conditions and events that are not relevant to the aims of the SA or ruled out by regulatory guidance (e.g. consideration of deliberate human intrusion). The FEP database is audited (checked for completeness) against international FEP databases.	The Opalinus Clay (OPA) FEP database for Project Opalinus Clay is given in Appendix 2 of Nagra (2002b). The audit against international FEP lists is covered in Appendix 3 of Nagra (2002b).
Identify key safety-relevant phenomena and check for completeness against the project-specific FEP databases	The key safety-relevant phenomena within the system concept and safety concept, together with their associated uncertainties, are identified and audited against the FEP database by checking that each FEP is included.	Key safety-relevant phenomena are given in Table 6.8-1 of Nagra (2002a) and in Appendix 2 of the present document. The audit against the OPA FEP database is described in Appendix 6 of Nagra (2002b).
Identify the various realizations of different phenomena ("super-FEPs") within the assessment cases and check for completeness against the project-specific FEP databases	The super-FEPs (broad groupings of related FEPs) that are represented (sometimes with alternative realizations) within the assessment cases are audited against the OPA FEP database. Provided the assessment cases have been properly derived and fully capture the key safety-relevant phenomena and their uncertainties, this audit should reveal no omissions.	The super-FEPs are given in Table 6.8-1 of Nagra (2002a). The audit against the OPA FEP database is described in Appendix 6 of Nagra (2002b).
Check that there are codes available that are suitable ("qualified") to analyze the assessment cases.	Available codes are audited against the super-FEPs that are to be represented. This may lead to the recognition of a need to develop a new code or make modifications to existing codes. Once the ability of a code to represent a given set of super-FEPs is established, the code is said to be *qualified*.	The qualification of the codes used in the project is covered in Appendix 8 of Nagra (2002b).

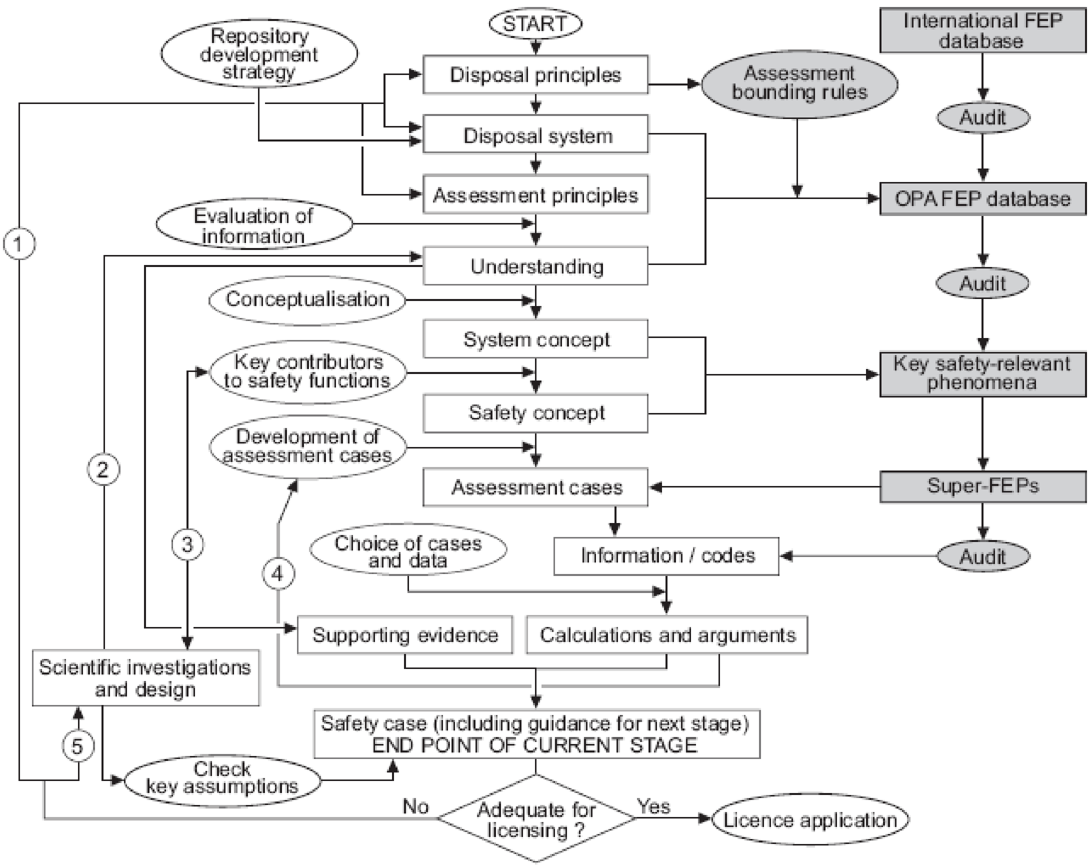

Figure 3.7 FEP management tasks (in grey) in the wider context of the Project Opalinus Clay assessment methodology (after Figure 3.7-2 of Nagra, 2002a).

Section 3.4 summarises NUMO's methodology on scenario analysis as developed at the time of writing this report.

3.4 Development of NUMO's methodology for scenario analysis

3.4.1 Introduction

The study of the scenario analysis methodologies presented in the previous sections covers the two major approaches followed to date, namely the FEP-based ("bottom-up") and the ("top-down") one based on the analysis of how the safety functions of disposal systems may be affected by relevant events and processes. Although this FEP-based "bottom-up" method can summarize and check completeness of system understanding, selecting key safety-relevant FEPs and combining them in an appropriate manner requires complex screening procedures and decision-making based on extensive multidisciplinary knowledge. In reality the complexity of the work was reduced on the basis of expert judgment, which was really the key factor on moving from large FEP lists to the limited number of scenarios considered for consequence

analysis.
The alternative ("top-down") method also requires extensive system understanding, especially to define the evolution of safety functions with time and to integrate safety-relevant characteristics into assessment cases in a transparent, traceable and comprehensive manner.
By combining the bottom-up and top-down approaches, a "hybrid" scenario analysis method has been developed. This aims to provide a traceable procedure of proceeding from a "storyboard", which depicts repository evolution with time on a range of spatial scales, to a set of scenarios that are associated with an assessment of their likelihood of occurrence. Based on a dry run of such hybrid scenario analysis, we confirmed that the storyboards could provide a platform to allow a wide range of experts to share system understanding. In addition, storyboards can form a useful interface for communication of this difficult topic with various stakeholders. The methodology is described in Wakasugi et al (2009).

3.4.2 Requirements defined for the scenario development methodology

The following requirements were specified for developing the new approach:

- Ensuring transparency and traceability
- Maintaining complete and comprehensive records of decisions
- Facilitating understanding of the associated arguments supporting decisions
- Compatibility with a staged approach to site selection
- Ease of integration of interdisciplinary knowledge
- Explicit consideration of various time frames (important to account for geological evolution of sites)
- User-friendliness
- Ability to serve as an interface with various stakeholder groups.

3.4.3 The scenario development logic and a first dry run

The general logic of the scenario development procedure ("work frame") is illustrated in Figure 3.8. This consists of a number of "Tasks" (T-1 to T-6), forming a work flow that is linked to an associated FEP Knowledge base. A provisional safety concept is the starting point of safety assessment, based on legal requirements and regulatory guidelines. This safety concept is closely linked to specific geological settings and repository concepts that are, in turn, derived from preliminary site characterization, safety assessment and repository design (NUMO, 2007). Thereafter, a key feature of the process is development of a "storyboard". Conventionally, a storyboard is a scene-by-scene description of the progress of a film which focuses on developing the story in terms of text plus images. In the present context, it refers to a time sequence of images indicating the evolution of a repository system, which includes a "zoom" representation of such evolution at different spatial scales and in different locations. The images are complemented by explanatory text, which is related to the FEPs that are relevant at any particular time for a specific repository area. Clearly this needs input from generalists, with wide experience in not only safety, but also site characterisation and repository design / engineering.

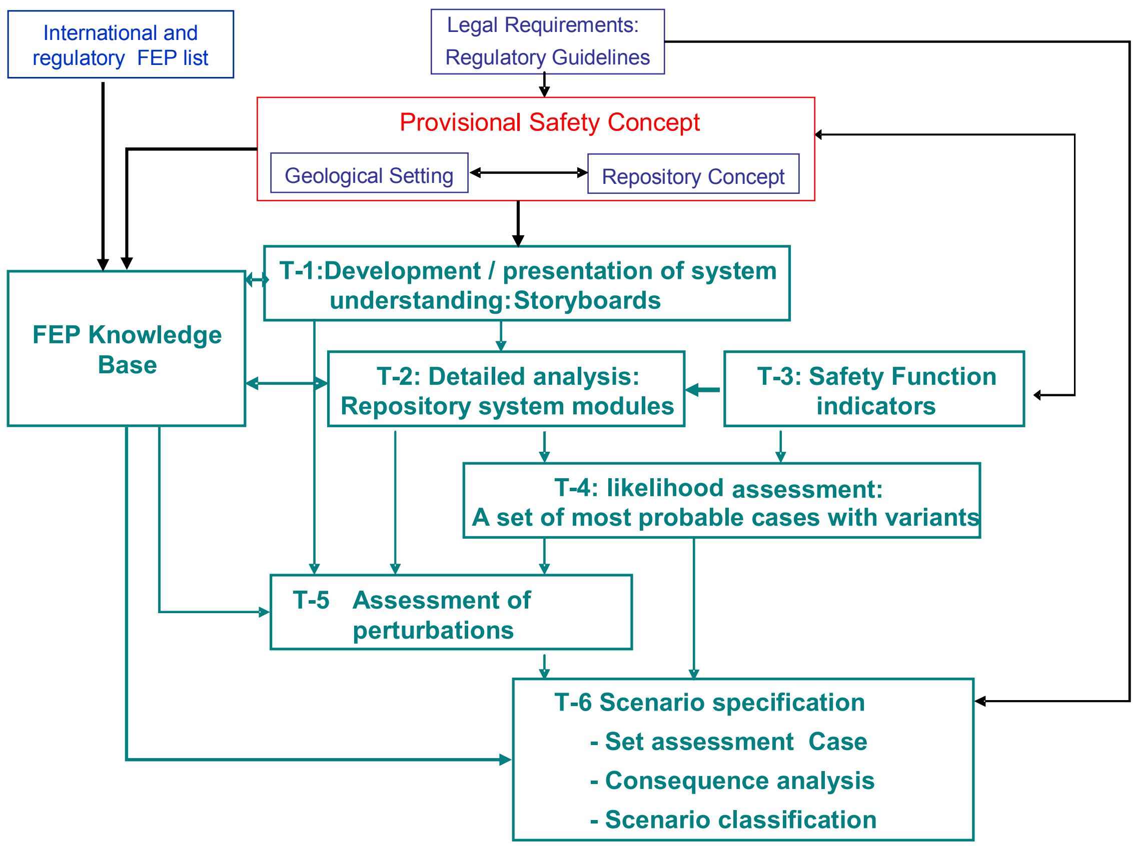

Figure 3.8 Hybrid scenario analysis workframe.

T-1 is the initial task, aimed at providing a synthesis of understanding of the technical basis for subsequent scenario development tasks. The goal is to illustrate understanding of the evolution of the key safety-relevant components of the entire repository system on the basis of the tacit knowledge of experts. A first outline must thus be produced by experienced staff with extensive system understanding (generalists). Thereafter, however, details can be refined by iteration with appropriate specialists.

As illustrated in Figure 3.9, working over storyboards can be a valuable aid to facilitating communication between geologists, design engineers and safety assessors and is an essential part of developing a safety concept. T-1 also provides the required transparency and traceability, in a manner that is easy to understand, while integrating interdisciplinary knowledge on a range of time frames and assessment scales (engineered barrier system, repository, natural barrier, surface conditions - see Figure 3.9. Assessment time frames are selected on the basis of expected periods over which key safety functions operate, which are defined in the provisional safety concepts.

T-2 provides more detailed analysis of repository system modules (e.g. Figure 3.10, for the EBS module), developing more detailed storyboards for repository system modules on the basis of safety function/indicators and simple scoping calculations (in T3). This task assesses understanding compiled within the FEP knowledge base; in some cases gaps in knowledge may be identified, which lead to requirements for future R&D work. This process acknowledges the limitations in the extent to which performance can be assessed and is, in effect, a distillation by the PA team of the extensive expert knowledge resulting from the interactions to develop the T-1 storyboards. Complex evolution can be simplified by considering thermal, hydrological, mechanical, and chemical (THMC) components separately although, in real life, these may be strongly coupled. EBS components examined are the vitrified waste, steel overpack, bentonite buffer, concrete lining and backfilling (based on the H-12 repository concept – JAEA, 2000). Time frames are as for the T-1 storyboard. 300 years after repository closure corresponds to the estimated re-saturation period of the EBS and end of significant thermal transients. 1000 years is the complete containment lifetime of the overpack as established in the reference design. After re-saturation, preferential flow will occurred in the excavated damaged zone (EDZ) which could be a key radionuclide migration pathway. The T-2 storyboard in Figure 3.10 was developed in a 1st dry run using Japanese site-specific conditions.

The relationship between the FEP knowledge base and the storyboard development tasks is illustrated in Figure 3.11. The FEP knowledge base contains not only a list of disposal system specific FEPs, but also detailed background information in terms of safety functions and inter-relationships with other FEPs. The T2 storyboards are thus developed in an iterative manner, as understanding of the site-specific evolution of specific modules is developed and compared against the required safety functions. Through this iteration, uncertainties in specific space and time frames can also be identified and documented within the T-2 storyboard.

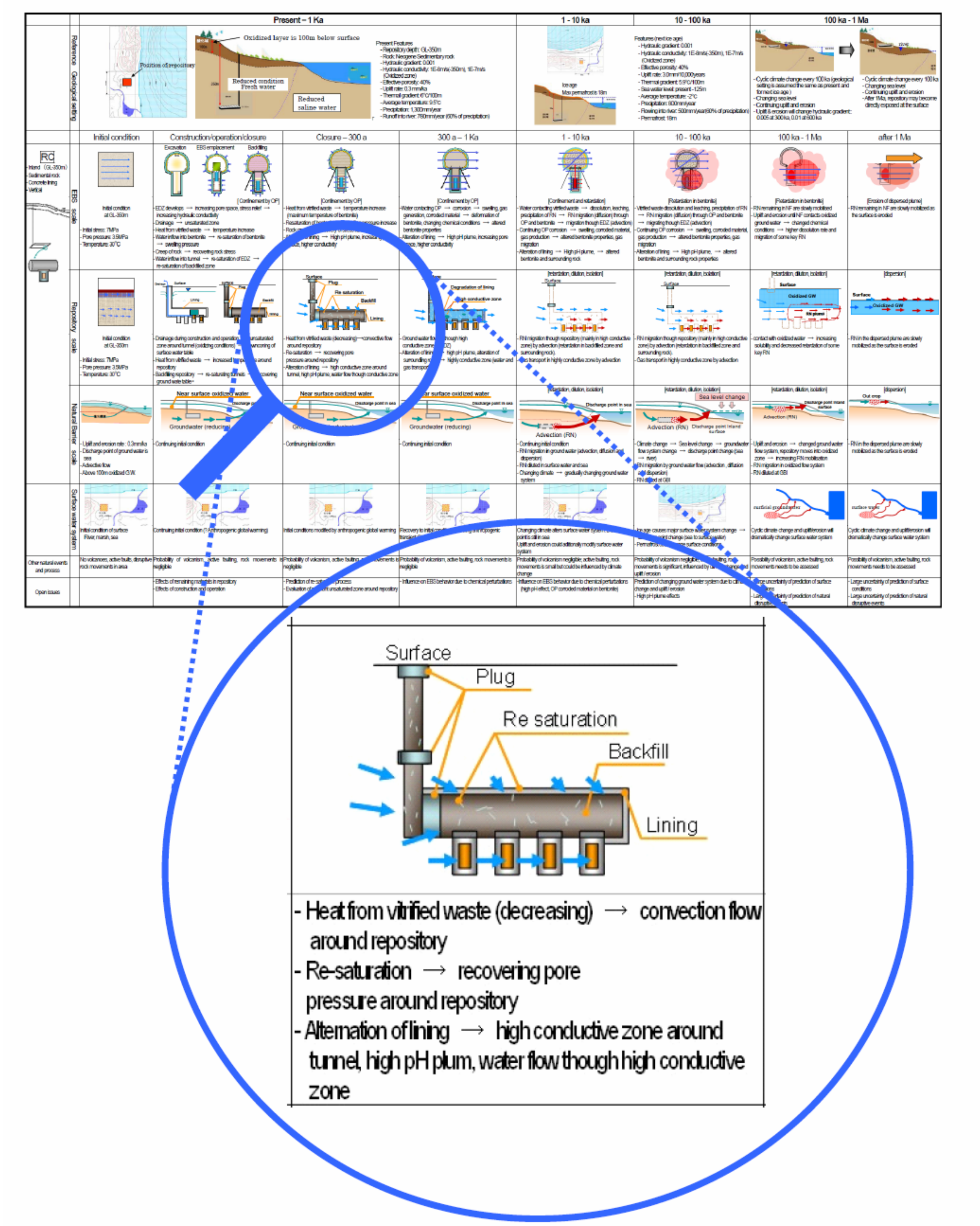

Figure 3.9 T-1 Storyboard – Overview of total system evolution based on the H-12 repository concept.

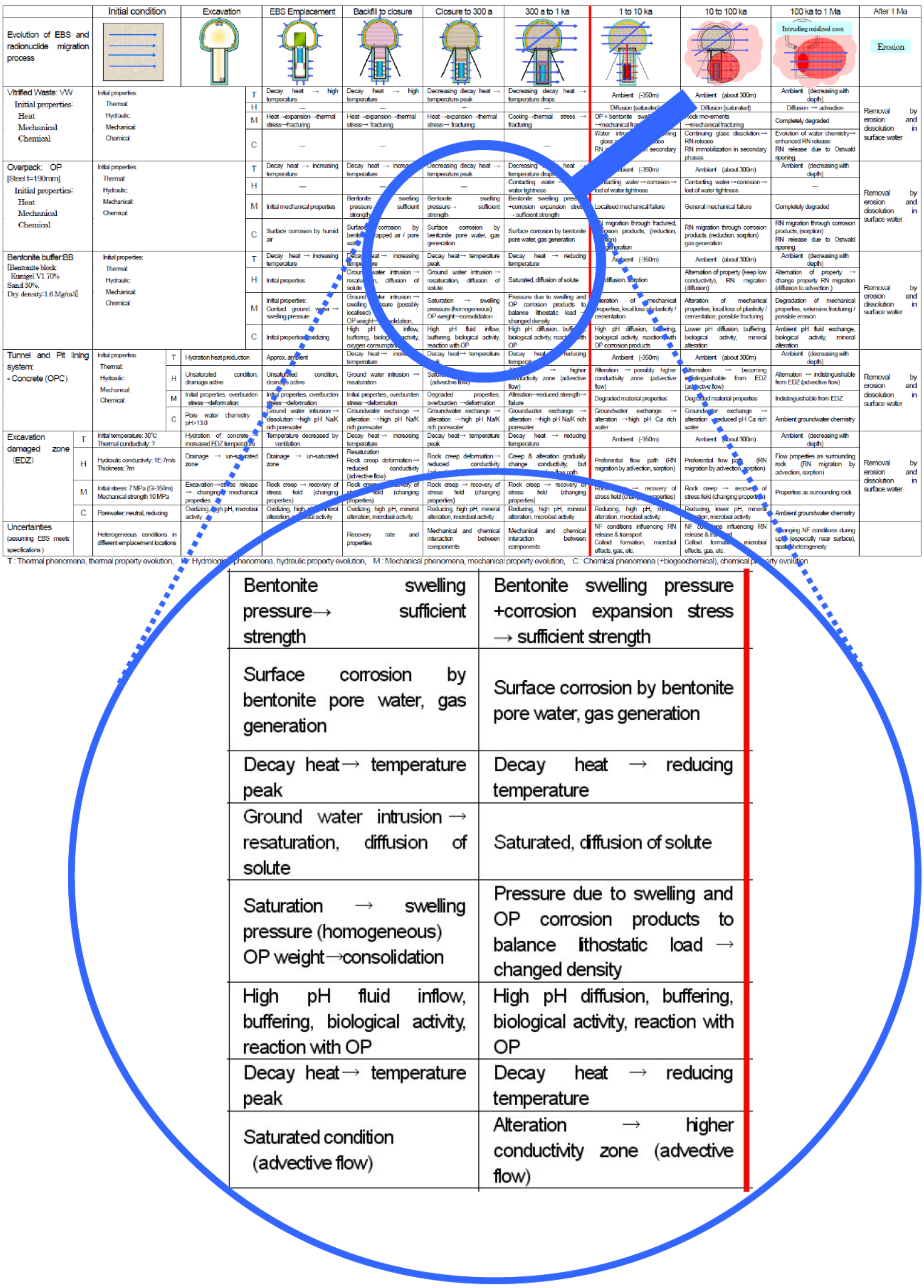

Figure 3.10 T-2 Detailed storyboard of EBS module (THMC analysis).
The red line indicates the starting point of radionuclide migration following failure of the overpack.

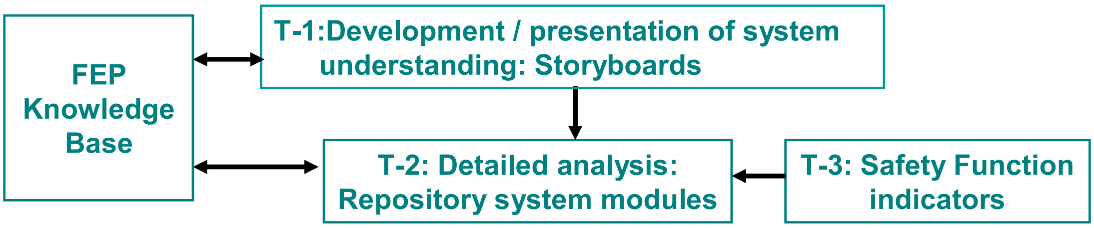

Figure 3.11 Relationship between the FEP knowledge base and tasks T-1, T-2 and T-3.

T-3 provides safety factors and indicators derived from the provisional safety concept, which is a conceptual outline of how safety will be demonstrated. Safety functions can be conveniently subdivided in terms of the key functions of Containment, Retardation, Dilution (dispersion) and Isolation. In Figure 3.12, safety functions and function indicators are outlined for the EBS modules and, for the specific case of the buffer, key phenomena that influence these functions are identified.

Module	Safety function		Safety function indicators
Vitrified waste	Containment	Preventing RN release	Dissolution rate: glass material, surface area, fracture distribution, temperature and water chemistry (esp. pH)
	Retention	Precipitation of RN	Formation of secondary phases: porewater chemistry (esp. Eh)
Overpack	Containment	Maintaining tightness	Corrosion rate and mode: material, thickness, chemistry, corrosion rate, corrosion mode, solute flux
			Mechanical properties: strength, thickness, stress field
	Retardation	RN sorption	Eh buffering, chemistry of porewater, corrosion products
Buffer	Containment	Preventing overpack sinking	Mechanical characteristics: **density**, **homogeneity**
		Stress and chemical buffering	Deformability: **composition**, **density**, **thickness** Chemical buffering: **mineralogy**, **density**, **thickness**
	Retardation	Maintaining diffusion	Low permeability: **density**; Self sealing: **composition**, **density**
		Colloid filtration	**Density**, **homogeneity**; Self sealing: **composition**, **density**
		Sorption	Retardation factor: **density**, **mineralogy**, **porewater chemistry**

Buffer: Density, mineralogy, homogeneity and geometry (thickness) are identified as key safety function indicators allowing phenomena that influence them (these are safety relevant Super FEPs) to be identified from T-2.

Safety function indicators	Significant phenomena
Mineralogy	Chemical alteration by high pH plume
Homogeneity	Alteration → cementation / fracturing
Density	Dissolution, erosion → density reduction
Geometry	Density reduction → deformation

Figure 3.12 Safety functions and safety function indicators of EBS module.

A synthesis of the output from T-2 and T-3, results into the expected periods of safety function operation for EBS components and it highlights the safety-relevant characteristics of each EBS component; the latter facilitates development of realistic assessment cases, instead of the over-simplified cases considered in the past.

T-4 identifies the key safety functions of T-2 system modules for specific time frames, using safety function indicators together with likelihood estimates from the FEP knowledge base (complemented by simple scoping calculations). Using the T-1 storyboard overview, these characteristics are arranged into a series, representing evolution in a base case scenario. In this process, likelihoods and uncertainties are assessed, which produces variations of this scenario (Figure 3.13).

T-5 identifies perturbations of more probable assessment cases based on the geological setting, considering site specific natural events (illustrated in T-1), their likelihood and their potential effects on relevant safety functions.

Finally, T-6 involves classification of assessments cases into various scenario classes, as defined by regulator, based on T-5 (perturbations), T-4 (more probable cases) and scoping calculations of effects. In the first step, the most likely case(s) is assessed, together with its uncertainties in the various space and time frames. The base case conceptual model can then be defined as a base case scenario with expected safety functions. Some variations of the conceptual model can be handled by simplified mathematical models and codes. The FEP knowledge base can also provide required system geometry, chemical, hydrological, mechanical, biological and physical behaviour characteristics, allowing T-6 to be carried out in an iterative manner.

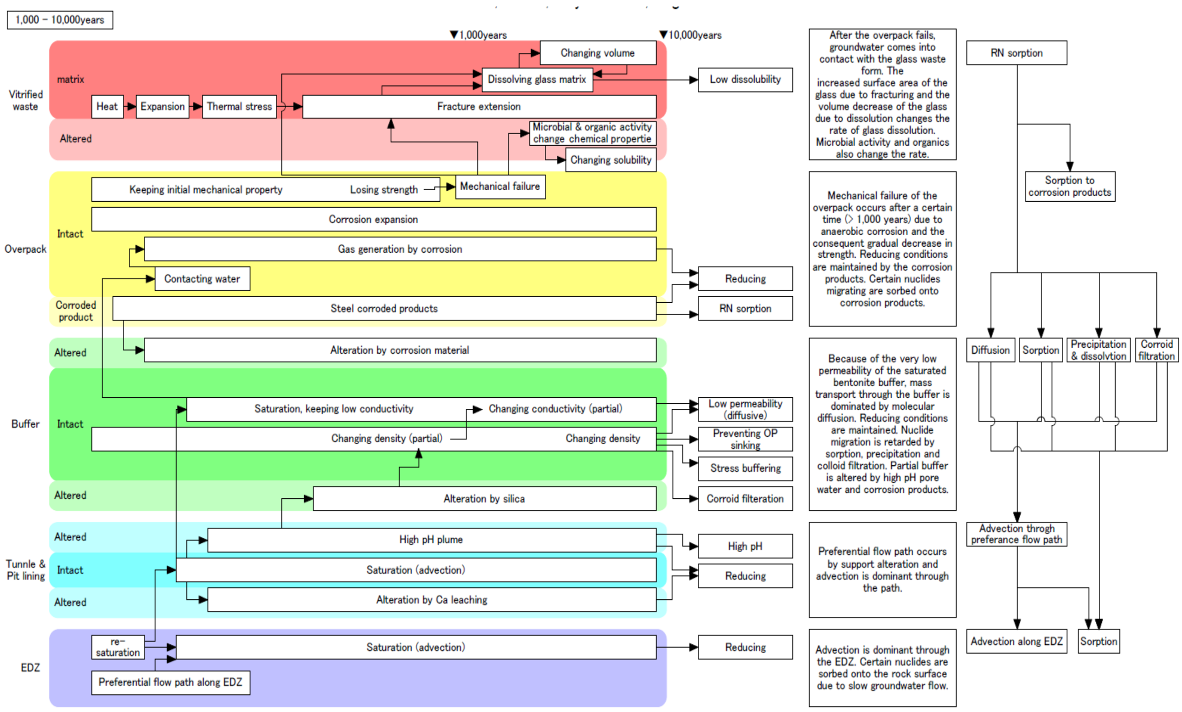

Figure 3.13 Sequences of more probable safety-relevant phenomena derived from T-2.

3.4.4 Discussion and further developments

The work frame approach adopted here is readily amenable to the treatment of uncertainties. T 1 and T-2 storyboards can document uncertainties identified within the compilation of multidisciplinary system understanding. In particular, long time disposal system evolution is influenced by natural processes and events with intrinsic uncertainties. During the dry run, several Japan specific uncertainties have been identified, for instance:

- Possible volcanic activities beyond 100ka
- Change of near field conditions due to contact with oxidized groundwater beyond 1Ma
- Change of surface conditions beyond the next ice age
- Interaction between steel corrosion products and bentonite buffer beyond 10 ka
- Chemical and mechanical interactions of cementitious material and bentonite buffer
- Possible influence on safety functions due to gas and microbial activity.

Handling uncertainties needs to be developed further, however, with a more practical method of record keeping within storyboards. In the next stage of development, the method will be applied to a wider range of repository concepts and siting environments to check that it has the flexibility required to respond to the challenges of NUMO's volunteering siting program.

4 Development of a Requirements Management System (RMS)

4.1 Introduction

The concept of requirements management has been in use in the engineering industry for some time but is only just starting to infiltrate the world of radioactive waste disposal. The key strength of requirements management (RM) is that it documents the decisions involved and their justification, in terms of both hard information (data, models, system understanding, etc.) and softer, more qualitative grounds for any given project. Thus, it also forms a memory of important historical information about a project.

This is increasingly becoming an issue as radioactive waste programs around the world head into their third and fourth decades with new staff who are not familiar with decisions made more than 20 years ago. As the older staff responsible for these decisions leave, the danger always exists that the transfer of knowledge about fundamental program decisions will be lost, leaving new staff to "reinvent the wheel".

NUMO has thus decided to include an RMS as part of its radioactive waste management program. Various RM approaches and systems were examined as part of this collaboration. At the end, because NUMO would like to expand the definition of the RMS to also include a record of the decisions taken (and the rationale behind them), NUMO decided to develop its own RMS in order to implement the Japanese geological disposal project in an efficient, sustainable and consistent manner. This chapter introduces some of the highlights derived from the NUMO-Nagra collaborative study on RMS development.

4.2 RMS development in oversea organizations

4.2.1 Information exchange meeting in 2007

Within the period of this collaborative project on RC development, an information exchange meeting on RMS development was organized in 2007. The meeting took place at the SKB offices, with participants from NUMO, Nagra, SKB and, as support to NUMO, Obayashi. All the participants in the information exchange meeting were involved in RMS development for their own national program. The aims of the meeting were specified in advance as follows:

Overall aim

- Exchange of information on RM/RMS among the lead organizations (SKB-NUMO-Nagra).

More specific aims

- Understanding the background and boundary conditions of RM/RMS development in each organization
- Understanding similarities and differences in RM/RMS development among organizations
- Identifying common issues for RM/RMS development among the programs
- Identifying areas / topics of mutual benefit
- Each organization to provide updated information on RMS development.

In order to exchange the basic information in a structured manner, the following template was used for the presentation of each organization:

- Aims of requirements management (RM)
- Structure of the requirements
- Who defines the input to the RMS and who uses the RMS
- Experience to date
- Current open issues.

Detailed presentations and discussions, as well as the main points brought up by each organization during the meeting, are summarized in an internal report: Record of the Information Exchange Meeting on Requirements Management System (RMS) between NUMO, SKB and Nagra, Stockholm/Sweden, 10 September 2007".

4.2.2 The SKB case

SKB has defined three aims for RMS development, namely:

- Aim 1: Facilitate the license application
  - For SKB
  - For reviewing authorities
- Aim 2: Facilitate communication among repository designers / constructors
  - Settle design premises
  - Identify couplings and dependencies
- Aim 3: Make decisions and the development of the design traceable.

The requirements should be used for:

- Communication
  - Definition of problem and scope

    - Understanding the context
- Design
    - Making the right "things"
    - Optimization
    - Risk management
    - Change control
- Quality assurance
    - Qualification – controlling – testing
    - Traceability.

It is recognized that there are different types of requirements as shown in Figure 4.1. SKB defined two domains in the RMS structure - the problem domain and the solution domain. In the problem domain, the problem is clearly defined considering the stakeholder requirements (top-level requirements). In the solution domain, system requirements are derived from stakeholder requirements and design requirements are further derived from system requirements. For system requirements and design requirements, system concept and specific solutions are identified respectively.

SKB then put the requirements into a hierarchical structure as shown in Figure 4.2. The basic concept was taken over from the V-model used for the DOORS system (see Reference list) and modified to suit SKB's needs. The requirements structure was defined at different levels, namely stakeholder, system requirements, sub-system requirements, design requirements and specifications. The top-level requirements (stakeholder requirements) are given conditions for SKB, while system requirements and sub-system requirements should be defined by SKB. Furthermore, detailed requirements such as design requirements and specifications could be defined by designers, who could be supporting organizations specialized in facility design.

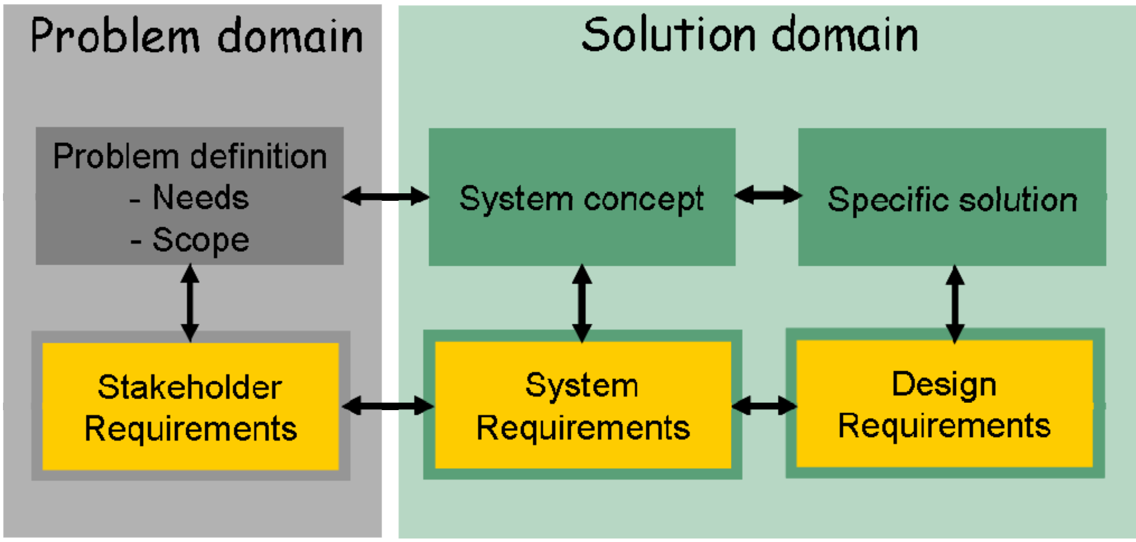

Figure 4.1 SKB's concept of different types of requirements for a radwaste disposal project.

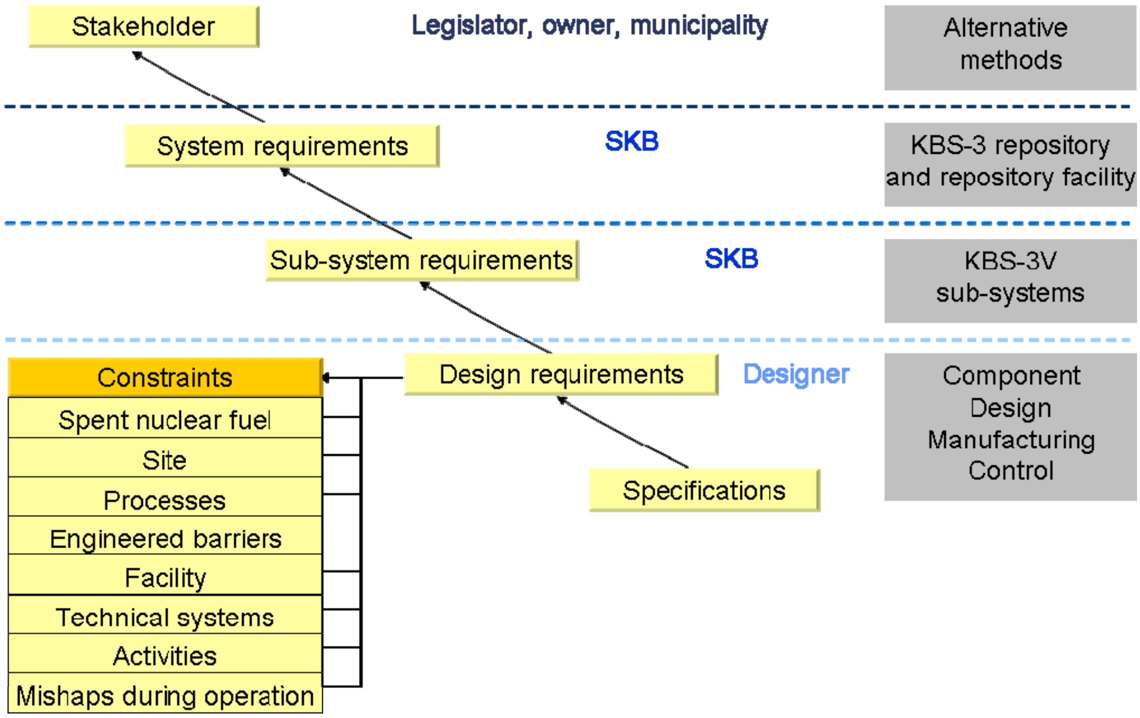

Figure 4.2 SKB's hierarchal structure of the RMS.

The different types of requirements shown in Figure 4.1 are defined more precisely as follows:

- Stakeholder requirement: A requirement expressing SKB's objectives for a system and the principles which will form the basis for the system design
- System requirement: A requirement expressing functions, characteristics or qualities a system must have to meet the stakeholder requirements
- Sub-system requirement: A requirement expressing the functions, characteristics or qualities a sub-system must have to meet the system requirements

- Design requirement: A requirement expressing how the product and/or the process of installation, manufacturing, building, sealing or testing must, given the constraints, be designed to meet the sub-system requirements
- Specification: Document which specifies requirements on a product and/or process of installation, manufacturing, building, sealing or testing.

In addition to the requirements, SKB introduced the concept of "constraints" as shown in Figure 4.2. The constraints are given conditions for designers that have to be accounted for. In the following, examples of such constraints are provided:

- Spent fuel
  - Data from the nuclear power plants and CLAB
  - Cost calculations (plan reports)
- Site characteristics
  - Site description
- Processes in repository evolution
  - Background reports to safety assessment
- The system itself – results from previous design stages
  - Engineered barriers
  - Activities
  - Technical systems
  - Facility
- Mishaps during operation
  - Mishaps defined in the operational safety assessment.

SKB has also introduced the basic principle of a "link" between higher levels of requirements and lower levels of requirements. The links are to be stated with specific expressions, for example, the link from higher levels of requirements to lower levels of requirements should be described with the statement "this implies that …" or "this leads to that …", whereas the link from lower levels to higher levels should be qualified with the statement "because the …" or "to meet the requirement that …".

Based on the conceptual development of the RMS, the structure of the database system has been established by SKB as shown in Figure 4.3. All the contents related to the RMS are included in the database system and links between the contents are established in the system.
Figure 4.4 shows an impression of the SKB decision-making process. The process starts with writing requirements by responsible experts and then suggestions will also be made by

responsible experts. The suggestions are reviewed by "external" reviewers (experts in the area of interest) and then passed on to the decision-maker to look at the issue with a higher or wider perspective. Finally, the decision should be made by decision-makers considering all of the input given by responsible experts and reviewers.

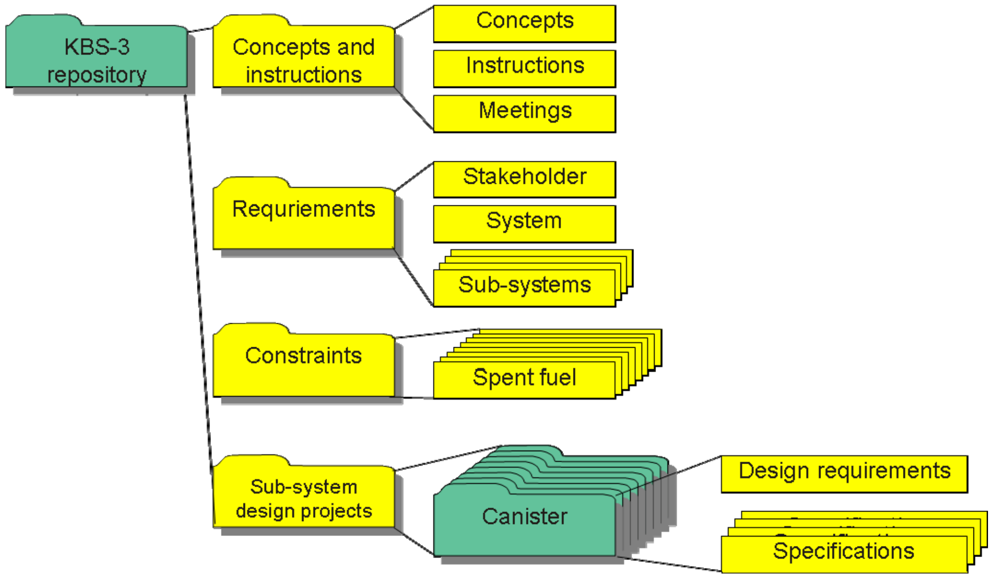

Figure 4.3 Organization of database system for the SKB RMS.

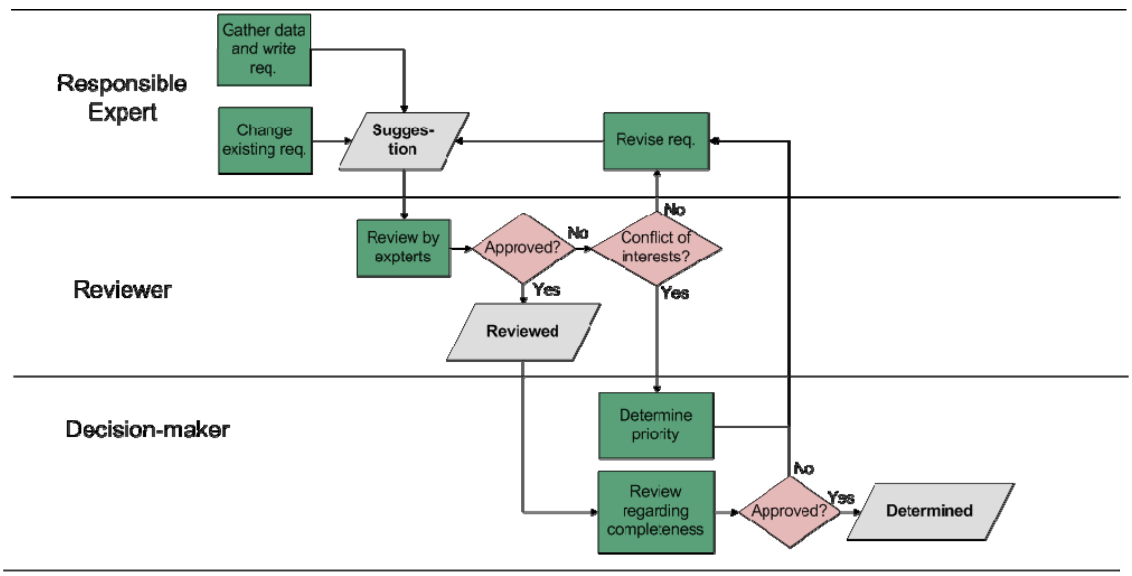

Figure 4.4 An example of a decision-making process by SKB.

Table 4.1 shows, as an example, the staff who should be involved in developing and using SKB's RMS.

Table 4.1 Main players involved in developing and using SKB's RMS.

	Higher level requirements -stakeholder, system and sub-system requirements	**Lower level requirements, design requirements, specifications and constraints**
Responsible experts (writers)	Requirements and database managers	Experts on the sub-system or component to be designed Requirements and database managers
Reviewers	Experts on radioactive waste management Experts on applications Lawyers	Persons responsible for the sub-systems and components the requirement is linked to Experts invited by the authors
Decision-makers	Project leaders of final repository project Council of requirements	▪ With vital importance for nuclear safety and radiation protection: project leaders of final repository project, council of requirements ▪ Regarding facility design: project leaders of facility design projects ▪ Regarding engineered barriers: managers of technique development unit ▪ Regarding parts of the facility or technical equipment: designers

The experience with the RMS up to the date of the workshop and open issues identified by SKB for further development were summarized in the workshop as follows:

- Introducing an RMS brings about new ways of organizing work, particularly for designers and constructors
- The RMS and management systems must be integrated
  - RMS – quality assurance of product
  - Management system – quality assurance of work and activities
- Introducing an RMS is a slow process
  - It requires communication
  - It is initially hard to see the benefits
- It is hard to separate the requirements from the solution – strict rules for how to write requirements must be applied
- Requirements indirectly affecting the design, e.g. the use of best available, robust and reliable, are hard to handle
- Many open issues on design requirements and constraints (reference design).

4.2.3 The Nagra case

Nagra emphasized that its RMS is part of the Quality Management System (QMS). Nagra's QM system is run by Intranet within Nagra in order to ensure that all the users have easy access to the most updated QM system. Figure 4.5 shows a screen image of Nagra's QM system. It was pointed out that the RMS is part of the strategic planning (formal process, shown as part of 1.1 in the figure) with periodic check-points, but it has direct links to the projects (input to development of requirements, boundary conditions for projects, etc).

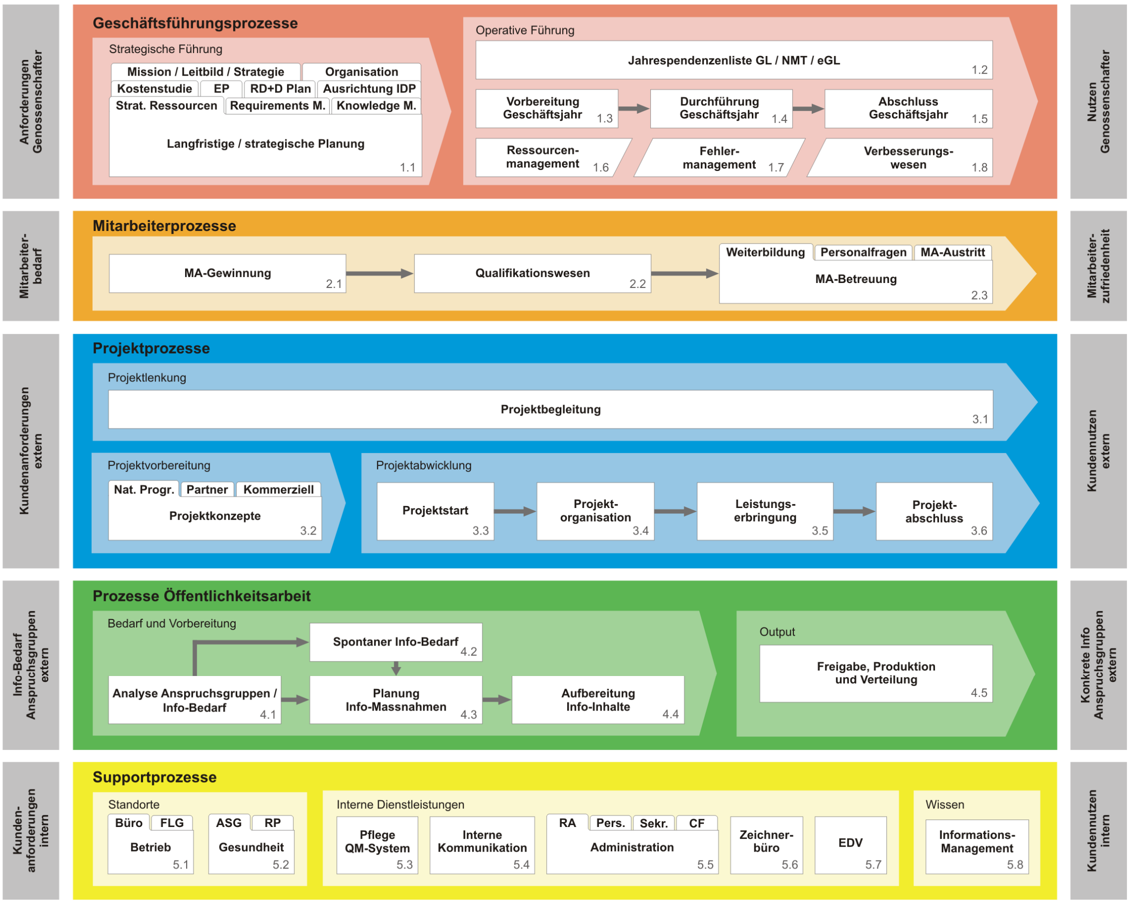

Figure 4.5 Screen shot of Nagra's QM system.

The broad aims of the RMS being developed by Nagra can be summarized as:

- Aims at a systematic and traceable approach to developing, eliciting and treating/respecting requirements
- Ensures that no important requirements are "forgotten" (comprehensiveness in development and treatment of requirements)
- Allows requirements (requirements, preferences, issues) to be prioritized
- Provides an overview of and handles contradictory requirements

- Provides an organizational memory of important issues (requirements)
- Provides an adequate structure for their application in projects / activities (→ better overview: what, where, when, why, how)
- Reflects on various requirements (categories) and how they relate to each other (interdependencies)
- Documents (all) the relevant requirements obeyed by a project
- Facilitates communication between different disciplines within the organization / project
- Facilitates interaction with different groups of interests (project, management, waste producers, authorities, public, etc.)
- Helps to develop an adequate "work culture" (team, interdependence).

Considering the above aims, Nagra has been developing an RMS with a relatively simple structure to gain initial practical experience in implementing an RMS for the radioactive waste disposal program. The following points were introduced to summarize the observations and experience with the RMS up to the date of the workshop:

- Requirements can be related to hardware, reports, procedures, etc.
- Requirements are sometimes related to a specific concept, design, etc.
  - Need to link to "configuration data"(→ data clearance)
  - Some requirements are conditional (distinguish from generic)
  - It may be useful to keep track of "flexibility left" due to alternatives
- Requirements are often the result of a line of reasoning → need to link with the report that contains the reasoning (still the main emphasis of Nagra work)
- Treatment / application of requirements may require specific procedures
- Decision-making and corresponding reports are not replaced by "ticking-off" all requirements, but "managing" requirements may be essential in preparing reports/arguments.

The text below documents the requirements management activities at Nagra. It should be noted that Nagra initiated identification of the requirements based mainly on the Sectoral Plan for Deep Geological Repositories prior to the system development. A large number of requirements are defined both explicitly and implicitly in the Sectoral Plan; for the latter, Nagra is required to interpret and translate all implicit requirements into a more practical form for implementation of the disposal program in Switzerland.

- Development of requirements
  - Top down: hierarchical structure of requirements → develop structure and derive requirements (e.g. safety concept → safety functions →…)

    - Bottom up: at the start of a major project, evaluate explicit and implicit requirements that are essential for, or contribute effectively to, successful completion of the project (adequate design, site, etc.)
- Application of requirements (boundary conditions)
    - At the start of each important project / activity: check for relevant requirements (ear-mark critical requirements)
    - Then: translate requirements into boundary conditions and work processes for conducting the project (→ measures to be taken)
    - When completing the project / activity: check that requirements have been fulfilled
- Project manager: ensure that, for a given issue, the same requirements (→ specifications / assumptions) are used by all projects / activities (data clearance process → part of QMS (through IT-tool)).

The basic principles for developing a database for the requirements management system are:

- Development of requirements underway (specific projects)
    - Waste management program
    - Site selection process
    - Repository design
    - General license application
- As soon as (preliminary) results are available feed into database (significant backlog)
- Application of requirements (procedures): underway
- Database content to date: high-level (legal) requirements
- Technical-scientific requirements are currently being entered (in parallel with the production of reports)
- Data entry is slow / few users as yet!
- Database: FileMaker Pro.

Finally, "challenges" in developing the requirements management system are shown below, grouped into two categories:

- Challenges related to RM
    - Links between different (e.g. higher-level to lower-level) requirements
    - Distinguishing between "hard" requirements as opposed to "nice to have" features
    - Large number of high-level (legal) requirements
    - Missing requirements, ambiguous and unclear requirements

  - Coping with uncertainties in scientific understanding
- Difficulties related to RM as a process
  - Many high-level (legal) requirements, but only few lower-level requirements are recorded (although many of them are described in documents)
  - Requirements as part of projects are fully recognized, but their management within a formal system is still under development.

At the time of the workshop, experience and "lessons learned" had already been obtained and were summarized as follows:

- Two possible approaches to deriving requirements
  - Develop requirements through dedicated projects (often top-down)
  - Collect / elicit continuously (hidden) requirements based on scientific understanding, experience, etc. (bottom-up)
  - But: need for iteration (screening for rubbish, conflicts, misunderstandings, poor documentation, nomenclature, etc.)
- Requirements should be clearly linked to their origin or basis (stakeholder requirement / experimental data / technical constraints, etc.) and their line of argument (incl. how to apply)
- The need to consider uncertainties → requirements may change
- Low-level requirements should be explicitly linked to higher-level requirements
- Start with a simple software tool: the intended purposes of the system should be further defined (based on company-wide experience) before selecting another tool or upgrading the existing tool
- Do not make it too clever / too detailed.

4.3 Overview of the current N-RMS being developed by NUMO

4.3.1 Background of N-RMS development

As mentioned many times to date, NUMO intends to proceed with its program following the principle of the NUMO Structured Approach (NSA). The aims of NSA can be summarized as below:

- To consistently implement the stepwise approach of the geological disposal program in the stages of site selection, licensing, construction, operation and closure
- To satisfy the engineering, social and legal requirements for the disposal program with an appropriate degree of flexibility
- To maintain the traceability of the decision-making processes of NUMO.

In this context, the main aim of the N-RMS development is:

- The comprehensive information management of the requirements and decision-making processes in a structured manner for the geological disposal program.

The following key functions are expected for the N-RMS:

- Record-keeping of all relevant information for the implementation of the disposal system
- Approval system for the decision-making
- Change management
- Project management.

4.3.2 Development process of the N-RMS

As shown in Figure 4.6, the N-RMS will be developed in 4 stages - the NSA development stage, the trial RMS stage, the practical RMS stage and, finally, application to the implementation process. The current N-RMS is being developed within the framework of the trial RMS stage and it is expected that this stage will continue into another phase from FY'08 onwards. It is, however, not known whether NUMO will continue with the same contractor group and will develop the next phase of the N-RMS fully utilizing the current version of the trial N-RMS.

Figure 4.7 shows the detailed development process of the N-RMS. The process starts with the "conceptual design based on the NSA" and continues with "analysis of the structure of the technical work". Based on this, there is a very important step, namely structuring the N-RMS. The structuring includes establishing NUMO's entire work structure and structuring of NUMO's technical work. The next step is to "design the trial RMS". During this step, it is expected that the system components and database structure based on the DCRA (decisions, considerations, requirements, arguments) model will be developed. The next step is "preliminary description of the DCRA database" and NUMO decided to use the information from the H12 report and from other reports to supplement H12 (should there be more recent work since H12). Finally a dry-run will be performed to check the feasibility of the developed trial N-RMS.

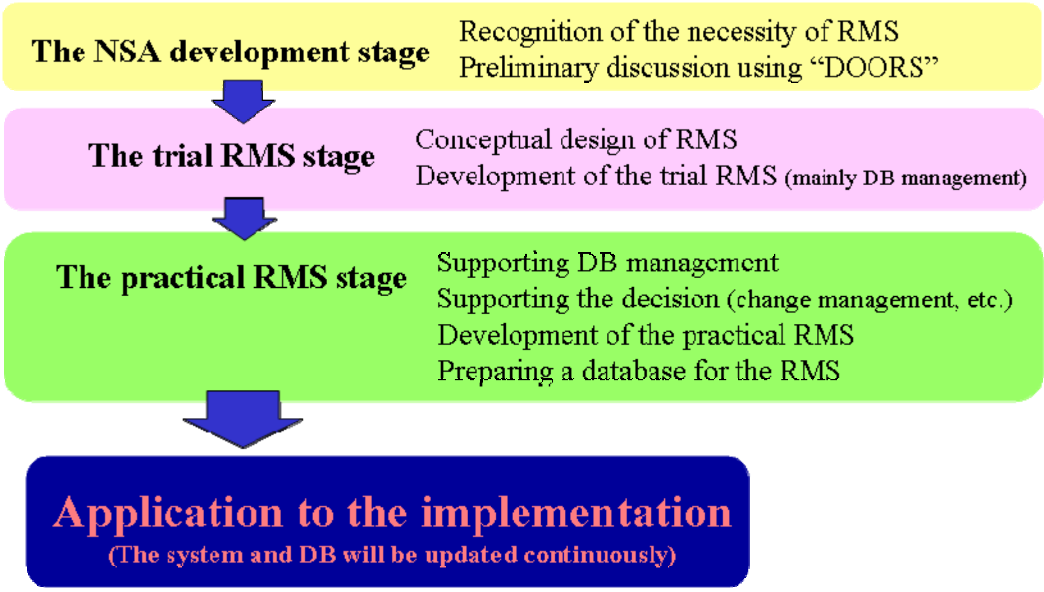

Figure 4.6 Flow diagram of the development process of the N-RMS.

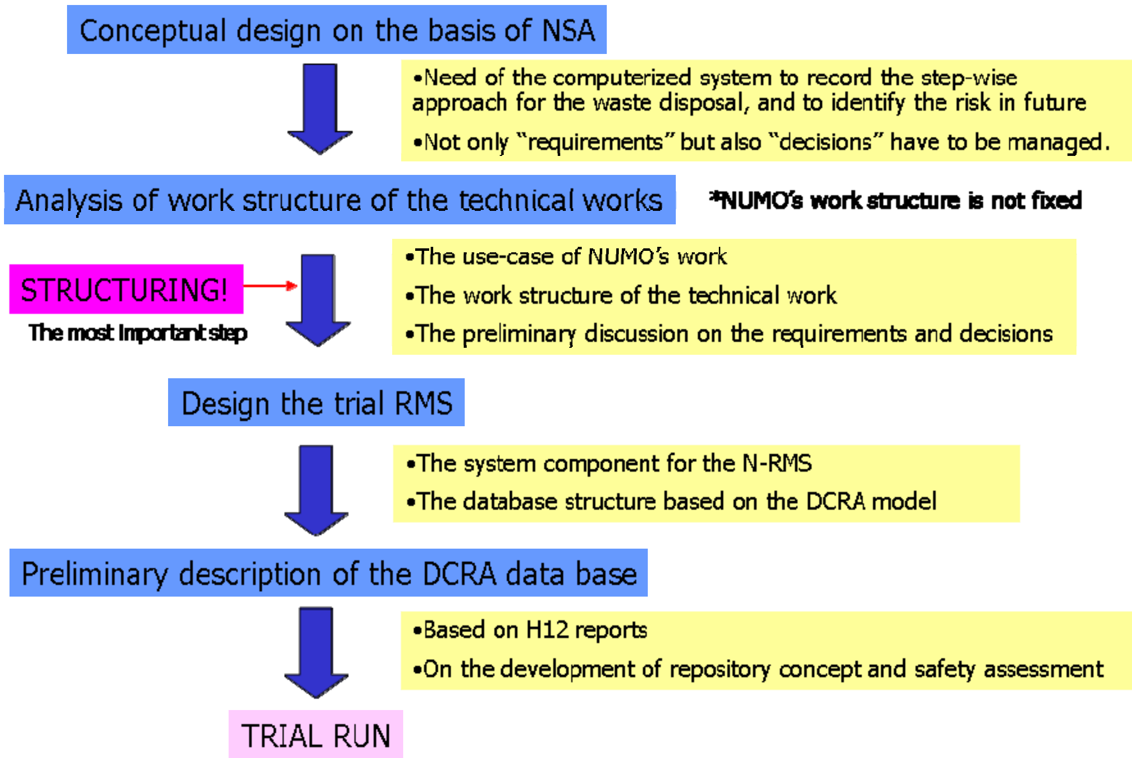

Figure 4.7 Procedure for development of the trial RMS.

4.3.3 Overall structure of the N-RMS

Figure 4.8 shows the overall structure of the N-RMS, consisting of the following three sub-projects:

- Sub-project 1: Repository concept and safety assessment

- Sub-project 2: Management of technical work
- Sub-project 3: Site characterization

As shown in Figure 4.8, the function of sub-project 2 plays a central role in the N-RMS. It defines the high-level requirements for the sub-projects 1 and 3 in order to optimize the overall technical project scheme in a top-down manner. Sub-projects 1 and 3 will then define further detailed requirements and the decisions will be made within the N-RMS.

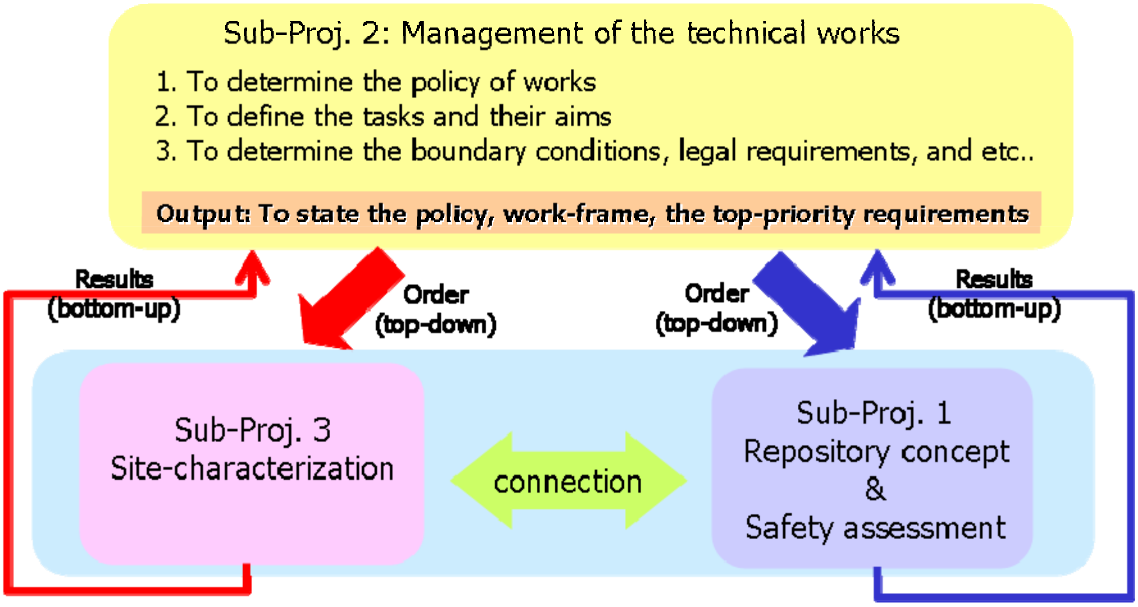

Figure 4.8 Overall structure of the N-RMS and expected interactions between the sub-projects.

Figure 4.9 shows the overall system concept of the N-RMS. The N-RMS is expected to have two functions, namely a "decision-making support function" and an "RMS database management function". The decision-making support function consists of the RMS browser, management of "decisions" and change management. On the other hand, the RMS database management function consists of the database corresponding to the management of the DCRA and the one corresponding to the support in constructing the DCRA.

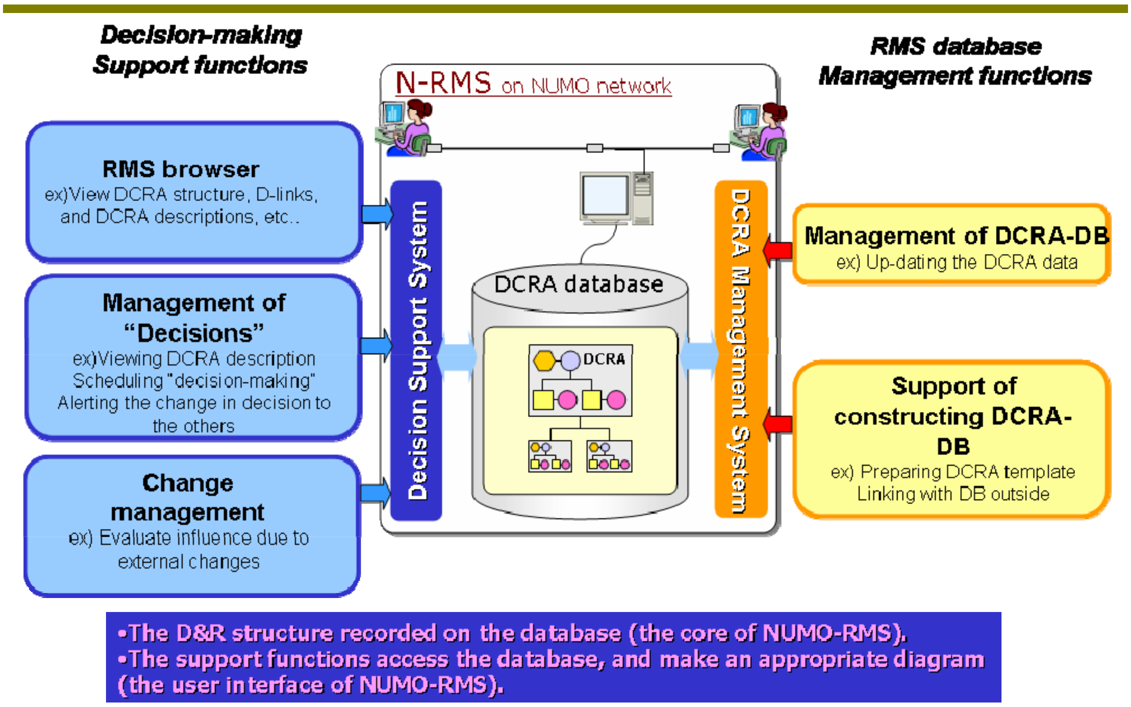

Figure 4.9 **Overall system concept of the N-RMS with two functions – decision-making support function and RMS database management function.**

Figure 4.10 shows screen shots of the N-RMS. The trial system was developed as a bilingual system and language can be changed between Japanese and English. Since it is on an open webpage, the system is protected by user name and password. Figure 4.11 shows an example of the N-RMS screen. The left window in the figure shows the hierarchical structure of the requirements, which provides a good overview of the N-RMS structure. The right window has 6 tags consisting of "main information (1)", "main information (2)", "requirements", "related information", "auxiliary information" and "master information". Each tab has its own description and files can be attached in the attachment box. Under the requirements tab, the requirement is stated with a short text. In the requirements tab, many requirements can be included and each requirement has its own description called "argument of requirement" and "background knowledge". Since the requirement itself is described with a short text, a detailed explanation of the requirement can be written under the "argument of requirement" tab.

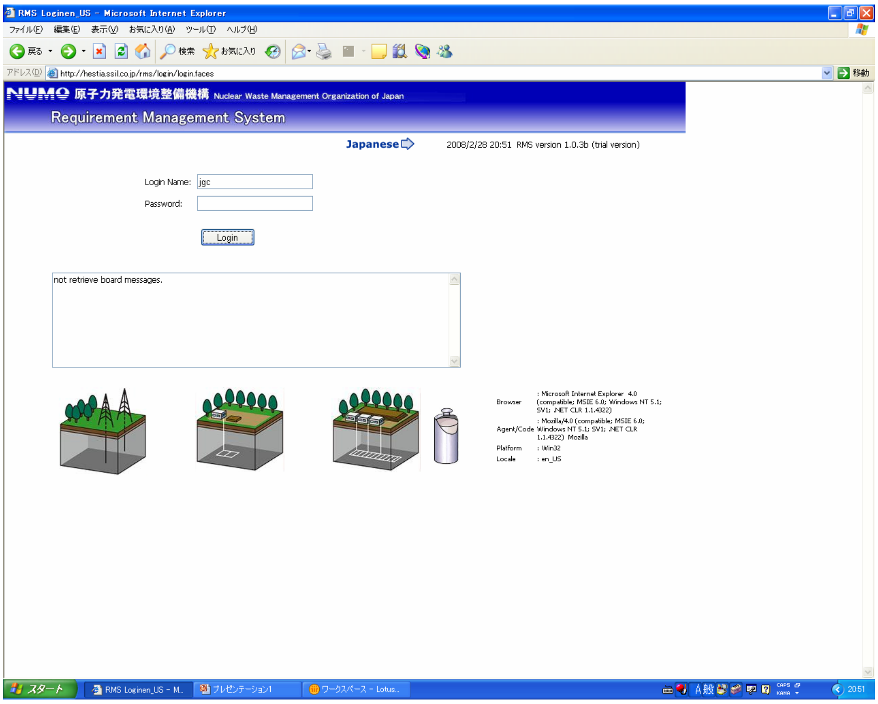

Figure 4.10　Initial screen shot of the N-RMS.

The language can be changed between Japanese and English.

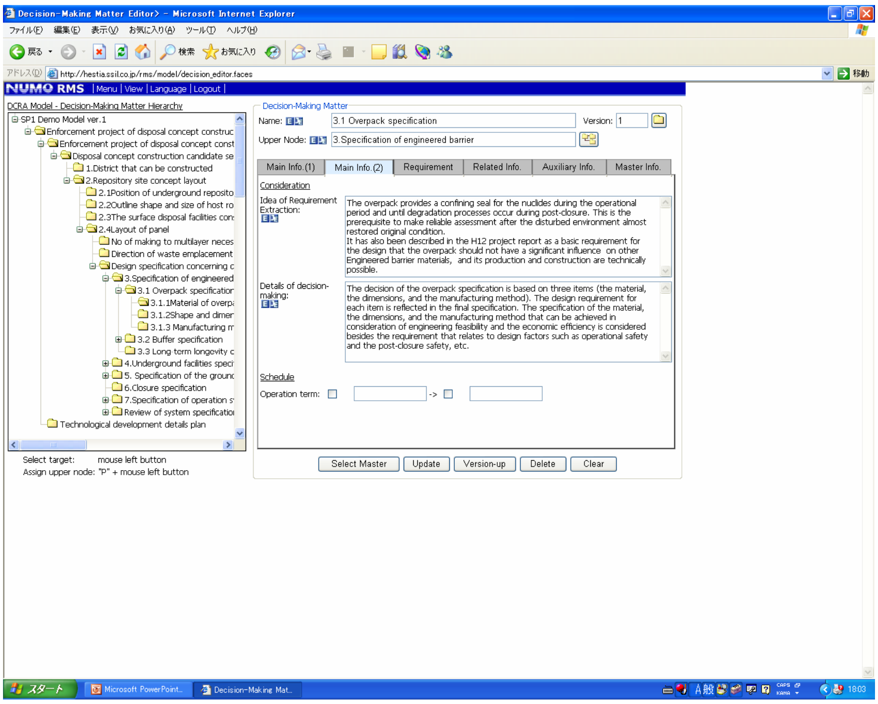

Figure 4.11　Typical screen shot of the N-RMS.

The left window shows the structure of the N-RMS and the right windows are for further detailed information.

5 Concluding remarks

A broad range of issues has been studied by the NUMO-Nagra team as part of the collaborative studies on repository concept development. A summary of the first part of these studies can be found in NUMO (2004a).

Some of the main topics studied over several years include:

- Strategy and methodology development for tailoring repository concepts (e.g. NUMO Structured Approach, PI roadmap, uncertainty treatment, engineering constraints and geosynthesis)
- Requirements Management System and
- Improvement of performance assessment (scenario development methodology).

In addition, topical issues were also studied to review the latest developments in overseas programs (e.g. iron/bentonite interactions, high temperature effects on bentonite, CO2 sequestration, SKB production line reports).

This report summarizes three of the specific areas studied and advances made through this collaboration in the period FY 2003 to FY 2007, namely:

- Development of NUMO's PA/RD roadmap
- Scenario development
- Development of a requirements management system.

The project has established a platform for a compact, efficient and quick information exchange and know-how transfer both at strategic and program level, as well as at the technical level. Consistent with NUMO's mission, the emphasis was on developing the strategies and tools that will allow successful management of the program for a geological repository for specified radioactive waste in Japan.

Developments in some areas will continue to keep abreast of the best available technology at the international level, but instruments and technologies will also be tailored for application within the Japanese environment. The project team remains confident that the results from this study have contributed, either explicitly or implicitly, to advancing the Japanese geological disposal program.

Acknowledgements

The authors value the contributions from a wide range of RC Collaboration Team members. In particular, we would like to express our gratitude to Dr. H. Umeki (JAEA), Mr. Y. Sakabe (Hokkaido Electric) and Mr. Y. Sugita (JAEA) for their contributions to both project coordination and technical development. It should also be noted that the work was performed with extensive contributions from the Nagra Technical Support Team, including Dr. P. Smith (SAM), Dr. I. McKinley (McKinley Consulting), Dr. J. Andersson (JA Streamflow AB), Dr. S. Mishra (Intera) and Dr. H. Kawamura (Obayashi).

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Appendix A: Survey of focused PA issues in European countries

A.1 Issues addressed

Among the various issues addressed in recent PAs in European countries, the issue of how specific elements of engineering practice affect the initial state and subsequent evolution of the repository is receiving increasing attention. The general issue of how to assess the significance of possible deviations from the planned initial state is considered in Section A.2, focusing on deviations from planned buffer density. In addition, following the recent experience from the earthquake near the Niigata-Kariwa nuclear power plant in Japan, an issue of considerable interest to NUMO is the detection and evaluation of consequences for a repository of earthquakes occurring on active faults. Although active faults will be avoided when designing a repository layout, earthquakes on such faults could lead to secondary shear movements along fractures that intersect the repository tunnel system and could potentially damage the barrier system. Work on this topic has been carried out recently by SKB and Posiva in the context of post-glacial earthquakes and is summarized in Section A.3. Finally, in Section A.4, the issue of the treatment of the near-field/geosphere interface is discussed. Potential gains in calculated system performance compared with H12 may be obtained by adopting the model assumptions employed by SKB and Posiva in their safety assessments. The conditions under which these model assumptions may be valid are discussed.

A.2 PA issues arising from engineering considerations

A.2.1 The need for interaction between PA analysts and engineers in identifying key issues

Typically, a repository for radioactive waste will evolve from its initial state, when the first waste packages are emplaced, through an early, transient phase in which, for example, the buffer saturates and heat output from the waste declines to low levels, towards a quasi-steady state (the "target state", see Figure A.1). In this quasi-steady, target state, the key safety-relevant physical and chemical characteristics of the barriers (e.g. temperature, buffer density and swelling pressure) are subject to much slower changes than in the transient phase and the main safety functions of barriers are expected to be provided.

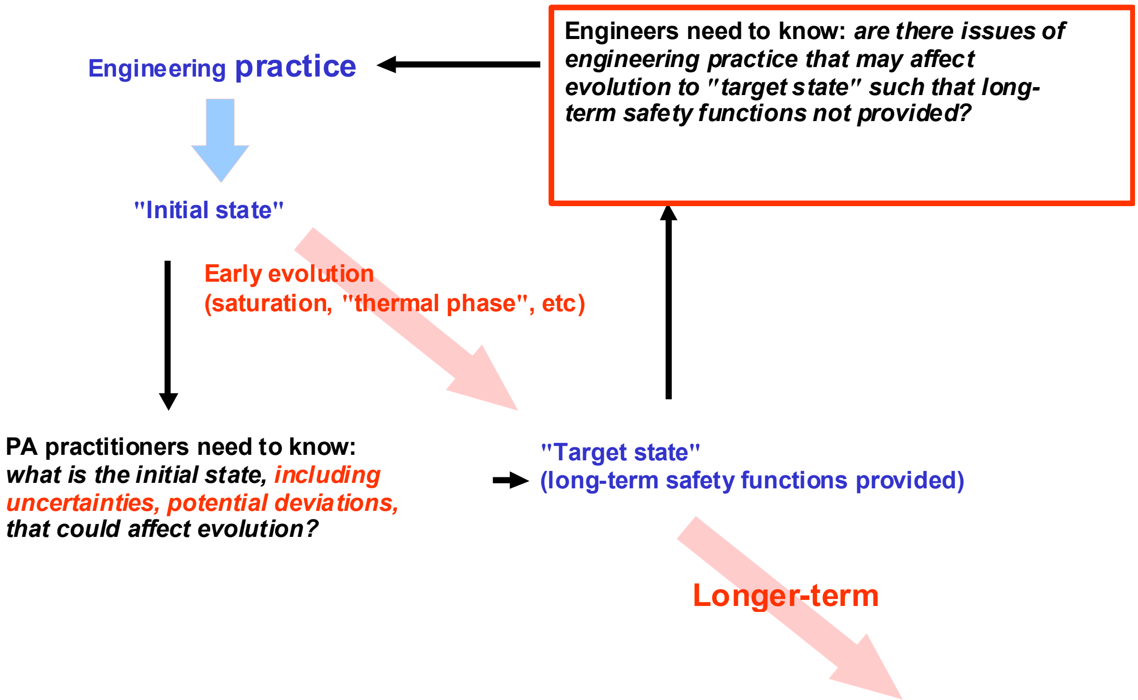

Figure A.1 **The need for interaction between PA practitioners and engineers in defining the repository "initial state" and its subsequent evolution.**

Describing the evolution of the repository towards the target state and beyond, taking into account all relevant uncertainties, is the responsibility of PA practitioners. The way in which the system evolves, however, depends on its initial state and this initial state will depend on decisions taken by engineers on how to implement the chosen repository design. In PAs carried out at the early stages of a repository program, an idealized view is often taken of the initial state. It may be assumed, for example, that the buffer is perfectly homogeneous, that there are no stray materials present that could interfere with the repository safety functions and that mishaps or accidents during manufacture and emplacement of the engineered barriers can be avoided, or the consequences rectified. Table A.1, however, shows how engineering experience to date indicates that obtaining an "ideal" initial state can be difficult, or at least subject to some significant uncertainty. Thus, as a program matures, the validity of these assumptions regarding the initial state must be evaluated and alternative, more realistic assumptions considered if necessary. In order to define a realistic repository initial state, PA practitioners need information from engineers on operational procedures and other elements of engineering practice that may give rise to uncertainties and potential deviation from design values of key parameters, such as buffer density. Engineers, on the other hand, need to know whether or not their engineering decisions could have a potential adverse effect on the capacity of the repository to perform its safety functions as it evolves over time. Figure A.2 illustrates how the long-term safety functions and corresponding requirements on each barrier component affect the required conditions after the initial, transient period (the "target state" in Figure A.1). These in turn affect the engineering measures employed and the overall planning of repository construction and operation. Thus, overall, repository design and PA both require interaction between PA practitioners and engineers.

Table A.1 Examples of experience to date on engineered barrier emplacement.

Examples from the Grimsel Test Site, Switzerland	
FEBEX	More effort than originally thought was required to emplace bentonite blocks
GMT	Buffer was emplaced by in-situ compaction - good quality control was demonstrated, but operation is difficult if no contact handling is allowed (e.g. in the HLW case)
EB	Buffer was emplaced by combination of blocks (lower part) and pellets (upper part) - auger emplacement system was demonstrated, but significant effort was required to achieve high buffer density and homogeneity (partly due to too many obstacles, e.g. instrumentation)
ESDRED	Demonstration and optimisation of different emplacement measures
Examples of tests of KBS-3 emplacement methodologies	
DEMO TEST	Canister emplacement machine built and tested. Further modification of the machine or repository design is required
Prototype repository	Engineered barrier emplacement was achieved in a quality assured manner, but plastic sheets had to be used to avoid contact between bentonite blocks and inflowing water in deposition holes

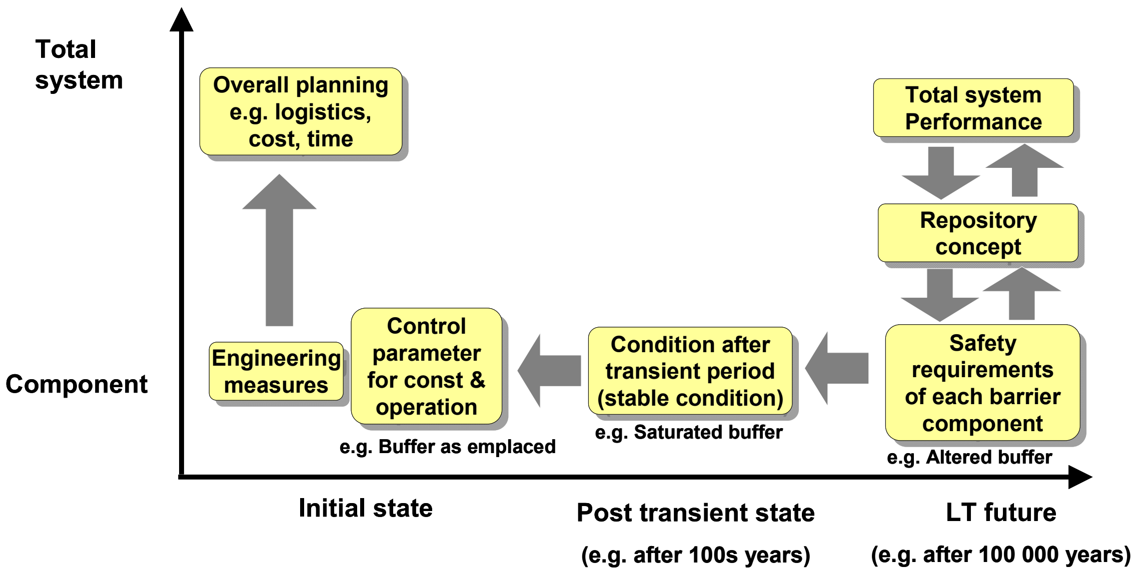

Figure A.2 Illustration of how long-term safety requirements influence the engineering measures employed and the overall planning of repository construction and operation.

A.2.2 Examples of issues of engineering practice of potential significance to PA

Table A.2 gives some examples of elements or issues of engineering practice that may give rise to uncertainties and potential deviation from design values of key PA parameters. The corresponding PA issues (issues/processes for long-term safety) are also shown. Since NUMO has not, as yet, fixed its reference repository concept, the list of issues is not comprehensive and the descriptions are, of necessity, rather general.

Table A.2 Examples of elements or issues of engineering practice that may give rise to uncertainties and potential deviation from design values of key PA parameters and the corresponding issues/processes for long-term safety.

Engineering practice	Issues / processes for long-term safety
Canister	
Damage to canister during transportation or emplacement (e.g. by dropping, derailing, fire, flooding)	▪ Loss of mechanical integrity ▪ Cause of pitting corrosion ▪ What are the criteria for determining if canister to be retrieved or not
Erroneous emplacement of canister	▪ Loss of buffer thickness ▪ Further displacement (rotation) of canister due to gravity and unusual stress condition ▪ What is the minimum buffer thickness to maintain safety function?
Bentonite	
Early swelling of bentonite in vertical (pit) emplacement	▪ Loss of swelling pressure ▪ Lower density – higher hydraulic conductivity ▪ Difficulty in canister emplacement ▪ Bentonite swelling out of pits
Heterogeneity in bentonite density	
▪ Density difference between block section and pellet section	▪ Heterogeneity in swelling pressure ▪ Heterogeneity in hydraulic properties ▪ Heterogeneous stress condition for canister
▪ Density differences derived from gaps between bentonite blocks and components	▪ Heterogeneity in swelling pressure ▪ Heterogeneity in hydraulic properties ▪ Heterogeneous stress condition for canister
▪ Heterogeneous density due to pellet emplacement	▪ Heterogeneity in swelling pressure ▪ Heterogeneity in hydraulic properties ▪ Heterogeneous stress condition for canister
Emplaced buffer density too low	▪ Low swelling pressure ▪ High hydraulic conductivity ▪ Bentonite flushing out
Emplaced buffer density too high	▪ Extreme swelling pressure
Backfill	
Heterogeneous emplaced density	
Gaps at top of tunnel	▪ Preferential GW flow path
Low emplaced density	▪ Risk that materials will be flushed out
Rock	
EDZ	

Engineering practice	Issues / processes for long-term safety
▪ Initial thickness of EDZ	▪ Depending on excavation method ▪
▪ Development of EDZ with time	▪ Depending on the rock type – more critical for soft rock than hard rock ▪ Also depending on the rock support applied
Thermally induced rock spalling	▪ Depending on the rock properties and thermal load
Tunnel roughness and irregular diameter size	
Seals and plugs	
Large amount of cementitious materials	▪ High pH plume around seals and plugs
Bentonite-concrete composite design for hydraulic plug	▪ Interaction between bentonite and cement
Engineering materials potentially remaining post-closure	
Transportation: rails, concrete floor	▪ Mostly remain in tunnel ▪ Relatively large amount of material ▪ High pH issue for concrete ▪ Corrosion expansion and gas generation for metals (e.g. rails)
Rock stability: rock bolts, shotcrete, liner	▪ Remain in rock / tunnel ▪ Large amount of material ▪ High pH issue for concrete ▪ Corrosion expansion and gas generation for metals (e.g. rails)
Drainage: drain sheets, sumps, drainage pipes	▪ Remain in rock / tunnel ▪ Large amount of material ▪ Organic issues for drain sheet ▪ High pH issues for sumps
Utilities: lights, cables	▪ Will be removed after operation?
Ventilation: ducts, fans	▪ Will be removed after operation?
Handling: steel handling shell (PEM)	▪ Remain in tunnel ▪ Fe-bentonite interaction

Some potentially important PA issues may be summarized as follows:

Buffer density may deviate from the "target" value

A low average density could be caused, for example, by the presence of gaps or by piping (transient water flows) and erosion during saturation. A high average density could be caused by corrosion expansion of a metallic, prefabricated emplacement module (PEM), if this is used to emplace the engineered barrier system, or by tunnel convergence. Heterogeneous buffer density also is caused by the above-mentioned affects, as well as by the combined use of bentonite blocks and pellets.

Buffer-rock interface may be perturbed

Physical disturbance to the buffer/rock interface could be caused, for example, by the presence of an excavation damaged zone (EDZ), by rock spalling, which is the brittle fracturing of the rock surface into splinters, chips or fragments (spalling could occur as a result of the relief of high initial rock stresses upon rock excavation or as a result of thermal-mechanical effects following waste emplacement) or by the physical degradation of tunnel support (liner), if such support is used. Chemical disturbance could be caused, for example, by cement/bentonite and cement/rock interactions, or by iron/bentonite interactions.

Engineered barrier system may generate gas

Gas may be generated, for example by corrosion of the overpacks, the metallic shell of the PEMs, if these are used, transportation rails and other metallic structures.

Engineered barrier system may interact with stray materials

Stray materials, if present in sufficient amounts, could damage the canister surfaces or otherwise adversely affect the repository safety functions. Organic substances or their degradation products could, for example, form complexes with radionuclides that would lower radionuclide sorption and thus increase radionuclide release and transport rates in the event of canister failure.

Table A.3 shows the potential causes of each of these factors, the PA assumptions or parameters potentially affected, the potential effects on system performance and the information requirements to quantify these effects.

How to evaluate whether potential deviations from target values are significant from a PA perspective is discussed further in Section A.2.3, using the example of deviations from the target value of saturated buffer density.

Table A.3 Examples of PA-relevant issues, their potential causes, the PA assumptions or parameters potentially affected, the potential effects on system performance and the information requirements to quantify these effects.

<table>
<tr><th rowspan="2">Issue</th><th rowspan="2">Potential causes in engineering practice</th><th rowspan="2">PA assumptions or parameters potentially affected</th><th rowspan="2">Potential effects on system performance</th><th colspan="2">Information required to quantify effects</th></tr>
<tr><th>General</th><th>Engineering</th></tr>
<tr><td colspan="6">Buffer density may deviate from "target" value</td></tr>
<tr><td rowspan="3">Low average buffer density (with respect to design value)</td><td rowspan="3">▪ Early swelling of buffer in vertical (pit) emplacement
▪ Emplaced buffer density too low (large gaps for blocks, low bulk density of pellets, insufficient in-situ compaction, etc.)
▪ Piping and erosion during operational phase</td><td>Swelling pressure provides a tight seal between the buffer and the drift wall</td><td>▪ Increased mass transfer across buffer/rock interface
▪ Potential for flow and radionuclide transport along this interface</td><td>▪ Minimum swelling pressure to achieve a tight buffer/rock interface
▪ Relationship between swelling pressure and buffer density (will be a function of GW composition)</td><td rowspan="3">Range of possible buffer density reduction due to identified potential causes, e.g. engineering emplacement experiment under realistic underground conditions</td></tr>
<tr><td>Canister sinking is negligible</td><td>Sinking of canister through low-density buffer could lead to reduced physical protection of canister by buffer and lower buffer transport distances for released radionuclides</td><td>Minimum buffer density that still prevents significant canister sinking
Potential measures:
▪ Long-term experiment
▪ Modeling</td></tr>
<tr><td>Buffer provides an effective colloid filter; radionuclides transported through buffer only as solutes or gas</td><td>Colloid transport through buffer gives reduced limitation of radionuclide releases by buffer</td><td>Minimum buffer density that still achieves effective colloid filtration</td></tr>
</table>

Issue	Potential causes in engineering practice	PA assumptions or parameters potentially affected	Potential effects on system performance	Information required to quantify effects	
				General	Engineering
		Microbial activity is low within the saturated buffer	Reduced canister lifetime	Minimum buffer density that still suppresses microbial activity	
		Transport in the buffer is diffusion-dominated	Advective transport gives reduced attenuation of radionuclide releases by buffer	Minimum buffer hydraulic conductivity that still ensures diffusion-dominated transport; hydraulic conductivity as a function of buffer density	
		Radionuclide diffusion parameters for buffer based on design buffer density	Increased radionuclide diffusion rates	Diffusion parameters as a function of buffer density	
High average buffer density (with respect to design value)	▪ Emplaced buffer density too high ▪ Accumulation due to piping/erosion elsewhere ▪ Corrosion expansion of metals (e.g.	Buffer swelling pressure insufficient to perturb host rock by opening existing fractures or creating new fractures	Reduced attenuation of radionuclide releases during geosphere transport	▪ Stress distribution in host rock ▪ Rock strength ▪ Fracture behavior under high stress (by in-situ test)	Range of possible buffer density increase due to identified potential causes by e.g. LT experiment or

Issue	Potential causes in engineering practice	PA assumptions or parameters potentially affected	Potential effects on system performance	Information required to quantify effects	
				General	Engineering
	PEM, canister) ▪ Volume reduction due to tunnel convergence (e.g. OPA case)	Buffer swelling pressure insufficient to lead to isostatic collapse of canister	Reduced canister lifetime (isostatic collapse or stress induced corrosion) N.B. canister thickness is determined by radiolysis of the water and some margin exists for stress failure in H12 case	▪ Minimum swelling pressure required for isostatic collapse ▪ Swelling pressure as a function of buffer density	modeling
		Buffer sufficiently plastic to protect canisters against small rock shear movements	Reduced canister lifetime		
		Relatively fast saturation leading to high/moderate thermal conductivity of buffer	Low thermal conductivity of buffer resulting in heat degradation of buffer properties	Saturation period of high density buffer materials	
Heterogeneous buffer density (design value may be achieved on average)	▪ Gaps between bentonite blocks ▪ Gaps at top of tunnel ▪ Localized piping and erosion ▪ Heterogeneous filling with pellets ▪ Difference in density between block-filled and pellet-filled parts of buffer	▪ Buffer transport properties homogeneous (or at least diffusion-dominated in any location) ▪ No regions of locally reduced density giving advective transport paths	Advective transport paths through buffer give reduced limitation of radionuclide releases by buffer	▪ Degree and rate of homogenization of buffer ▪ Possibility of continuous low density and low hydraulic conductivity transport paths	Range of possible local buffer density variations due to identified potential causes by, e.g. in-situ emplacement test
		Pressure on canister is uniform (isostatic) following buffer saturation	Reduced canister lifetime (collapse due to non-uniform loading)	Degree and rate of homogenization of buffer	
Buffer-rock interface may be perturbed					

Issue	Potential causes in engineering practice	PA assumptions or parameters potentially affected	Potential effects on system performance	Information required to quantify effects	
				General	Engineering
Physical disturbance of buffer/rock interface (EDZ, rock spalling)	▪ Stress relief during excavation ▪ Long-term development of EDZ due to high stress and creep behavior ▪ Thermal-mechanical impact of heat-emitting waste	Buffer/rock interface treated as highly conductive "mixing tank" (H12 assumption may be over-conservative if disturbance is small; see Section 4.3.2)	Extent of physical disturbance affects rate of radionuclide transport across buffer/rock interface	▪ Rock stress distribution ▪ Thermal-mechanical properties of rock ▪ Local rate of buffer saturation and swelling pressure build-up ▪ Self-sealing capacity of rock	▪ Drift separation and canister pitch ▪ Use of rock support ▪ Physical extent and hydraulic properties of disturbed zone
Degradation of tunnel support (e.g. shotcrete, liner)	▪ Tunnel support required under some conditions (e.g. soft rock)	Tunnel support will not be a preferential flow path	Due to the degradation of tunnel support, concrete becomes porous and acts as a radionuclide transport pathway along the tunnel	▪ Long-term degradation of cementitious materials ▪ Properties of degraded concrete	▪ Type and amount of concrete used for tunnel support
Cement/bentonite interactions and cement/rock interactions	High-pH leachates from cement in plugs and seals, concrete flooring, shotcreting, etc.	Physical and chemical properties of buffer and host rock unperturbed by cement/rock interactions	Similar to iron/bentonite interactions (below) but note that high-pH conditions, if they were to reach the canister surface, could be favorable in terms of corrosion rate	▪ General scientific understanding of rates and products of cement /bentonite interactions and cement/rock interactions ▪ Mass transport properties and long-term stability of the interaction products	▪ Reference design (including quantities and distribution of cementitious components) ▪ Likelihood of removal of cementitious components

Issue	Potential causes in engineering practice	PA assumptions or parameters potentially affected	Potential effects on system performance	Information required to quantify effects	
				General	Engineering
Iron/bentonite interactions	Corrosion of steel handling shell (PEM), transportation rails, liner, etc.	Physical and chemical properties of buffer and host rock unperturbed from interactions with cement	Loss of swelling pressure could give increased mass transfer across buffer/rock interface; potential for flow and radionuclide transport along this interface Change to a less plastic material could compromise the ability of the buffer to protect the canister from rock movements Change to a less plastic material with reduced self-sealing capacity could lead to buffer fracturing and reduced attenuation of radionuclide releases by affected parts of buffer	▪ General scientific understanding of rates and products of iron/bentonite interactions ▪ Mass transport properties and long-term stability of the interaction products	▪ Reference design (including quantities and distribution of iron/steel components) ▪ Likelihood of removal of iron/steel components
Engineered barrier system may generate gas					
Impact of repository-generated gas	Corrosion of steel handling shell (PEM), transportation rails, rock bolts, liner, etc.	No accumulation of gas; physical and chemical properties of buffer and host rock unperturbed by gas pressurization and transport	▪ Gas transport pathways could (if not resealed) provide preferential pathways for radionuclide transport ▪ Delayed repository saturation where host rock relatively tight could	▪ Gas generation rate and migration behavior ▪ General scientific understanding of gas transport in the buffer (including breakthrough pressures),	▪ Reference design (including quantities and distribution of iron/steel components) ▪ Likelihood of removal of iron/steel components

Issue	Potential causes in engineering practice	PA assumptions or parameters potentially affected	Potential effects on system performance	Information required to quantify effects	
				General	Engineering
			delay/limit radionuclide releases	EDZ and host rock ▪ Self-sealing capacity of these components following gas breakthroug h	
Engineered barrier system may interact with stray materials					
Interactions involving other stray materials	Stray materials of interest to PA include those containing nitrogen compounds, such as ammonium nitrates and NOx species injected into rock during blasting, and organic materials	No significant interactions involving other stray materials	Organic materials (including materials such as plastics, cellulose, hydraulic oil and surfactants, and also cement additives released as cement degrades) will decompose and add reducing capacity to the repository near field	Rate of decompositio n of nitrogen compounds; potential complexes and their sorption properties	Range of possible quantities and compositions of stray materials
			Organic materials could form complexes with radionuclides that would lower radionuclide sorption and thus increase radionuclide release and transport rates		
			Nitrogen compounds could potentially damage the canister surfaces		

A.2.3 Significance of the issues from a PA perspective - example of issues affecting buffer density

In order to evaluate whether potential deviations from the target value for saturated buffer density are significant from a PA perspective, two questions need to be addressed:

- What is the potential range of deviation?
- What is the range of values for buffer density consistent with the buffer performing its safety functions?

The potential range of deviation can be assessed using detailed process modeling, simplified scoping calculations or qualitative arguments, depending on the understanding that is available for the different potential processes leading to the loss or redistribution of buffer mass.

Several scoping calculations have been performed for such processes in the course of the safety assessment for a KBS-3H repository at the Olkiluoto site, Finland (Gribi et al., 2007; Smith et al., 2007).

Figure A.3 shows, as an example, the results of scoping calculations of variations in buffer density caused by piping and erosion during the repository operational period and subsequent period of buffer saturation.

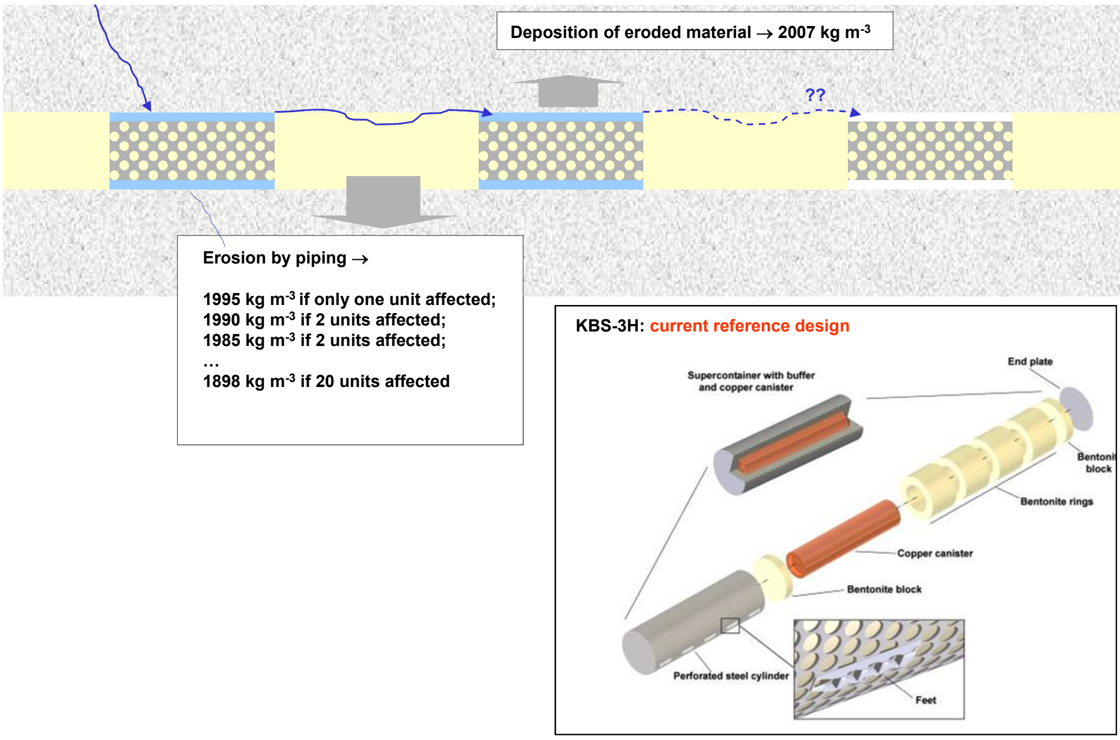

Figure A.3 Example layout adaptation of a KBS-3H repository at Olkiluoto (see Gribi et al., 2008; Smith et al., 2008).

In the current KBS-3H reference design, as analyzed in Gribi et al. (2007) and Smith et al. (2007), each copper canister, with a surrounding layer of bentonite clay, is placed in perforated steel cylinders prior to emplacement in horizontal deposition drifts. The entire canister/buffer/cylinder assembly is called the supercontainer. There is an initial gap between each supercontainer and the drift wall, which becomes filled with bentonite as the buffer swells. The supercontainers are separated one from another by relatively tightly fitting bentonite distance blocks.

During operation of the drift and subsequent saturation, localized water inflow, which could vary significantly along the drift, may potentially give rise to large hydraulic pressure differences between the void spaces around neighboring supercontainers. This is because water will enter these void spaces at different rates, depending on the local characteristics of intersecting water-conducting fractures. The concern is that, if high pressure differences develop too rapidly, this could result in transient water flows ("piping") along the interface, which could in turn lead to erosion and loss of bentonite density in some supercontainer sections and possibly an increase in density in others.

The scoping calculations show how the saturated buffer density of the buffer in the drift section where piping originates varies according to the (uncertain) number of downstream supercontainer units affected. The results indicate that the average saturated density is:

- 1995 kg m^{-3}, if only 1 supercontainer unit is filled with a water / bentonite suspension
- 1990 kg m^{-3}, if 2 supercontainer units are filled
- 1985 kg m^{-3}, if 3 supercontainer units are filled
- 1898 kg m^{-3}, if 20 supercontainer units are filled.

In the downstream supercontainer units that become filled with the water / bentonite suspension due to piping and erosion, the average saturated density of the buffer is increased to 2007 kg m 3, irrespective of the number of filled units.

The issue of what is the range of values of buffer density consistent with the buffer performing its safety functions has been addressed by SKB in the SR-Can safety assessment (SKB, 2006). SR-Can introduced the concepts of safety function indicators and safety function indicator criteria. A safety function indicator is a measurable or calculable property of the system that is critical to a safety function being fulfilled. If the safety function indicators fulfill certain criteria, then the safety functions can be assumed to be provided. If, however, plausible situations can be identified where the criteria for one or more safety function indicators are not fulfilled, then the consequences of loss or degraded performance of the corresponding safety function should be evaluated in PA. Safety function indicators for the buffer include buffer density and also other properties that are related to density, namely swelling pressure and hydraulic conductivity. The associated safety function indicator criteria developed by SKB are shown in Table A.4.

Table A.4 Safety function indicator criteria related to buffer density (based on SKB, 2006).

Buffer property	Criterion	Rationale
Bulk hydraulic conductivity	$< 10^{-12}$ m s^{-1}	Avoid advective transport in buffer
Swelling pressure at drift wall	> 1 MPa	Ensure tightness, self-sealing
Swelling pressure in bulk of buffer	> 2 MPa	Prevent significant microbial activity
	> 0.2 MPa	Prevent significant canister sinking
Saturated density	> 1650 kg m^{-3}	Prevent colloid-facilitated radionuclide transport
	< 2050 kg m^{-3}	Ensure protection of canister against rock shear

In PA, the buffer safety functions can be assumed to be provided as long as these various criteria are satisfied. However, in order to evaluate whether or not processes such as piping and erosion that give rise to buffer mass loss or redistribution can potentially lead to a failure to meet the criteria on swelling pressure and hydraulic conductivity, the particular relationship between these indicators and buffer density needs to be considered. This is complicated by the fact that swelling pressure and hydraulic conductivity are functions not only of buffer density, but also of the ionic strength of the buffer porewater (see, e.g. Figure A.4) and so the relationships are both site-specific and potentially time-dependent.

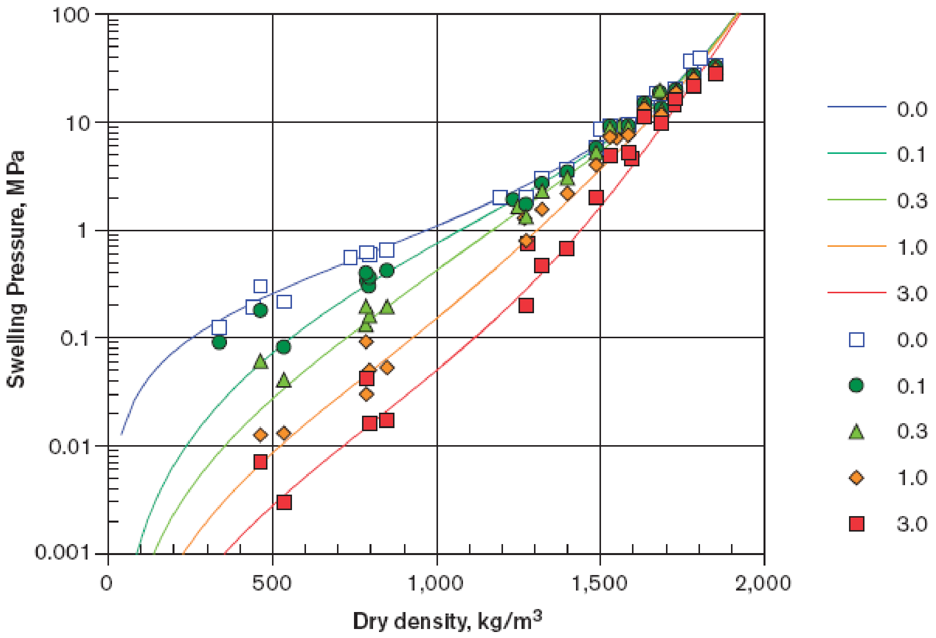

Figure A.4 Relationship between buffer swelling pressure, dry density and ionic strength, expressed as molar NaCl concentrations (after Figure 4-7 in SKB, 2006).

In the safety assessment of a KBS-3H repository at Olkiluoto, using these relationships and taking into account the expected site-specific evolution of ionic strength over time, a range of saturated buffer densities was derived - 1890 to 2050 kg m-3 - that, if maintained, should ensure that the buffer safety functions are provided, taking into account the evolution of groundwater and buffer porewater salinity until any future major climate change (Figure A.5; see Section 5.3.2 of Smith et al. 2007 for details).

Based on the above-mentioned scoping calculations, it was concluded in the safety assessment of a KBS-3H repository at Olkiluoto that the redistribution of bentonite by piping / erosion in a KBS 3H deposition drift has no significant effect on the density of bentonite (i.e. buffer density remains within the range 1890 to 2050 kg m-3), provided that only a few supercontainer units are filled and provided local density changes are quickly homogenized by the plasticity of bentonite.

If engineering or other issues are identified that could give rise to densities outside this range and PA analyses show that the consequent loss of buffer safety functions may have an unacceptable detrimental impact on safety, modified engineering designs may need to be considered. This is an example of feedback from PA to engineering design (Figure A.1).

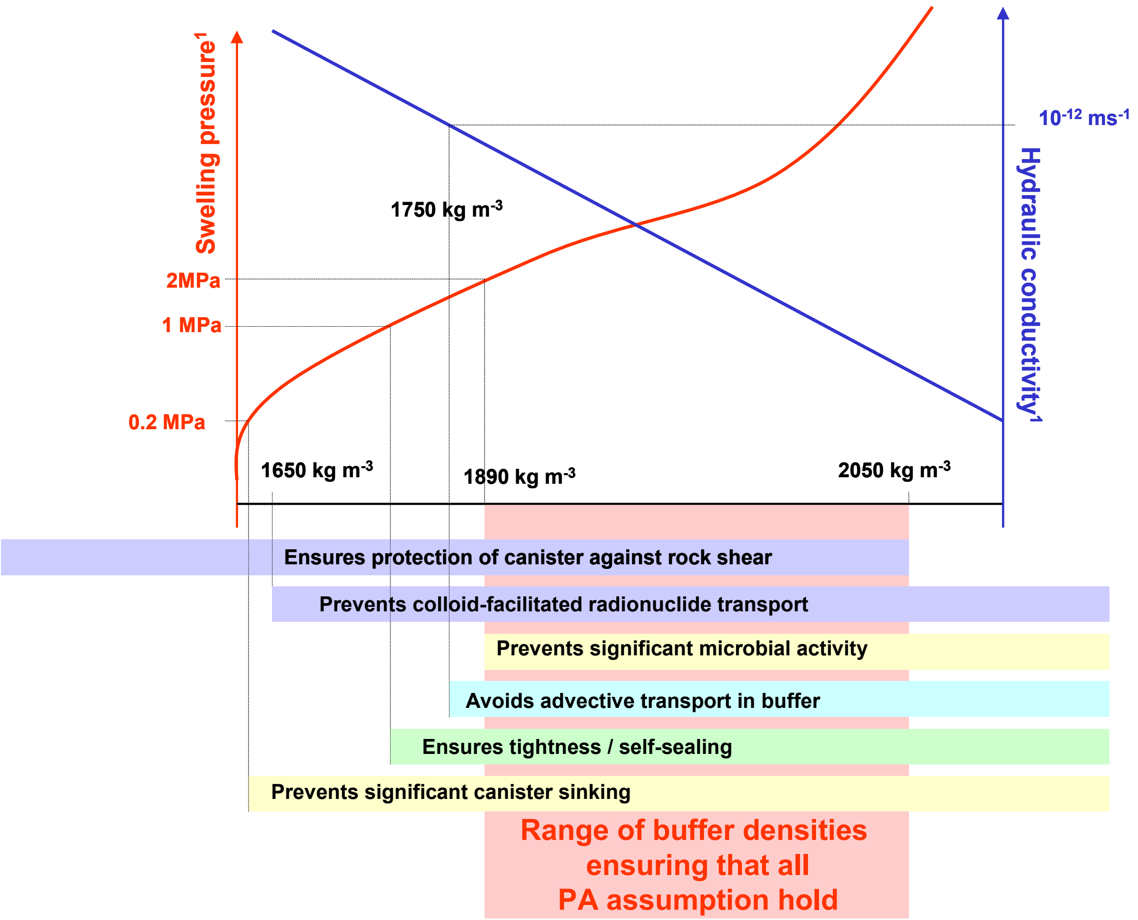

Figure A.5 Deriving a range of buffer density that, if maintained, should ensure that all the safety functions of the buffer are provided (typical PA assumptions hold).

Example from the safety assessment of a KBS-3H repository at Olkiluoto (see Section 5.3.2 of Smith et al., 2007 for details).

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原子力発電環境整備機構

（略称:原環機構）

Nuclear Waste Management Organization of Japan (NUMO)