Safety Assessment Methodologies for Near Surface Disposal Facilities

Results of a co-ordinated research project

Volume 1

Review and enhancement of
safety assessment approaches and tools

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FOREWORD

For several decades, countries have made use of near surface facilities for the disposal of low and intermediate level radioactive waste. In line with the internationally agreed principles of radioactive waste management, the safety of these facilities needs to be ensured during all stages of their lifetimes, including the post-closure period. By the mid 1990s, formal methodologies for evaluating the long term safety of such facilities had been developed, but intercomparison of these methodologies had revealed a number of discrepancies between them.

Consequently, in 1997, the International Atomic Energy Agency launched a Co-ordinated Research Project (CRP) on *I*mprovement of *S*afety *A*ssessment *M*ethodologies for Near Surface Disposal Facilities (ISAM). The particular objectives of the CRP were to:

- provide a critical evaluation of the approaches and tools used in post-closure safety assessment for proposed and existing near-surface radioactive waste disposal facilities;
- enhance the approaches and tools used;
- build confidence in the approaches and tools used.

The CRP ran until 2000 and resulted in the development of a harmonized assessment methodology (the ISAM project methodology), which was applied to a number of test cases. Over seventy participants from twenty-two Member States played an active role in the project and it attracted interest from around seven hundred persons involved with safety assessment in seventy-two Member States.

The results of the CRP have contributed to the Action Plan on the Safety of Radioactive Waste Management which was approved by the Board of Governors and endorsed by the General Conference in September 2001. Specifically, they contribute to Action 5, which requests the IAEA Secretariat to "develop a structured and systematic programme to ensure adequate application of the Agency's waste safety standards", by elaborating on the Safety Requirements on "Near Surface Disposal of Radioactive Waste" (Safety Standards Series No. WS-R-1) and the Safety Guide on "Safety Assessment for Near Surface Disposal of Radioactive Waste" (Safety Standards Series No. WS-G-1.1).

The report of this CRP is presented in two volumes; Volume 1 contains a summary and a complete description of the ISAM project methodology and Volume 2 presents the application of the methodology to three hypothetical test cases.

The IAEA expresses its appreciation to all ISAM participants who contributed to the success of the project and to the preparation of the associated documentation, and to R. Little (UK) for technical review of the report. The IAEA officers responsible for the ISAM project were C. Torres-Vidal and B. Batandjieva of the Division of Radiation, Transport and Waste Safety.

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SUMMARY

For over forty years now, many countries have been developing near surface facilities for the disposal of low and intermediate radioactive waste (LILW) generated within the nuclear fuel cycle and from the use of radioactive sources for different purposes. In line with the internationally agreed principles of radioactive waste management and the related safety standards, the safety of these facilities needs to be ensured during all stages of their lifetime, including the post-closure period. Formal methodologies for evaluating the long term safety of such facilities have been developed over the years, but intercomparisons of these methodologies carried out by the IAEA [1] have revealed a number of discrepancies between them. As a result of these findings, the IAEA organized a co-ordinated research project on Improvement of Safety Assessment Methodologies for Near Surface Disposal Facilities (ISAM) to improve and harmonize the approach to such safety assessment, which has resulted in development of the ISAM project methodology.

The ISAM project involved the review and enhancement of post-closure safety assessment methodologies and tools for both existing and proposed near surface radioactive waste disposal facilities. The main objectives of the project were to:

(a) Provide a critical evaluation of the approaches and tools used in the post-closure safety assessment of proposed and existing near surface radioactive waste disposal facilities;
(b) Enhance the approaches and tools used;
(c) Build confidence in the approaches and tools used.

In order to help achieve these objectives, the ISAM project paid particular attention to discussing, agreeing and setting down a safety assessment methodology.

The ISAM project primarily focused on developing a consensus on the methodological aspects of safety assessment, but also gave considerable attention to illustrating the application of the methodology to three main types of disposal facilities (vault, RADON and borehole type disposal facilities).

THE ISAM PROJECT METHODOLOGY

Taking into consideration the more recent approaches to safety assessment for near surface disposal facilities, the ISAM project identified the need to address the following key components:

- Specification of the assessment context;
- Description of the waste disposal system;
- Development and justification of scenarios;
- Formulation and implementation of models;
- Analysis of results and building of confidence.

Each of these components was extensively analysed and discussed during the project and the results and conclusions are summarized below.

Specification of assessment context

Post-closure safety assessment of a radioactive waste disposal facility is generally undertaken to provide an assurance to stakeholders (such as government, regulatory authorities, the

general public and other technical/scientific groups) that the facility has been or will be sited, designed, constructed, operated and closed in such a manner as to ensure protection of humans and the environment over long timescales. However, this generic objective does not provide a very precise description of what has to be considered in the assessment. Throughout the development of a disposal facility (i.e. the siting, design, construction, operation, closure, post-closure steps), the safety assessment will also be performed, becoming more detailed and specific as the facility evolves. At the early stages of the development of the facility, where a number of sites or a number of design options may be under consideration, a more general assessment may be undertaken with less detailed information on the exact waste inventory and form, the disposal facility design or the facility site. Following selection of a site, much more detailed information will become available on the site and its characteristics and detailed design options will be considered. For existing sites there may be a need to update an already existing assessment or carry out a completely new assessment. As such, the context in which the assessment is being carried out will significantly influence its structure, content and level of detail.

The safety assessment context is intended to clarify what is going to be assessed and why is it going to be assessed. In addressing the assessment context, information should be provided concerning the following key aspects that need to be considered at the start of the safety assessment: purpose; regulatory framework; assessment end-points; assessment philosophy; disposal system characteristics; and time frames. It should be noted that many components of the assessment context are inter-related, and that decisions relating to one component can influence other components. For example, the end-points assessed should be appropriate for the time frames considered in the assessment.

Purpose

Most safety assessments of radioactive waste disposal facilities have the principal purpose of demonstrating that an acceptable level of protection of human health and the environment will be achieved both now and in the future. In addition to this overall demonstration of safety there can be a variety of additional purposes, such as derivation of quantitative acceptance criteria.

In any specific case, however, the purpose of conducting an assessment may vary from considering initial ideas for disposal concepts using simple calculations, to support for a licence application for disposal or for upgrading the safety of an existing facility; requiring detailed, site specific safety assessment to demonstrate compliance with regulatory criteria.

The party to whom the outcome of the safety assessment will be presented should be considered. The general purpose and the target group (e.g. regulators, operators, waste producers, public, local, regional and national politicians) will play a role in defining relevant assessment end-points, assumptions concerning the disposal system, justification of the assessment scenarios, as well as the approach for presentation of the assessment results.

Regulatory framework

In undertaking an assessment, it is necessary to consider the regulatory requirements that are relevant to the safety assessment. At one extreme these may be specified, prescriptive quantitative requirements, and at the other they could be non-prescriptive performance oriented requirements or may not have been fully developed. In all cases, it is important that consideration should be given to international guidance on the regulation of radioactive waste disposal such as the IAEA Principles of Radioactive Waste Management [2], the Safety

Requirements for Near Surface Disposal of Radioactive Waste [3], the Safety Guide on Safety Assessment for Near Surface Disposal of Radioactive Waste [4] and Publications 77 and 81 of the International Commission on Radiological Protection (ICRP) [5, 6].

Assessment end-points

The end-points of an assessment need to be well defined and correspond with the safety assessment purpose, and the associated regulatory framework, and take into account the assumptions made concerning timescales and critical groups.

An additional consideration is the trend in safety case development not to rely on evaluation of just a single end-point, such as individual dose or risk (dose was the most commonly used end-point in a survey of ISAM participants, see this document). Multiple lines of reasoning may be useful since the use of a wider range of arguments and end-points will help to establish the adequacy of a safety case. A variety of additional indicators may be used to complement those of dose and risk (such as radionuclide fluxes and concentrations).

Assessment philosophy

The assessment philosophy is an expression of the extent to which the assessment is designed to provide a “realistic” estimate of potential impacts for comparison with the assessment end-points, or whether more cautious, or pessimistic assumptions should be adopted for the purposes of demonstrating compliance with safety requirements.

Disposal system characteristics

The disposal system can be considered to consist of: the near field, the geosphere, and the biosphere. These components are described in more detail in the next step of the assessment approach, the system description. However, it is useful to provide, within the assessment context step, a brief overview of the present-day system and to document any associated fundamental assumptions.

As part of the initial description of the system, assumptions concerning future human actions should be defined, such as the level of technological development, type of society, and the basis for its habits and characteristics. Similarly, assumptions concerning the characteristics of any groups of people, who might potentially be exposed to radionuclides migrating from the disposal facility, should also be defined. Alternatively they can be defined during the scenario development and justification process. What is important is that these assumptions are clearly identified and as far as possible justified at either of these two stages of the assessment process.

Assessment time frames

The waste disposal option adopted should ensure equitable protection of both current and future generations and this will involve balancing greater certainty for shorter time periods with increasing uncertainty over longer time periods. The timeframe for the post-closure safety assessment should be defined, recognising the inherent limitations and uncertainties in assessment approaches, as well as constraints on the scientific credibility of long term estimates of disposal facility performance, which could be influenced by large-scale environmental changes. The timescale of interest for an assessment is a function of the nature of the waste disposal system and the external influences on it, and the longevity of the radionuclides in the wastes. Therefore the timescales of an assessment should be justified on a case-by-case basis, although some may also stem from regulatory requirements (e.g. institutional control period).

Description of disposal system

The disposal system description needs to collate information on:

- *the near field* - e.g. waste types, waste forms, waste inventory, waste emplacement practices, engineered barriers, facility dimensions;
- *the geosphere* - e.g. lithology, hydrogeology and transport characteristics; and
- *the biosphere* - e.g. exposure pathways, human habits and behaviour.

This aspect of the safety assessment is important as it provides the information about the disposal system upon which the safety assessment will be carried out. It is necessary to ensure that the data collected are sufficient for the assessment context and appropriate description of the system. The limited availability or adequacy of data is an important factor in many safety assessments and hence when developing the system description, it is important to be aware of and to document any assumptions made and the associated uncertainties.

Development and justification of scenarios

The safety assessment for a waste disposal facility should address the performance of the disposal system under both present and future anticipated conditions, including events associated with the normal evolution of the facility and less probable events. This means that many different factors (e.g. conceptual model and parameter uncertainty, long time periods, human behaviour and climate change) need to be taken into account and evaluated in a consistent way, often in the absence of complete quantitative data. A very broad range of combinations can result from these considerations, which need to be addressed in a manageable way. This is often achieved through the formulation and analysis of a set of scenarios describing alternative future evolution and conditions. The selected scenarios need to provide a comprehensive picture of the system and its possible evolution within the assessment context and based on the system description. The choice of appropriate scenarios and associated conceptual models is very important and strongly influences the subsequent safety assessment of the waste disposal system.

There are several methods that can be used to generate scenarios. These may involve expert judgement, fault tree analysis and event tree analysis. A common element in many scenario generation methodologies is the systematic identification and consideration of Features, Events and Processes (FEPs) that can directly or indirectly affect the release and transport of radionuclides from a disposal facility. Whatever approach is selected, it is necessary to ensure that the scenario generation process is systematic, comprehensive, logical and transparent. By adopting such an approach, a defensible representation of the system and its likely evolution over time can be developed.

Formulation and implementation of models

Once the scenarios have been developed, their consequences need to be determined. First a conceptual level model representing each scenario should be established. Various assumptions will be necessary for this process addressing issues such as boundary conditions, FEPs, FEP relationships, etc. For some scenarios it may be necessary to use a qualitative assessment approach (e.g. when data are not available). For the scenarios that are to be assessed quantitatively, the scenarios need to be organized into a form that is amenable to mathematical representation. The conceptual models for each scenario must then be expressed in mathematical form, with appropriate and adequate initial boundary conditions. Application of the mathematical models is usually carried out by making use of one or more computer tools employing analytical and/or numerical techniques and appropriate input data. It is necessary to ensure that the selected models and associated data are appropriate and adequate for the assessment context and that they adequately represent the disposal system. The ability of the computer tools to solve the mathematical models correctly and accurately needs to be verified. Further, confidence needs to be developed in the model – that is if field and/or experimental results can be reproduced with sufficient accuracy (the process of validation). In this regard it must be borne in mind that there are limitations to the time frames over which such validation is possible.

Analysis of results and building of confidence

Once the scenarios and associated conceptual and mathematical models have been developed and implemented into software tools and the associated data collated, calculations should be undertaken to make an assessment of the impacts of the disposal facility. The results then need to be collated and analysed and comparison made with criteria set down for the particular assessment context. These will in most cases include regulatory criteria, although design and economic constraints may also be a major consideration. When analysing the results from an assessment, consideration should be given to the various sources of uncertainty (e.g. scenario, model, data uncertainty).

The final outputs from the assessment often have to be presented to different audiences and for different purposes. It is also therefore important that due care is given to selecting the approaches and means for presenting the results for the various interested audiences.

It is very important that the various parties who make use of the results have a reasonable degree of confidence in them and in the underlying assessment. Confidence in the results is strongly related to the consistency, logic and transparency of the overall safety assessment methodology used. Decisions on the adequacy of the assessment have to be made based on an interpretation and analysis of the safety assessment results and supporting arguments.

It is important to underline that the entire safety assessment process is iterative and that the first iteration in the process will usually be followed by one or more iterations. This process allows consideration of improvements to and optimization of the disposal system regardless of how favourable results initially appear. Subsequent iterations will often contribute to decisions on whether the safety case is adequate or if there is a need for further improvements. It also provides confidence in the understanding of the main safety related parameters (e.g. through sensitivity analysis) and the robustness of the disposal system under the assumed scenarios. Early iterations are undertaken with the data and assessment capability available at the time, and the iterations need only proceed until the assessment is judged to be adequate for its purpose. Furthermore, new data only need to be collected to the extent that they are required in order to reduce uncertainties with a view to providing an adequate basis for the decision.

TECHNICAL OUTCOMES

Review and enhancement of safety assessment approaches and tools

Development and justification of scenarios

The process of scenario development and justification has been debated at length and in depth over a number of years by the specialists involved in safety assessment for disposal waste facilities (see for example Refs [7] and [8]). Although several well-documented methodologies already exist for the generation of FEPs lists, the procedures for moving from an FEPs list to a set of justified scenarios has not often been well developed and documented in safety assessments for near surface disposal facilities. Therefore, a number of scenario development and justification approaches were developed and their application demonstrated in the ISAM Test Cases (see Volume II).

Since the development of an FEPs list is a common activity in many scenario generation methodologies, the development of an ISAM FEPs list for near surface disposal facilities was also undertaken by the Scenario Working Group and applied in three test cases (see Volume II). The Nuclear Energy Agency (NEA) FEPs list [9] for geological disposal facilities for solid radioactive waste was adopted and revised for use in near surface disposal facilities. The ISAM FEPs list, consisting of high level FEPs that could influence the behaviour of a near surface disposal system, is considered to be a useful tool when generating and comparing FEPs lists for specific safety cases.

The following points have been identified as important in the development and justification of scenarios:

- Scenario generation is an essential component of the safety assessment process, since scenarios are commonly used in post-closure safety assessments to address uncertainties associated with the future evolution of a disposal system.

- The definition of *scenario*, *feature*, *event* or *process* can be difficult and not straightforward. It is important to ensure that clear definitions of terms such as normal and alternative scenarios are consistent with the purpose and scope of the assessment, as well as the approach followed to generate the scenarios.

- It is important to use a systematic approach for scenario development and justification that clearly identifies and documents the underlying assumptions.This helps to make the scenario generation process transparent and facilitates its review. It also helps to provide an assurance that the assessment has effectively addressed all the potentially relevant FEPs and the interactions between them and to producean appropriate range of scenarios. There is no single approach for scenario generation that should be used in all assessments and therefore it is necessary to ensure that the approach selected is consistent with the overall objective and framework of the assessment as described in the assessment context.

- The use of an FEPs list plays a pivotal role in most approaches to scenario generation, although its application may vary depending on the assessment context. The list can be reduced (or enlarged) to satisfy site specific needs using expert judgement or pre-determined screening criteria, nonetheless the screening processes should be documented in a traceable and transparent manner.

— In most assessments, a scenario (often called the reference or design scenario) is developed for initial consideration and alternative scenarios are then developed to investigate the impact of scenarios that differ to a lesser or greater extent from the reference scenario. The reference scenario is often, but not always, considered to be the most likely scenario for the given safety assessment; however, it is usually considered to be a benchmark scenario against which the impact of alternative scenarios can be compared. In ISAM, for the sake of consistency, the term 'design scenario' was chosen for the reference scenario. The design scenario represents how the system might be expected to evolve, assuming that the design functions as planned.The consideration of alternative assumptions about external influences and their implications for the evolution of the system leads to identification of alternative scenarios.

— Several tools can be used to visually represent FEPs and their interactions in a logical, traceable and systematic way. However, it is emphasized that there is no single technique that is the best available for this function; each technique has its own particular strengths and weaknesses. The ISAM CRP showed that interaction matrices are amongst the more useful tools for illustrating the interactions between FEPs.

Formulation and implementation of models

Prior to the ISAM co-ordinated research project (CRP), the process of developing conceptual models for the assessment of near surface disposal facilities had often been conducted as a largely informal process in which assumptions and decisions were not well documented.However, conceptual models are fundamental to the transparency of a safety assessment and safety case and their defensibility, and are frequently the focus of attention for independent reviewers. The ISAM project therefore focussed on approaches that could be used to formalize the process of conceptual model development and justification. A number of approaches were evaluated in the ISAM project that would provide a robust basis for the treatment of alternative conceptual models in a traceable manner.

Many mathematical models of varying degrees of sophistication have been developed and documented to represent the processes considered in safety assessments (i.e. those associated with the migration and fate of radionuclides in the near field, in the geosphere and in the biosphere). A summary of the main models used, noting the associated assumptions and limitations, is provided in this report. Numerous computer tools have been developed to solve the mathematical models and a list of these has also been collated and presented in this document, along with example data for commonly used input parameters. One of the important issues associated with these computer tools is their verification and the application of quality assurance in their development and use, which is addressed in this report.

The following main points relating to the development and implementation of models were identified as important:

— The development of models for safety assessment should be carried out in a formal and transparent way that facilitates independent review. It covers the following three main stages:

(i) The generation of conceptual models describing the disposal system behaviour using information from the assessment context, system description and scenario generation steps of the safety assessment. A conceptual model needs to be made up of a description of: the basic FEPs; the relationship between these FEPs; and the scope of application in spatial and temporal terms. For the process of developing conceptual models it can be helpful to divide the system to be assessed into the near field, the geosphere, and the biosphere.

(ii) The representation of conceptual models and their associated processes in mathematical models. This usually involves sets of coupled algebraic, differential and/or integral equations with appropriate initial and boundary conditions in a specified domain.

(iii) Application of mathematical models in computer tools to solve the mathematical models. Four main groups of codes can be identified, those for: the near field; geosphere; biosphere; and the total system.

— The models used should be as simple as possible, whilst including sufficient detail to represent the disposal system behaviour adequately for the purpose of the assessment (e.g. ensuring compliance with relevant safety requirements). In particular, the model chosen should be consistent with the assessment objective, easy to use (considering the complexity of the system), and one for which data can be obtained. A simple modelling approach is likely to be more efficient, easily understandable and justified. However, it is also important to ensure that there is sufficient understanding of the disposal system and the related FEPs and scenarios that the models represent, thereby ensuring that the resulting analysis provides a meaningful assessment of the performance of the system. Assumptions should be made on the basis of available data and knowledge of the system or similar systems. The level of detail to which the models are developed will be a function not only of the assessment context but also of the stage in the disposal facility life cycle. For example, during the early stages (such as site selection or initial investigations) it might be sufficient to generate relatively simplistic models for scoping purposes, whilst models for later stages (such as the regulatory submission for the licensing of disposals) will need to be more comprehensive.

— Throughout this process, data are used to help develop the conceptual and mathematical models and provide input into the computer tools.The performance of safety assessment usually requires a significant amount of information and data related to the disposal system. The data are used throughout the safety assessment process, particularly in scenario development and justification, model formulation and implementation, and in the interpretation of the results. A number of issues were identified which should be considered:

(i) The sources of uncertainty in parameter values and methods for dealing with them in the safety assessment;
(ii) The use of generic data in the absence of site specific data and the trade-off between the use of generic data and the requirement for the collection of further site data; and
(iii) The choice of methods used to select appropriate ranges for input parameters.

— It should be borne in mind that uncertainties are associated with all stages of model formulation and implementation. These uncertainties need to be identified and quantified as part of the safety assessment, and reduced as far as possible.

— It is particularly important that, in common with the rest of the safety assessment procedure, the development of models and their implementation should be seen as an iterative process. Any lessons learnt in applying the model and interpreting its results should be used to re-consider assumptions and decisions made during the course of the model development. It is likely that such information can be used to refine the model, perhaps by identifying particularly important FEPs or sensitive parameters.

Building confidence

Developing confidence in the safety assessment and its outcomes involves a range of considerations. As discussed above, the assessment itself should be transparent, the scenarios used should be justified and the models representing the scenarios adequate and appropriate. Also important is a comparison of the safety assessment results with both national regulatory criteria and international guidelines. Some regulations may also include specific design criteria or release criteria. The Confidence Building Group considered which main regulatory requirements currently existed and which internationally agreed principles and standards were being applied in safety assessment activities in 17 countries.

A variety of indicators have been used in different countries to assist in interpreting the results of assessments for near surface disposal facilities and in considering the safety and acceptability of disposal facilities. These indicators include levels of natural background radiation; natural background concentrations of contaminants; risks arising from other activities; and/or concentrations of contaminants for which there have been no observed health effect. A list of relevant indicators was compiled and is presented in this document.

Sensitivity analysis can also contribute to the building of confidence in the results of safety assessments. Through this type of analysis the overall robustness of the disposal system can be demonstrated. Sensitivity analysis may also allow attention to be focused on those components of the system where the greatest performance increases can be obtained - and thereby assist in making decisions on design and regulatory acceptance. Methods and tools that have been found useful in performing sensitivity analyses have been catalogued in this report.

Different methods can be used for the presentation of results and the ISAM CRP investigated their usefulness. Many alternative representations are possible for displaying uncertainties and sensitivity analysis results for both deterministic and stochastic modelling outputs. Dose versus time curves showing the contribution to dose from significant radionuclides have been widely used. Other measures can also be adopted to help provide confidence including demonstration of transparency in all aspects of the assessment, providing additional information in support of the assessment (e.g. natural analogues) demonstrating good science and good engineering practice and application of a good quality assurance programme.

The following points relating to confidence building were identified as important:

- Safety assessments are structured in a way that provides maximum confidence in the decisions that are made relating to the radioactive waste disposal facility. Therefore confidence building is a process that needs to be followed through all steps of the safety assessment process.

- A majority of disposal regulations on near surface disposal are based on estimated doses to individuals, with estimated risk to individuals also used in some countries. However, safety assessments use a range of other criteria in addition to regulatory criteria, for comparing their modelling results. A common safety indicator used for comparison of estimated doses are natural background doses.

- The most appropriate method to represent the physical and chemical processes in mathematical models has not always been clear and model inter-comparison studies provide some insight into the effect of choosing different conceptual models or different mathematical representations of a conceptual model.

— In defining and considering the assessment context it is important to make use of safety criteria (in addition to those imposed by regulation) that should be:

(i) Reliable, based on well established principles and applicable over a wide range of situations;
(ii) Relevant to the safety and the features of the disposal facility and environment;
(iii) Simple and facilitate communication;
(iv) Directly and closely linked to the features of the system;
(v) Understandable for the different stakeholders;
(vi) Practical and available tools.

— Formalized quality assurance (QA) procedures are essential for the building of confidence in safety assessments for near surface disposal facilities, particularly procedures based on international standards. Their use helps build confidence in the assessment and its associated results. The ISAM CRP has contributed in this respect by developing a Parameter Input Form and Document Review Form for use in the safety assessment process.

— A variety of communication methods are actively being used by various organizations involved in radioactive waste disposal. Development of a comprehensive safety case is an important mechanism for communicating the results of the safety assessment and the overall safety argument for the disposal facility to the regulatory authorities (often the audience of prime concern). It is clear that there are some examples of commonality between various existing available safety assessment documentation.

ISAM Test Cases

Cautionary comments

The ISAM Test Cases were carried out to provide a practical demonstration of the application of the ISAM project methodology to conceptual disposal facilities. These were based on a number of actual facilities and their sites and made use of realistic information. However, there are limitations to the information that can be derived from them.

First, the ISAM project was restricted to post-closure radiological aspects of facility safety. Consequently, the test cases omitted consideration of pre-closure safety, the effects of non-radiological components of the waste, and the effects on non-human species. However, each of these areas may need to be addressed in the development of a complete safety case for a real site.

Second, the level of effort expended on the ISAM Test Cases are significantly less than that required for a complete safety case for an actual site. In particular, work on the test cases was only taken through a first iteration of the methodology (Vault and Borehole test cases), or through a limited second iteration (RADON test case). The application of the methodology in an iterative manner was therefore not fully studied in ISAM.

In addition, the test cases were conducted on conceptual disposal facilities without regulatory or other independent review. This inevitable feature of the project constrained the amount of realism in the project results in a number of areas. Among these is the application of confidence building techniques, aimed at building confidence of outside reviewers of the assessment. Since the ISAM Test Cases were not subjected to rigorous outside peer review or regulatory review, many times consuming confidence building approaches were not comprehensively applied. For example, the quality assurance procedures developed in ISAM were not applied to the ISAM Test Cases. In the development of a complete safety case, sufficient time and resources need to be allocated to conduct such functions. In a project such as ISAM, this was not possible due to resource constraints.

Despite these limitations, considerable progress was made during the project and the key issues, on which consensus was developed from the ISAM Test Cases are summarized below and presented in detail in Volume II of this report.

ISAM project methodology

Work was carried out within the ISAM project to apply the ISAM methodology to each of the three test cases. Conclusions drawn and lessons learned within the individual steps of the methodology are discussed in this sub-section.

Defining the assessment context provides a mechanism for clearly and explicitly establishing some of the key aspects of the safety assessment at an early stage in the process. This can be used to help justify decisions taken later in the assessment. Indeed, it is helpful to refer back to the assessment context as the safety assessment is developed.

The assessment context is very important and provides the framework within which to perform the safety assessment, and evaluate the results. If fundamental disagreements about aspects of the assessment context exist (e.g. applicable time frames, end-points, etc.) among interested parties, these should be resolved prior to conducting further safety assessment, or the subsequent work will be fruitless. A number of such issues were addressed in the ISAM Test Cases, and many of the assessment context issues proved to be contentious.

The system description effectively provides the existing data that are available for the assessment. The data, and the confidence in it, will be used to assist in taking decisions later in the assessment process. The description should be made with the assessment context firmly in mind.

In setting down the system description, it is important to distinguish between verifiable data and assumptions adopted for the purpose of the assessment. In particular, it is necessary to consider uncertainties associated with the knowledge and information on the system as it is at present and with its future evolution.

Developing a system description is an iterative process, and it does not need to be comprehensive at the start of the safety assessment. At first, available information specific for the disposal system collected and taken into account. In following iterations of the safety assessment, improvements in understanding and data availability will be made and safety critical data identified. Tracking the resulting changes in the system description, as it evolves through the assessment process and ensuring that it remains relevant and consistent with the assessment context, is an important aspect of confidence building, as is documenting and confirming the quality of the data used.

- The ISAM FEPs list proved to be a very useful tool in the scenario development and justification procedure. All three test cases used the FEPs list in somewhat different ways, illustrating the flexibility of the list for adaptation to differing approaches. The ISAM FEPs list can be used many times for auditing or checking during the development of an assessment and its use is not only limited to the scenario development and justification step of the assessment.

— Development of conceptual models and their mathematical representation is an important step of the safety assessment. It must be based on an appropriate definition of the main FEPs that are expected to affect the long term behaviour of the disposal system. There are a number of tools available for identifying and representing FEP interactions in conceptual models, such as Interaction Matrices and Process Influence Diagrams. Each tool has its advantages and disadvantages and the approach selected may depend on the preferences of the assessment team and on the assessment context.

It is important to ensure that safety assessors have a good understanding of the conceptual and mathematical models, the data, and the software tools being used and the associated uncertainties. It is important that they confirm that the models and data are appropriately used in their tools, and that their use and implementation is appropriately documented.

— Overarching all aspects of the safety assessment methodology is the need to develop confidence in the assessment. Relatively little work was carried out in the ISAM Test Cases on the analysis of results. In all of the test cases, there was not sufficient time to treat model and parameter uncertainty, quality assurance, data needs, and similar topics to the extent needed for a real disposal system. Undoubtedly more effort would be necessary in the context of an application for a disposal licence at an actual facility. However, it is noted that following the safety assessment process is, by itself, an exercise in developing confidence in the assessment.

— Development of the test cases showed that there is a need to investigate application of the safety assessment methodology in an iterative manner. In the RADON test case it was possible to conduct a limited second iteration based on revisions to the scenarios assessed. Such iteration was not undertaken for the Vault and Borehole test cases.

Illustrative application of the ISAM project methodology

The safety assessment methodology can be applied during all stages of a radioactive waste disposal facility life cycle. It can contribute to development of the safety case for site selection, design of a disposal concept, licensing, operation, and for closure of a disposal facility. The ISAM project methodology was found to be practical and helped ensure that the safety assessment was logical, well structured, well documented, transparent, and auditable. It should be applied in an iterative manner. To the limited extent that the iterative nature of the process was explored in the ISAM Test Cases, it proved to be very valuable. It is acknowledged that additional iterations of the safety assessment would be needed to justify a regulatory decision in a real situation.

Each of the test cases has contributed towards fulfilment of the ISAM objectives. In particular they: have demonstrated application of the ISAM project methodology; they provided participants with practical experience in the implementation of the approaches and tools and allowed confidence to be built in the approaches and tools used.

In each of the test cases it was observed that when multiple approaches are compared, misunderstandings and deficiencies in the analysis can be recognized. In particular, in each test case, it was advantageous to have independent teams of investigators and by comparing the approaches from each team an improved understanding was generated for all. In the future the ISAM project methodology and the illustrative test cases will be a useful source of information for experts involved in the development of post-closure safety assessment for near surface disposal facilities.

OVERALL CONCLUSIONS

Development of the ISAM project methodology

The ISAM project has resulted in the development of a consistent and transparent safety assessment methodology that can be applied during all stages of the life cycle of the disposal facility. The methodology can also be used to provide input to the decision making process concerning any potential remediation, upgrading of existing facilities and development of new ones.

Iterative character of safety assessment

The safety assessment methodology should be applied in an iterative manner so that the components can be reviewed and modified as appropriate. Iteration promotes the investigation of improvements to the assessment, regardless of how favourable results may initially appear. Subsequent iterations can be used to evaluate whether further improvements are necessary. These improvements may include changes in the description or design of the facility (e.g. waste acceptance, design), scenarios and improvements of models and use of additional data. As part of, or in addition to this further iteration, more emphasis needs to be placed on the presentation and analysis of results and the associated process of confidence building. The latter is important in the preparation of a safety case. For certain stages of the assessment process it can be helpful to develop a flow diagram of the basic steps in the process (for example the process of scenario development and justification). It is useful to review these flow diagrams after implementation and modify them in the light of experience. This is another example of the iterative nature of the safety assessment process.

Multiple lines of reasoning

If resources allow, it can be desirable to compare the results of multiple independent assessments in order to build confidence in the results of safety assessment. This provides better understanding of the disposal system assessed, the approach that has been used and identification of deficiencies in the assessments.

Consideration can also be given to the identification and development of indicators or aspects (additional to dose impacts) that can be used to help develop and support a safety case. Such issues might include factors of a more qualitative, less technical nature (for example social, political and economic aspects).

Development and illustrative application of the ISAM FEPs list

The ISAM FEPs list has been successfully developed and represents an important source of FEPs for consideration in the safety assessment of near surface disposal facilities. The ISAM Test Cases have also demonstrated the utility and value of the list during the assessment process. There is scope to further develop the ISAM FEPs list, taking into consideration the experience of its application in different national programmes.

Illustrative application of the ISAM project methodology

The ISAM Test Cases, as well as the test cases developed by individual participants, have successfully shown that the ISAM project methodology has been widely accepted to provide a good basis for a safety assessment for a near surface disposal facility as part of a site specific safety case. However, it should be emphasized that the level of effort expended on the ISAM

Test Cases is significantly less than that required for a complete safety case for an actual site. In particular, work on the test cases was only taken through a first iteration of the methodology, or through a limited second iteration. The safety assessment process should be applied in an iterative manner and there is scope for further iterations within the ISAM Test Cases. As part of, or in addition to this further iteration, more emphasis could be placed on the confidence building process, and the analysis and presentation of results in development of a safety case for near surface disposal facility.

Broad consensus

A broad consensus was developed within the ISAM project over a range of technical issues, including the ISAM methodology and the associated FEP list. This was achieved by the regular attendance of between 50 and 100 participants at the annual ISAM Research Coordination Meetings. The consensus was furthered by active participation in the associated working groups and test cases meetings. This helped to ensure that all useful inputs to the project were addressed. As the ISAM project developed, it became clear that the project output was of significant interest to a wide range of parties. Over 700 persons with an interest in safety assessment in over seventy Member States requested information about the project and its output. It was particularly encouraging that quite a number of participants applied the ISAM project methodology to assessment of their own countries, illustrating that the ISAM approach has gained broad international acceptance. The outcome of the ISAM project has also found broad application in the area of IAEA and national training courses and seminars.

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1. INTRODUCTION

1.1. BACKGROUND

The disposal of radioactive waste needs to be carried out in a manner that provides an acceptable level of safety and which can be demonstrated to comply with the established regulatory requirements and criteria. Safety assessment techniques are used to evaluate the performance of a waste disposal facility and its impact on human health and the environment.

Prior to the mid 1990's, considerable effort both nationally and internationally had been devoted to the development and application of safety assessment methodologies for radioactive waste disposal facilities for geological disposal of high level radioactive waste (HLW) and spent fuel (for example, the PAGIS study of the European Commission [1] and the SITE-94 study of the Swedish Nuclear Power Inspectorate [2]). Whilst certain individual countries had also developed similar formal methodologies for assessing the safety of near surface disposal facilities for low and intermediate level radioactive waste (LILW), comparatively little international effort had been addressed to the subject.

An initial attempt to improve confidence in certain aspects of safety assessment approaches for near surface disposal facilities was the International Atomic Energy Agency's (IAEA) Co-ordinated Research Project (CRP) entitled Near-Surface Radioactive Waste Disposal Safety Assessment Reliability Study (NSARS) [3, 4], which ran from 1990 to 1995. It focussed on developing confidence in the modelling of physical processes related to the safety of disposal facilities by conducting inter-comparisons between approaches for specific test cases that represented typical safety assessment problem.

This CRP was of considerable benefit as it clearly identified the need for improvements to be made to the overall safety assessment process, particularly in the methodology to be adopted and the various analytical tools required to apply the methodology. Thus, in 1996, it was decided to establish a new CRP to build on the experience of NSARS that would place special emphasis on the review and enhancement of post-closure safety assessment methodologies and tools to be applied to both proposed and existing near surface radioactive waste disposal facilities. In November 1997, the new CRP was launched entitled Improvement of Safety Assessment Methodologies for Near Surface Disposal Facilities (ISAM). The project was developed on the experience of the NSARS project and aimed to undertake a critical evaluation of the approaches and tools used in post-closure safety assessment for both proposed and existing near surface radioactive waste disposal facilities. This was with a view to enhancing them and developing confidence in safety assessments.

In order to test the ISAM project methodology, it was applied to three example test cases. These were based on current practices (vault facility), older practices (RADON[1] facility), and a proposed future disposal option for disused sealed sources (borehole facility).

It should be noted that there is consensus internationally on the broad features of this approach, although differences might be necessary in particular aspects of its application, especially on a site specific basis. Therefore, of importance, is that the approach is sufficiently

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[1] RADON facilities are comprised of a number of disposal facility types commonly found in former Soviet Union and Eastern European countries. The majority of these facilities were built in 1960s and are comprised of a variety of disposal units designs (trenches, boreholes and vaults) located at the same disposal site.

flexible and adaptable to a wide range of differing conditions in terms of disposal systems and regulatory approaches and contexts.

1.3. OBJECTIVES

The objective of this report is to provide a record of the work undertaken within the ISAM project and to report its conclusions and outcomes. It describes the safety assessment methodology developed within the project and presents the findings of ISAM relating to scenario development and justification, model formulation and implementation and confidence building (Volume I) and illustrates application of the methodology to three test cases (Volume II).

1.4. SCOPE

The two-volume report covers the review and enhancement of the methodological aspects for long term safety assessment for near surface radioactive waste disposal facilities, carried out within the ISAM project. The waste types addressed are low and intermediate level waste that could be generated in the nuclear fuel cycle and arising from research, industrial, medical, or other applications of radioactive materials. The project did not consider safety assessment of deep geological disposal facilities for high level waste, although many aspects of the safety assessment methodology are similar. Nor did it consider operational safety issues, although there is scope for application of the ISAM project methodology to such issues.

1.5. STRUCTURE

The report is presented in two volumes. Section 2 of this volume provides background information about the structure of the ISAM project and the main activities undertaken. Section 3 describes the steps of the ISAM project methodology and its main components, i.e. specification of the assessment context; description of the disposal system; development and justification of scenarios; development of conceptual and mathematical models and their implementation in computer codes; and analysis of results and the building of confidence. In Section 4, the work and findings relating to scenario development and justification are described together with the approaches used in the ISAM Test Cases for scenario generation are also described. Section 5 discusses the formulation and implementation of models associated with the identified scenarios. Each stage of the process is described, i.e. conceptual model development; mathematical model development; implementation in computer codes and specification of data. Section 6 addresses confidence building in the safety assessment. It discusses various aspects of the confidence building process, including: regulatory requirements, uncertainty and sensitivity analysis; quality assurance and communication with various audiences. Section 7 provides a summary of the main conclusions and recommendations both the ISAM project methodology and its applications, and the need for future work in the field of safety assessment for different purposes, such as licensing, derivation of waste acceptance criteria, etc. Application of the ISAM project methodology to three hypothetical test cases is illustrated in Volume II.

2. THE ISAM PROJECT

The ISAM project involved the review and enhancement of post-closure safety assessment methodologies and tools for both existing and proposed near surface radioactive waste disposal facilities. The main objectives of the project were to:

(a) Provide a critical evaluation of the approaches and tools used in the post-closure safety assessment of proposed and existing near surface radioactive waste disposal facilities;
(b) Enhance the approaches and tools used;
(c) Build confidence in the approaches and tools used.

In order to help achieve these objectives, the ISAM project paid particular attention to discussing, agreeing and setting down a safety assessment methodology, which is described in detail in this report and shown in Fig. 1.

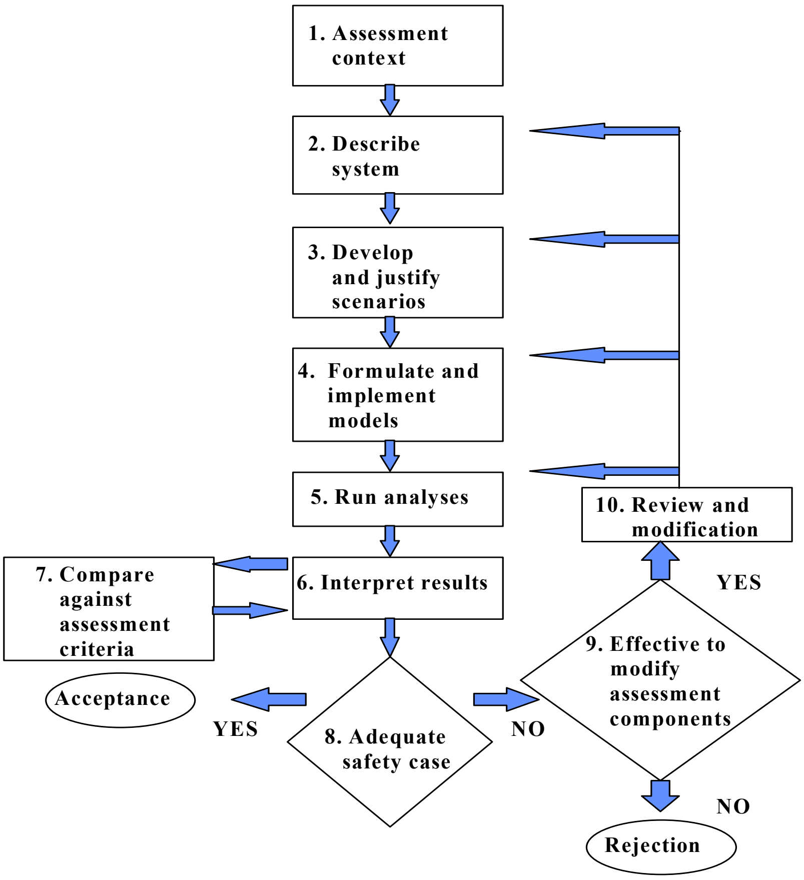

FIG. 1. The ISAM Project Methodology.

The ISAM project primarily focused on developing a consensus on the methodological aspects of safety assessment, but also gave considerable attention to illustrating the application of the methodology to three main types of disposal facilities (vault, RADON and borehole type disposal facilities).

The work undertaken concentrated on:

— Scenario development and justification;
— Model formulation and implementation, including input data; and
— Confidence building.

Three Working Groups (Scenario, Modelling, and Confidence Building) were set up within the ISAM project to deal with these important aspects of safety assessment methodology (see Fig. 2).

In order to illustrate application of the methodology developed, it was applied to three example test cases. The first was based on current disposal practices (vault facility), the second on older practices (RADON facility), and the third one – on a proposed future disposal option for disused sealed sources (borehole facility). The three test cases are documented in Volume II of this report. An attempt was made when developing these test cases to be as realistic as possible within the constraints of the project and to closely link them to the methodological aspects. In parallel, ISAM participants were encouraged to develop their own individual test cases. Both sets of test cases allowed participants to develop an understanding of the ISAM project methodology and to gain practical experience in its implementation. The test cases also provided the basis for open discussion of the many practical issues, which are encountered when undertaking an assessment, with the aim of reaching consensus in as many areas as possible.

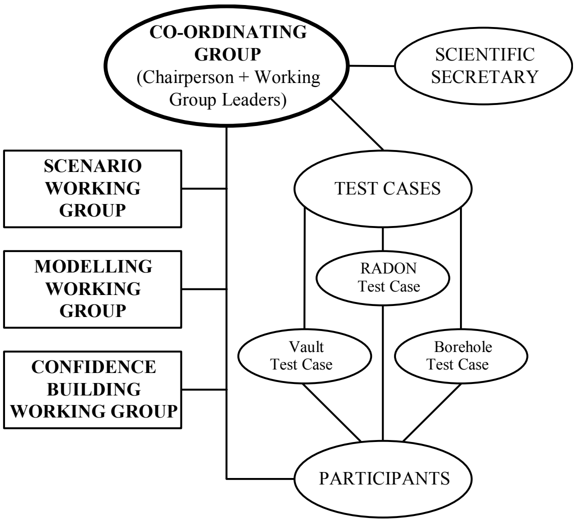

FIG. 2. The ISAM Organizational Structure.

Each working group and test case had a leader and a number of participants. The overall project was co-ordinated by a co-ordinating group led by a chairperson and supported by an IAEA Scientific Secretary (see Annex I).

3. ISAM PROJECT METHODOLOGY

Various methodologies have been and are being developed to assist in evaluation of the long term safety of near surface disposal facilities. Whilst there are differences in the detail of the approaches used, many of the more recent safety assessment methods, such as ISAM, have the following key components (Fig. 1):

- The specification of the assessment context;
- The description of the disposal system;
- The development and justification of scenarios;
- The formulation and implementation of models; and
- The analysis of results and building of confidence.

Each of these components is discussed below.

3.1. SPECIFICATION OF THE ASSESSMENT CONTEXT

Post-closure safety assessment of a radioactive waste disposal facility is generally undertaken to provide confidence to government, regulatory authorities, the general public and technical/scientific personnel that the facility has been/will be sited and engineered to ensure the safety of people and protection of the environment over long timescales. However, this generic objective does not provide a very precise description of what has to be considered in the assessment. The assessment context is intended to provide the next level of description and should answer the two questions:

- What is being assessed? and
- Why is it being assessed?

In a quantitative assessment, these questions become:

- What is being calculated? and
- Why is it being calculated?

Historically, the questions have not been answered very clearly. The answers to the two questions were for the waste form and package:

(1) Radionuclide release from the near field; and
(2) To provide input for geosphere assessment.

For the geosphere assessment, the answers were formulated as follows:

(1) Radionuclide release from the geosphere; and
(2) To provide input for the biosphere assessment.

For the biosphere component of the assessment, the answers were not so simple. Concerning what is to be calculated, there was generally no agreement on what type of dose or risk to calculate: dose to whom? risk of what? Concerning why, sometimes the intentions would be to make assessment of the dose, in other cases the intention would be to demonstrate that a dose level would not be exceeded. Without guidance, the person undertaking the biosphere assessment could be left to make their own decisions. Sensible approaches were taken in isolation, but the result could be inconsistent, both within the individual total system assessments, and when different assessments were compared.

The assessment context provides a framework for performance of the safety assessment, and it covers the following key aspects: purpose; regulatory framework; assessment end-points; assessment philosophy; disposal system characteristics; and timeframes.

3.1.1. Purpose

Most safety assessments of radioactive waste disposal facilities have the principal, objective to demonstrate that an acceptable level of protection of human health and the environment will be achieved both now and in the future. In addition to this overall demonstration of safety there can be a variety of additional purposes.

In any specific case, however, the purpose of conducting an assessment may vary from testing initial ideas for disposal concepts with simple calculations, to support for a licence application for disposal or for upgrading the safety of an existing facility requiring detailed, site specific safety assessment against regulatory criteria. In addition there can be a variety of additional purposes, such as derivation of quantitative acceptance criteria.

The audience to whom the results of the safety assessment will be presented should be identified in advance. The general purpose of the assessment and the nature of the target audience (e.g. regulators, operators, waste producers, public, local, regional and national politicians) will play a key role in defining relevant assessment end-points, assumptions concerning the disposal system and in the identification and justification of the assessment scenarios.

3.1.2. Regulatory framework

In undertaking a safety assessment it is vital to consider the regulatory requirements that apply the assessment. At one extreme these may be prescriptive quantitative requirements, at the other they could be non-prescriptive performance oriented requirements or may not have been fully developed. While national regulatory requirements vary considerably, they mostly should have a link to international recommendations relating to safety of management of radioactive waste, such as the IAEA Principles of Radioactive Waste Management [5], the Safety Requirements for Near Surface Disposal of Radioactive Waste [6], the Safety Guide on Safety Assessment for Near Surface Disposal of Radioactive Waste [7], and Publications 77 and 81 of the International Commission on Radiological Protection (ICRP) [8, 9].

3.1.3. Assessment end-points

The end-points of a safety assessment need to correspond with its purpose and the associated regulatory requirements and take into account the assessment assumptions such as timescales and critical groups. It is important to ensure that the end-points, such as dose and risk, are adequately defined.

An additional consideration is that the trend in safety case development is not to rely on evaluation of just a single end-point, such as individual dose or risk (dose was most commonly used as an end-point is a survey of ISAM participants – see Section 6). Multiple lines of reasoning may be useful since use of a wider range of arguments and end-points will help to establish the adequacy of a safety case. A variety of additional indicators may be used to complement those of dose and risk (such as radionuclide fluxes and concentrations).

3.1.4. Assessment philosophy

Different approaches can be applied to the calculation of assessment end-points. Not only does the nature of the end-point have to be clearly defined, but the nature of the approach used to calculate the end-points also needs to be made clear. From this perspective, the assessment philosophy is an expression of the approach that will be applied to the assessment. In particular, it is necessary to consider: the nature of the overall approach that will be used for the assessment (e.g. systematic, iterative, transparent); the nature of the assumptions to be adopted (e.g. realistic, cautious); the availability of data for use in the assessment (e.g. generic, site-specific); and the approach to be adopted for the treatment of the various sources of uncertainty (e.g. scenario, model and data).

3.1.5. Disposal system characteristics

The waste disposal system can be considered to consist of: the near field; the geosphere; and the biosphere (Section 3.2). These components are described in more detail in the next step of the assessment approach, the system description. It is useful to provide, within the assessment context, an overview of the present-day system and to document any associated fundamental assumptions.

As part of the initial description of the system characteristics, assumptions concerning future human actions can be defined, such as, level of technological development, type of society, and basis for habits and characteristics. Similarly, assumptions concerning the characteristics of any groups of people, who might potentially be exposed to radionuclides released from the disposal facility, can also be defined. Alternatively they can be defined during the scenario development and justification process (Section 3.3). What is important is that they are clearly identified and justified at either of these two stages of the assessment process.

3.1.6. Timeframes

Radioactive waste disposal should ensure equitable protection of both current and future generations. Time-related factors that need to be considered in a safety assessment include:

- The duration of the operational period
- The duration of the institutional control period (both the active control period and the passive control period);
- The natural and human induced environmental changes;
- The degradation of the engineered barrier system; and
- The half-lives of relevant radionuclides.

The timeframe for the post-closure safety assessment should be selected, recognising inherent limitations and uncertainties in assessment approaches, as well as constraints on the scientific credibility of long term estimates of disposal facility performance imposed by large scale environmental changes. The timescale of interest for an assessment can be a function of the nature of the waste disposal system and the external influences on it, and the longevity of the radionuclides in the wastes. Therefore the timescales of an assessment should be justified on a case by case basis, although some may also be imposed by regulatory requirements.

3.2. DESCRIPTION OF THE DISPOSAL SYSTEM

The disposal system can be considered to consist of the following components:

- The near field — the waste, the disposal area, the engineered barriers of the disposal facility including the disturbed zone of the natural barriers that surround the disposal facility.
- The geosphere — the rock and unconsolidated material that lies between the near field and the biosphere. It can consist of both the unsaturated zone (which is above the groundwater table) and the saturated zone (which is below the groundwater table).
- The biosphere — the physical media (atmosphere, soil, sediments and surface waters) and the living organisms (including humans) that interact with them.

The division between these disposal system components, especially the geosphere and biosphere, is somewhat arbitrary for a disposal facility that is located at or within a few metres of the ground surface. However, it is usually found convenient within a safety assessment to distinguish between the three components. It is therefore important to provide a clear definition of these components and their associated interfaces (such as the geosphere-biosphere interface) in the assessment. When developing conceptual models of a disposal system (see Section 5), it is particularly important to consider how the nature and position of these interfaces might change as a function of time and as a function of the radionuclide release mechanisms from the disposal facility.

The disposal system description should contain information on:

- The near field — e.g. waste origin, nature, quantities and properties, radionuclide inventory, engineered barriers (waste packages, disposal units, disposal facility cover), and extent and properties of the disturbed zone;
- The geosphere — e.g. geology, hydrogeology, geochemistry, tectonic and seismic conditions; and
- The biosphere — e.g. climate and atmosphere, water bodies, human activity, biota, near surface lithostratigraphy, topography, geographical extent and location.

It is important to ensure that the data collated is pertinent to the assessment context. Given that long term safety of a disposal facility essentially relies on the features of the multi-barrier system proposed (such as the choice of: a specific disposal site, a given host geology at a certain depth, specific features of the engineered and natural barriers), it is particularly important to ensure that the relevant characteristics of this multi-barrier system are documented. The description that is developed should be a qualitative and quantitative description of the system components. All sources of data used in the description should be documented and referenced to ensure that an appropriate audit trail of information is maintained.

The description of the disposal system should be undertaken with the assessment context firmly in mind (in particular the assessment purpose, end-points, philosophy and timescales), and so ensure that the system is described to a level of detail that is appropriate for the context being considered. For the first iteration of the approach, emphasis could be placed mainly on the collation of existing data rather than the collection of new data. For subsequent iterations, the emphasis could shift towards the collection of new data.

When describing the disposal system, it is important to recognize that there are two significant sources of uncertainty that need to be taken into account. When developing the system description, it is important to be aware of and to document the contribution of these two sources of uncertainty. First, there is uncertainty associated with characterising the system as it is at present. Second, there is uncertainty associated with the future evolution of the disposal system. As noted, the system can be expected to evolve over the timescales considered in an assessment. Typically, the description of system developed at this stage of the assessment process will relate to its present-day status and its assumed status at closure of the disposal facility (or whenever the assessment assumes as a start time for impact calculations). Assumptions concerning its evolution thereafter are typically addressed as part of the scenario development and justification process.

3.3. DEVELOPMENT AND JUSTIFICATION OF SCENARIOS

In a safety assessment of a waste disposal facility, it is important to assess the performance of the disposal system under both present and future conditions, including anticipated and less probable events. This means that many different factors (e.g. conceptual model and parameter uncertainty, long time periods, human behaviour and climate change) should be taken into account and evaluated in a consistent way, often in the absence of quantitative data. This is often achieved through the formulation and analysis of a set of scenarios.

Scenarios are descriptions of alternative, but internally consistent, future evolution and conditions. Scenarios handle future uncertainty directly by describing alternative outcomes. They also allow for a mixture of quantitative analysis and qualitative judgements. The selected scenarios should together provide an appropriately comprehensive picture of the system and its possible evolutionary pathways based on the assessment context and system description. The choice of appropriate scenarios and associated conceptual models is very important and strongly influences subsequent safety analysis of the waste disposal system. In some countries scenarios are specified by the regulator, although the operator may also choose to consider others. In other countries, the operator may select the scenarios and be required to justify the selection to the regulator.

There are several methods that can be used to generate scenarios, none of them claiming to be the only or right one. Indeed, techniques relevant to near surface disposal are currently being reviewed in the ISAM project. They include methodologies such as expert judgement, fault tree and event tree analysis. It is increasingly recognized that systematic techniques are especially helpful, in particular because they develop a justified and documented audit trail, and thereby enhance the transparency and defensibility of the assessment. It should be mentioned that in most of the cases, the conclusions reached by the different techniques are very similar; the output is, or should be, the selection of a small set of scenarios encompassing most of the possibilities in terms of potential impact.

A common element in many scenario generation methodologies is the initial construction of a list of all FEPs that could directly or indirectly influence the disposal system and the migration and fate of radionuclides within it. These FEPs are usually identified from the disposal system description. The list of FEPs should be generated and documented in a systematic way. When the list is complete, the relative importance of each FEP is reviewed, often using expert judgement. This review and judgement process results in the screening of FEPs into those that can be ruled out and those that need to be considered further in the safety assessment analysis. The screening of a FEP can be supported by calculations. A FEP can, therefore, be ruled out on either quantitative or qualitative criteria or both.

The resultant list of FEPs is used together with the system description to formulate scenarios. Judgements are then made as to which of the scenarios should be further analysed. The chosen set of scenarios depends on the purpose of the assessment and should provide a picture of future evolution, critical issues and system robustness taking into account the assessment context. A transparent scenario generation and selection methodology is an important part of confidence building, especially since scenario generation is often a focus of attention during independent reviews.

3.4. FORMULATION AND IMPLEMENTATION OF MODELS

Once the scenarios have been developed, their consequences in terms of the assessment context should be analysed. Depending on the nature of the scenario, an appropriate approach for its analysis is chosen. For some scenarios it may be appropriate to use a qualitative assessment approach (e.g. when data is not available). For the scenarios that are to be quantitatively assessed, the scenarios should be organized into a form that can be mathematically represented. A set of model-level assumptions (about dimensionality, boundary conditions, FEPs, FEP relationships, etc.) is needed for each of these scenarios. These assumptions comprise the conceptual model. More than one conceptual model may be consistent with available information for a scenario. A conceptual model should comprise a description of:

- The model’s FEPs;
- The relationships between these FEPs; and
- The model’s scope of application in spatial and temporal terms (i.e. its domain).

A description of the scope of the model is necessary in order to record the assumptions under which it has been developed and the situations to which it applies. This in turn is important in ensuring fitness for purpose and avoiding inadvertent use of the model outside its intended domain of applicability. The conceptual model will form the basis of the mathematical model that is used to describe the behaviour of the system and estimate its performance over time.

The conceptual models for each scenario are expressed in mathematical form as a group of algebraic and differential equations with appropriate and adequate boundary and initial conditions that then need to be solved. These equations may be empirically and/or physically based, depending upon the level of understanding and information concerning the processes represented. Yet again, more than one mathematical formulation might be appropriate for the conceptual models considered. These equations and their associated parameters form the basis of the mathematical models. These mathematical models should be developed from the conceptual model. However, it is all too often more convenient to develop a mathematical model to be consistent with the immediately available tools due to limited resources. When this approach is taken, the reasons for adopting the approach should be explained and the associated limitations documented.

Solution of the mathematical models is usually achieved by implementing one defined or more computer tools using analytic and/or numerical techniques. These tools may be proprietary tools and/or tools specifically developed for implementation of the chosen mathematical models. If there is only a limited set of conceptual and mathematical models to be represented, it may be possible to use one computer tool. However, if models differ markedly in terms of the processes or level of detail represented, it is often not desirable or feasible to use a single tool.

It can be convenient to develop a mathematical model that is consistent with existing computer tools. When this approach is taken, it is important to ensure that any associated limitations, such as the exclusion of certain FEPs identified in the scenario and conceptual model development processes, are documented and justified. In particular any potential impacts on the calculation of the assessment end-points should be noted.

In order to allow the computer tools to be run, data for the input parameters need to be specified. Data relating to disposal system parameters (e.g. facility dimensions, flow path lengths), human exposure parameters (e.g. food produce consumption rates, occupancy rates), and radionuclide/element dependent parameters (e.g. distribution coefficients, transfer factors, dose coefficients) are required. In specifying data, consideration should be given to the treatment of uncertainties associated with the parameter values. These should be dealt with consistent with the assessment philosophy guidance given in the assessment context. Uncertainties can arise due to a number of factors such as the spatial and temporal variability of parameter values, and uncertainties in the measurement and derivation of values. Data collated under previous elements of the assessment process can be used. However, further site specific and/or generic data may also be required. If the computer tools are to be used in probabilistic mode (i.e. with sampling of input parameters), then parameter distributions need to be specified. A range of techniques can be used to derive parameter distributions.

The level of detail to which the models are developed and the associated amount and quality of data required will be a function not only of the assessment context but also the stage of iteration of the assessment process. For example, during early iterations (such as site selection or initial investigations) it might be sufficient to generate relatively simplistic models for screening purposes that can be implemented using simple computer tools such as spreadsheets, and data that are readily available. Following review of the results it might be appropriate to enhance certain models and collect further data and implement them using more sophisticated computer codes. Models and data for later iterations, especially the final safety case, may need to be even more comprehensive.

Confidence can be built in the ability of the computer tools to solve the mathematical models correctly and accurately through the use of verification. Verification is the process of showing that a mathematical model, or the corresponding computer code, behaves as intended, i.e. that it is a proper mathematical representation of the conceptual model and that the equations are correctly encoded and solved. Verification of the method of calculation is achieved by solving test problems designed to show that the equations in the mathematical model are solved satisfactorily in the associated computer codes. Further confidence can be built in the model if field and/or experimental results can be reproduced with sufficient accuracy (the process of validation), although the temporal scales over which such validation is possible are limited.

Uncertainties associated with the conceptual and mathematical models and their associated parameters and parameter values can be assessed in a number of ways. Examples include the use of probabilistic computer tools which allow the output of results in probabilistic format (e.g. mean values and associated confidence intervals), and the re–running of deterministic tools with different conceptual and mathematical models and/or parameter values.

Notwithstanding the importance of developing a suitable audit trail at each stage in the model-building process, it is particularly important that any lessons learned in applying the model and interpreting its results should be used to revisit assumptions and decisions made during the course of model development. It is likely that such information can be used to refine the model, perhaps by identifying particularly important FEPs or sensitive parameters. The importance of the methodology therefore continues after the assessment tool has been developed in so far as, contrary to past experience in the development and application of assessment tools, there should be a well-defined basis for each of the decisions taken during the model-building process.

3.5. ANALYSIS OF RESULTS AND BUILDING CONFIDENCE

Once the scenarios, and associated conceptual and mathematical models have been developed and implemented in software tools and the associated data collated, calculations can be undertaken to assess the impacts of disposal facility. The results then need to be collated, analysed and presented.

Interpretation of results represents the first opportunity for the analyst to examine quantitative results from the modelling of scenarios. The results should be compared with applicable criteria from the assessment context. The assessment context will include regulatory criteria and may also include other indicators against which results can be compared. Results can also be compared against results from other assessments to help build confidence, although care should be taken to ensure the compatibility of the comparison. The results interpretation represents the way the modelling outputs are eliminated, screened or conditioned to facilitate comparison with the assessment context.

When analysing the results from an assessment, it should not be forgotten that several kinds of uncertainties associated with such quantitative safety assessments. Uncertainties can be considered to arise from three sources [10].

- Uncertainty in the evolution of the disposal system over the timescales of interest (scenario uncertainty);
- Uncertainty in the conceptual, mathematical and computer models used to simulate the behaviour and evolution of the disposal system (e.g. owing to the inability of models to represent the system completely, approximations used in solving the model equations, and coding errors); and
- Uncertainty in the data and parameters used as inputs in the safety assessment.

It is also important that due care and attention is given to the presentation of results. Different methods can be used for the presentation of results to different audiences. Many alternative representations are possible for displaying uncertainties and sensitivity analysis results for both deterministic and stochastic modelling outputs. For example, dose versus time curves showing the contribution to dose from significant radionuclides have been widely used. It is vital to ensure that the form of presentation used is appropriate for the audience to which the results are being presented.

One of the key purposes of many assessments is to provide a level of confidence to all interested parties that it is reasonable for waste disposal programme to proceed and that human health and the environment are protected.

Confidence building is involved in all aspects of developing an safety assessment.

In its most basic form, confidence building involves the practice of citing references and the use of transparent logical reasoning, multiple lines of reasoning, and factual data to support the safety assessment. Application of a quality assurance programme is another confidence building measure. Activities associated with use of good science and good engineering practice can add an additional level of confidence. Consideration of sensitivity and uncertainty may also be helpful, as might the use of simple scoping calculations. In particular, sensitivity analysis can be used as a method for providing confidence in results. Through this type of analysis the overall robustness of the disposal system can be demonstrated. Sensitivity analysis may also allow attention to be focused on those components of the system where the greatest performance increases can be obtained.

Interpretation, analysis and presentation of the results are followed by the decision process. This is multi-faceted in that several varied and sometimes competing factors should be brought together and reconciled to reach a decision as to whether the system and the assessment are adequate. The entire assessment process is iterative and the first pass through the process should usually be followed by one or more iterations. This promotes the examination of improvements to the disposal system regardless of how favourable results initially appear. Subsequent iterations will often contribute to decisions whether the safety case is acceptable or there is a need for further improvements. These improvements may include facility changes (e.g. waste acceptance, design), scenario changes and model and/or data improvements. Early iterations are undertaken with available data and assessment capabilities and the iterations need only to proceed until the assessment is judged to be adequate for its purpose. Furthermore, new data need only be collected to the extent that they are required in order to provide an adequate basis for the decision.

4. DEVELOPMENT AND JUSTIFICATION OF SCENARIOS

4.1. INTRODUCTION

The objectives and associated set of internationally agreed principles of radioactive waste management state clearly that radioactive waste has to be dealt with in a manner that protects human health and the environment, both now and in the future without imposing undue burdens on future generations [5]. A major effort in a post-closure safety assessment of radioactive waste disposal facilities is therefore to determine what potential effect the disposed waste may have on future generations and the environment. These assessments should also consider what future conditions may exist, something that is obviously not known with certainty.

Depending on the characteristics of the disposed waste, a post-closure safety assessment could be concerned with the impact of the waste on humans and the environment over time scales of many thousand years. Incomplete knowledge of how the disposal system will evolve in future is a major source of uncertainty in the safety assessment of radioactive waste disposal systems. One of the difficulties experienced is that the assessment often has to be performed before the disposal system is built. The assessment could therefore be influenced adversely by factors such as potential differences between the original design of the disposal facility and the as-built facility, or the intended and actual waste emplacement schedule and configuration, or a change in the political and social conditions. Factors such as these can, to a certain extent, be controlled on a regulatory basis and their impact assessed through the continued iterative use of safety assessment during the life cycle of the disposal facility. There are other factors, however, such as the habits and behaviour of people in the future, as well as natural and human induced disruptive events and processes, which cannot be controlled in the same manner, and should be addressed explicitly in the assessment. The approach commonly used in post-closure safety assessments to address these uncertainties in the future evolution of a disposal system is the development and analysis of scenarios.

Scenarios are descriptions of alternative, but internally consistent, future evolutions and conditions of the waste disposal system. They handle future uncertainty directly by describing alternative futures and allow for a mixture of quantitative analysis and qualitative judgements. Essentially, the main purpose of scenario generation in the post-closure safety assessment of a radioactive waste disposal system is therefore to use scientifically-informed expert judgement to guide the development of descriptions of the disposal system and its future behaviour. It does not try to predict the future; rather, the aim is to identify salient changes, based on analysis of trends, within which variants are explored to investigate the importance of particular sources of uncertainty. The emphasis is therefore on providing meaningful illustrations of future conditions to assist in the decision-making process [11].

Scenario generation is important to the safety assessment for several reasons:

- Scenarios provide the context in which safety assessments are performed. One cannot analyse the long term performance of a radioactive waste disposal system without considering future conditions of the site;
- Scenarios influence model development and data collection efforts;
- They provide an important area of communication between repository developers and regulators, and other stakeholders with an interest in repository safety; and
- They have become a very important aspect of confidence building for the post-closure safety assessment and therefore also a focal point of independent reviewers of the assessment.

A scenario generation strategy aims at producing a complete set of most relevant scenarios. Nonetheless, one should strive for completeness in considering relevant issues. This means that care should be taken to ensure that the selected scenarios provide an appropriately comprehensive picture of key aspects of the system, their possible evolutionary pathways, critical events and system robustness. In this context, it is extremely important to have a systematic scenario generation approach and to document all steps in the generation of the scenarios. This permits analysis of a reasonable set of scenarios that can be used to assure confidence that the system will remain safe in the future.

The need for these formal approaches has resulted in the production of a considerable number of documents on scenarios in the radioactive waste literature. In addition, it has led to the development of a significant amount of specialized terminology that should be understood to appreciate the literature on scenarios. This terminology is reviewed in Section 4.2. In Section 4.3, a discussion is presented on the approaches implemented in the ISAM project to evaluate scenarios for safety assessments of near surface waste disposal facilities. This has been one of the first applications of formal scenario analysis approaches to near surface disposal facilities, and a significant accomplishment of the ISAM project. Finally, the key lessons learnt and conclusions are presented in Section 4.4.

4.2. TERMINOLOGY

4.2.1. Scenarios

According to the Oxford English Dictionary the word scenario has many meanings and is overused that it is not always possible to determine its precise meaning. This is illustrated by the wide diversity of definitions summarized in Table 1.

As mentioned in Definition 1 in Table 1, scenario analysis was first developed in the context of futurological studies where the interest was to define hypothetical futures in order to assist in decision-making. In this context, scenarios were not intended to be predictive but to illustrate alternative future possibilities that should be considered. The term is also used in statistical analysis where it has a specific meaning. Indeed, Definition 2 has been adopted by AECL in their probabilistic calculational method. A more generalized and qualitative definition has been used, as illustrated by Definition 4 given by the NEA Working Group that examined this topic. In various safety assessment studies since, more precise definitions have been given but these diverge and are framed so as to be consistent with the particular assessment and calculational approach favoured. For example, Definition 5 from the USA is framed to be consistent with the view that scenarios are distinct alternative entities to which probabilities (summing to one) can be assigned. This is consistent with the regulatory requirement in the USA for quantitative assessment of cumulative release taking account of all processes and events that may affect the disposal system [12]. In contrast, Definition 6, developed from experience in the Swedish SITE-94 study, allocates a more illustrative function to scenarios, consistent with the dose-based and more qualitatively framed Swedish regulatory guidance, e.g. see [13].

TABLE 1. DEFINITIONS OF "SCENARIO" FROM GENERAL DECISION THEORY, STATISTICAL LITERATURE AND FROM REPOSITORY SAFETY ASSESSMENT LITERATURE

Definition	Source, context and comments
1. Scenarios are hypothetical sequences of events constructed for the purpose of focusing attention on causal processes and decision-points. They answer two kinds of questions: (1) Precisely how might some hypothetical situation come about, step by step? and (2) What alternatives exist for each actor, at each step, for preventing, diverting, or facilitating the process?	From Kahn and Wiener [1967], "*The Year 2000, A Framework for Speculation*", Macmillan, New York. Herman Kahn is widely regarded as the father of scenario analysis who developed this method of system analysis in the 1950s, initially in the context of decision making related to options for civil defence measures in response to thermonuclear war, and later in the context of other futurological research.
2. A scenario is a particular situation, specified by a single value for each input variable. It defines a single point on the response surface. We can describe a scenario as a vector of values for the inputs, for example: $X = (x_1, x_2)$.	From Morgan and Henrion [1990], *"Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis"*, Cambridge University Press, Cambridge. This statistical definition is from a reputable text on the subject. For many years, this has been the definition adopted by AECL in their post-closure assessment method, i.e. a scenario is a single simulation or "run" of their SYVAC code.
3. Scenario - An assumed set of conditions and events used in facility planning/design, assessment or regulatory activities.	From IAEA [1993], "*Radioactive Waste Management Glossary"*, International Atomic Energy Agency, Vienna. Referring to the use of the term in a number of different contexts within nuclear waste management.
4. A single scenario specifies one possible set of events and processes and provides brush description of their characteristics and sequencing.	From NEA [1992], "*Systematic Approaches to Scenario Development*", A report of the NEA Working Group on the Identification and Selection of Scenarios for Performance Assessment of Radioactive Waste Disposal, Nuclear Energy Agency of the Organization for Economic Cooperation and Development, Paris. This, from the report of the NEA Working Group on the Identification and Selection of Scenarios, has a degree of international acceptance.
5. There is a universe of possible futures, which is the set of all possible occurrences within the 10,000-year regulatory time frame. For analysis, this universe is divided into subsets of occurrences - scenarios – that are defined practically to include similar future occurrences. Each scenario is defined by a combination of occurrence and non-occurrence of all potentially disruptive events and processes.	From US DOE [1996], "*Compliance Certification Application for the Waste Isolation Pilot Plant*", 40 CFR Part 191, Volume 1, United States Department of Energy, Carlsbad Area Office, Carlsbad, New Mexico. This definition is developed from the representation of risk as a set of ordered triples (What can happen? What is the probability of this? What is the consequence?) developed in [12], which is the basis for representation of results in terms of a CCDF as required by WIPP-specific regulations [14].
6. A scenario is a hypothetical sequence of processes and events, and is one of a set devised for the purpose of illustrating the range of future behaviours and states of a repository system, for the purposes of evaluating a safety case.	From Chapman *et al.* [1994], "*Devising scenarios for future repository evolution: a rigorous methodology*" MRS Symposium on the Scientific Basis for Nuclear Waste Management, Kyoto, Japan. This was based on experience in the SKI SITE-94 study, which gave special attention to the development of scenarios through formal techniques, e.g. use of Process Influence Diagrams (PIDs).

To find a definition for scenario that will be most suitable for *all* analysts undertaking post-closure safety assessments is difficult. From Definitions 5 and 6 in Table 1, it is clear that the definition chosen could depend on the assessment and calculational method adopted and on the context of the regulatory guidance. At best an operational definition of scenario should be provided that is consistent with the scenario generation methods that were being developed and tested in the Scenario Working Group and in the ISAM Test Cases. For this purpose, Definition 6 in Table 1 has been judged to be most appropriate and, as such has been adopted within the ISAM project.

4.2.2. Features, events and processes

A common element in many scenario generation methodologies is the initial construction of a comprehensive list of what are known as Features, Events and Processes (FEPs) that could directly or indirectly influence the disposal system and the migration and fate of radionuclides within it. These FEPs are usually identified from the disposal system description. Attempts to independently define these terms for the development of a safety case have not been undertaken to date. This is most probably because whether a physical entity is thought of as a feature, event or process depends on the temporal and spatial scale on which it is viewed. The definitions provided in the Longman dictionary [15], illustrate this point:

Feature	–	*a prominent or distinctive part or characteristic (of the repository or its environment);*
Event	–	*a qualitative or quantitative change or complex of changes located in a restricted portion of time and space;*
Process	–	*a phenomena marked by gradual changes that lead towards a particular result.*

The term FEP was originally proposed by experts (Jim Campbell and Bob Cranwell) at Sandia National Laboratory in the United States of America, and was later adopted by the NEA Scenarios Working Group and the Joint SKI/SKB Scenario Development Project [16] where it is stated that:

"... safety analysis ... involves the consideration of all possible Features, Events and Processes, FEPs, that could, directly or indirectly, influence the release and transport of radionuclides from the repository."

In principle it is possible to identify specific features (e.g., engineered cap, concrete walls, etc.), events (e.g., rainfall, waste emplacement, backfilling, etc.) and processes (e.g., climate change, groundwater flow) for a safety assessment using these definitions. If the temporal and spatial scale from which these FEPs are viewed changes, however, then a process might become an event, e.g. groundwater flow. It therefore also depends on how the FEP is represented in the model used to evaluate a safety case. It is thus clear that to have specific definitions for a feature, event or process might be problematic in the development of a post-closure safety case.

To circumvent this problem, AECL in Canada have preferred to use the terms "Factor" [17] and "Issue" [18] in their safety analyses and scenario developments. This somewhat broader perspective is not influenced by temporal and spatial definitions of features, events and processes. It also allowed AECL to include modelling and regulatory context factors/issues in their compilations. Using this approach it is possible to include all the things that could, *"... directly or indirectly, influence the release and transport of radionuclides from the repository influence*". Hydraulic conductivity (K), for example, is a parameter that influences groundwater flow. Using the above definition, K is not a feature, or an event or a process, but definitely something that influences the movement of radionuclides.

The NEA Working Group on FEP Databases [19] discussed the relative merits of the terms "FEP" and "Factor" and also considered whether there was merit in distinguishing features, events and processes. In summary, it concluded that:

- The term factor is preferable to FEP in some respects because it captures the wider meaning of all things that should be considered in an assessment, including non-physical factors, e.g. Assessment Context. The term FEP, however, is so well established in safety assessment literature (and was also given in the terms of reference of the Scenario Working Group) that it was decided to use the term FEP.
- There is no merit in attempting to either define feature, event or process, or distinguish between them in drawing up FEP lists or catalogues. This is because such decisions are analysis specific.

For the ISAM project, it was proposed that the term "FEP" still be used because of its common use in the assessment literature. A definition for FEP can be based on the SKI/SKB definition but should be consistent with the broader NEA usage of the term. Thus:

A FEP is a feature, event, process or other factor, that may be necessary to consider in a repository safety assessment. This includes physical features, events and processes that could directly or indirectly influence the release and transport of radionuclides from the repository or subsequent radiation exposures to humans, plus other factors, e.g. regulatory requirements or modelling issues, that constrain or focus the analysis.

4.2.3. Reference and alternative scenarios

In most assessments, a single reference scenario is developed for initial consideration and alternative scenarios are then developed to investigate the impact of scenarios that differ to a lesser or greater extent from the reference scenario. Indeed in some cases, the alternative scenarios can be seen as little more than sensitivity analysis of the reference scenario. The reference scenario is often, but not always, considered to be the most likely scenario for the given safety assessment; it is usually considered to be a benchmark scenario against which the impact of alternative scenarios can be compared. Terms such as normal evolution, design, base case, central have been used in a variety of assessments instead of the term reference. Similarly terms such as altered evolution and deteriorated evolution have been used instead of alternative. The key issue is to ensure that any terms that are used to describe the different types of scenario in an assessment are defined and their purpose clearly explained.

4.3. APPROACH TO SCENARIO GENERATION IN THE ISAM PROJECT

4.3.1. Introduction

Scenario generation as a method to address uncertainties associated with the future evolution of the disposal system has been the subject of a number of studies. However, as can be seen in Appendix A, these studies have been limited to geological disposal systems, while very little effort has been expended on near surface disposal facilities. Since the introduction of the ISAM project, this has changed and a number of near surface disposal programmes are now conducting formal scenario analyses.

Indeed, very little work has been published on the subject of near surface FEPs prior to ISAM CRP start. This could be attributed to the fact that for past practice facilities, scenario generation and justification were not always required as part of the safety case. The IAEA developed a high level list of phenomena potentially important for safety assessments for near surface disposal facilities [20], but these were not taken any further. However, more recently a number of near surface disposal programmes have started to conduct formal scenario analyses. Examples include the ANDRA approach for Centre de l'Aube, which is an existing facility, and the AECL IRUS facility in Canada, which is a planned disposal facility. These approaches are discussed in Appendix B.

An alternative approach to the more formal approaches to generate scenarios, which has often been used for near surface disposal systems in the past, are generic scenarios. In some countries, regulatory authorities have established sets of generic scenarios that serve as guidance of what scenario to consider for a specific setting and facility type. For deriving generic scenarios, two approaches can be identified. The first is to compile a list of scenarios used in actual safety assessment analysis given certain conditions and the second is to follow a formal procedure to develop a set of generic scenario. Both of these approaches are described in Appendix B.

4.3.2. Systematic approach for scenario generation

The generation of scenarios and their associated justification methodology has become a very important aspect of confidence building for post-closure safety assessments, and has largely replaced generic and *ad hoc* approaches used in the past. The scenarios and the methods to generate them have become also a focus of independent reviewers of the safety assessment. Against this background, the adoption of a systematic assessment framework is intended to provide a formal basis for external review of the logic of the underlying assumptions adopted in a safety case. This approach helps to provide assurance that the assessment has effectively addressed all potentially relevant FEPs and taken account of the ways in which combinations of these FEPs might produce qualitatively different outcomes. In addition, a systematic approach should provide the setting for demonstrating how uncertainties associated with the future evolution of the disposal system have been addressed and assimilated into the safety case.

Some basic requirements can be identified for a systematic scenario generation approach. In particular, the approach should attempt to ensure:

- Transparency, including a plan for documentation and handling of expert judgement;
- Comprehensiveness – all possible FEPs, which could significantly influence the disposal system and the release of radionuclides, should be considered;
- That relevant future evolutions are described;
- That critical issues are identified; and
- That the robustness of the system is investigated.

4.3.3. ISAM FEPs list

A FEPs list for near surface disposal facilities is important because it is a common initial activity in most scenario generation approaches. From Appendix A, it is clear that a huge effort has been expended on the development of a comprehensive FEPs list for geological disposal facilities to date. This led to the development of an international database of features, events and processes relevant to the post-closure safety of geological repositories for solid radioactive waste [19].

Prior to ISAM, a similar level of effort had not been expended on the development of FEPs list for near surface disposal facilities. To fulfil the objectives of the Scenario Working Group, it was decided to adopt the NEA FEPs list for ISAM, and to revise it to be suitable for near surface disposal facilities. In this section, the structure of the ISAM FEPs list is discussed.

The general objective of a safety assessment is to determine what impact the disposed waste will have on individuals and their environment as a function of time. This requires consideration of how radionuclides may be released from the disposal facility, the pathways along which they can migrate, and their impacts on human. To achieve this, one can develop a process system. The components of the process system can be conveniently divided into internal and external components. The internal components are those components that are situated within the spatial and temporal boundaries of the disposal system, while the external components are situated outside these boundaries. The selection of the boundary between these two is made for convenience of the assessor, based on the level of information available on important events and processes. These components can often be further divided into a number of subsystems or subcomponents, which are affected by various internal and external features, events and processes, as presented in Fig. 3.

Classification scheme

Figure 4 illustrates the classification scheme used in the ISAM FEP list. At its centre, the classification scheme includes processes related to contaminant release, migration and exposures (radionuclide and contaminant factors). It is also necessary to consider the features of the disposal system (wastes, engineered and natural barriers and human behaviour) and events and processes, which may cause the system to evolve (environment factors). Beyond this, there are processes and events originating outside the disposal system, but which act upon it (external factors). These external factors (or external FEPs) are often considered to be scenario generating FEPs. By changing their status, different scenarios can be generated.

Safety assessments are not expected to predict how the environment or radiological impacts will actually evolve in the far future. Rather, they are designed to produce estimates of quantities required by regulatory guidance or for comparison with other design targets. In deciding the scope of an assessment, it is necessary to consider not only of physical factors that might be relevant but also the regulatory guidance and aims of the assessment. These may constrain the extent to which some FEPs are considered or the way in which they are treated in the assessment, e.g. regulatory time periods and the use of critical groups as representative of future human populations at risk. Therefore, a fourth layer is added – assessment context. These four layers lead to the structure illustrated in Fig. 3:

- Assessment Context
- Disposal System Domain: Radionuclide/Contaminant Factors;
- Disposal System Domain: Environmental Factors; and
- External Factors.

Definitions for each layer category of the scheme are given in Table 2. The scheme is intended to guide the allocation of FEP descriptions. It is clear however, that a FEP allocated to any particular category may have consequences for FEPs within other categories.

Design of the ISAM FEPs list

The ISAM FEPs list is a list of FEPs relevant to the assessment of long term safety of near surface disposal facilities, which attempts to be comprehensive within reasonable bounds. It consists of 141 FEPs presented here based on the classification scheme presented in Fig. 3 (Table 3). In Table 3 each FEP has been assigned an identifying number:

Layer . category . number.

This information may be useful when examining the ISAM FEP List arranged in alphabetical (or any other) order. For example:

Accidents and unplanned events 1.1.12

indicates that, in deriving the List, this FEP was considered as an "External Factor" and a "Repository Issue".

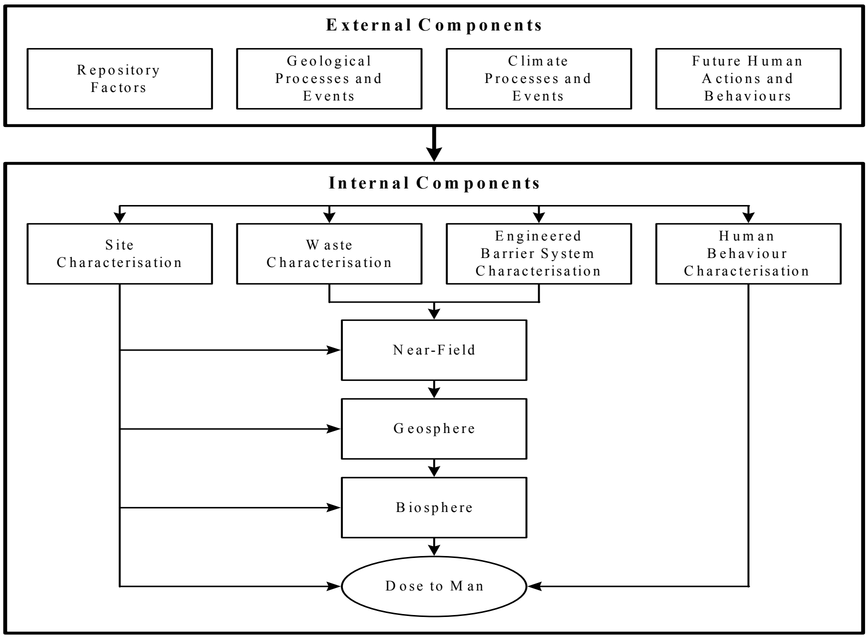

FIG. 3. Conceptual representation of the different components of a process system, and the flow of information between them.

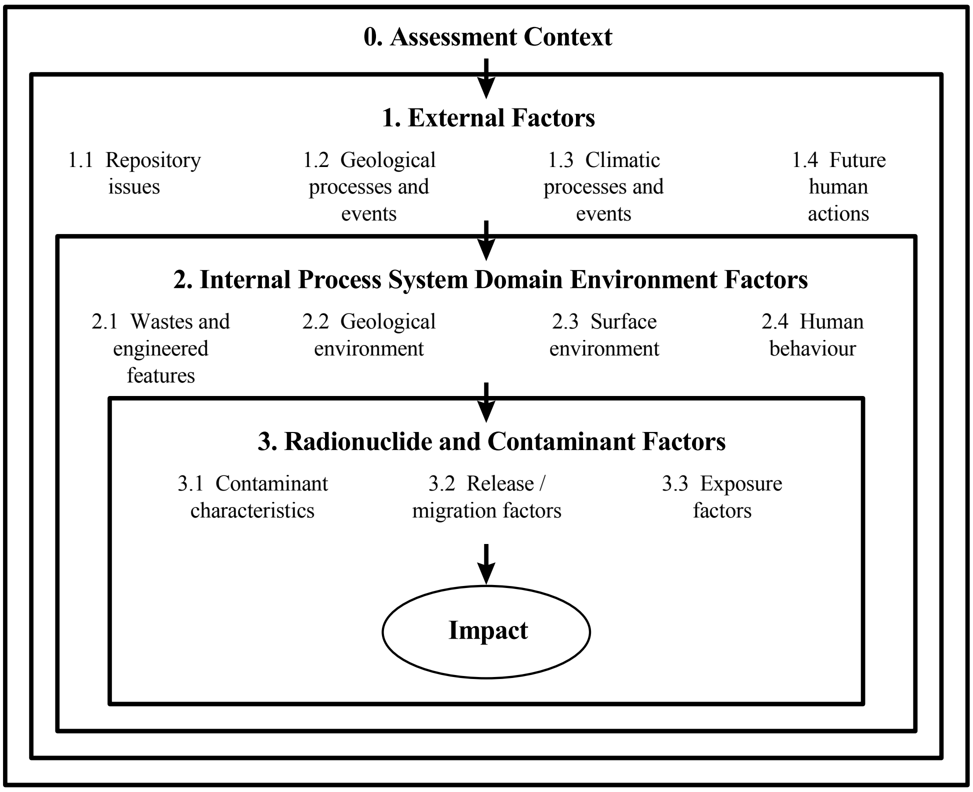

FIG. 4. Illustration of the Classification Scheme Used in the ISAM FEPs List (derived from [19]).

TABLE 2. DEFINITION OF LAYERS AND CATEGORIES WITHIN THE CLASSIFICATION SCHEME USED IN THE ISAM FEP LIST

LAYERS AND CATEGORIES OF THE CLASSIFICATION SCHEME

LAYER 0. ASSESSMENT CONTEXT

Assessment context factors are factors that the analyst will consider in determining the scope of the analysis; these may include factors related to regulatory requirements, definition of desired calculation end-points and requirements in a particular phase of assessment. Decisions at this point will affect the phenomenological scope of a particular phase of assessment, i.e. what “physical FEPs” will be included. For example, some classes of future human actions or extreme future events unrelated to the repository may be excluded.

Layers 1, 2 and 3 are defined relative to a definition of the “Disposal System Domain”.

The disposal system domain consists of the wastes, engineered and natural barriers which are expected to contain the wastes, together with the potentially contaminated geology and surface environment, plus the further geology, surface environment and human behaviour that are generally considered together in order to estimate the movement of radionuclides, and exposure to man, following repository closure. The domain thus has both spatial and temporal extent.

LAYER 1. EXTERNAL FACTORS

External Factors are FEPs with causes or origins outside the disposal system domain, i.e. natural or human factors of a more global nature and their immediate effects. Included in this layer are decisions related to repository design, operation and closure since these are outside the temporal bound of the disposal system domain.

In general, external factors are not influenced, or only weakly influenced, by processes within the disposal system domain. In developing models of the disposal system domain, external factors are often represented as boundary conditions or initiating events for processes within the disposal system domain.

The following categories are used:

1.1 Repository issues - decisions on design and waste allocation, and also events related to site investigation, operations and closure;

1.2 Geological processes and effects – processes arising from the wider geological setting and long term processes;

1.3 Climatic processes and effects – processes related to global climate change and consequent regional effects;

1.4 Future human actions - human actions and regional practices in the post-closure period, that can potentially affect the performance of the engineered and/or geological barriers, e.g. intrusive actions, but not the passive behaviour and habits of the local population, see 2.4;

In general, there are few significant direct interactions between FEPs in the different categories of external factors.

LAYERS AND CATEGORIES OF THE CLASSIFICATION SCHEME

Within the Disposal System Domain, Environmental and Radionuclide processes occur.

LAYER 2. DISPOSAL SYSTEM DOMAIN: ENVIRONMENTAL FACTORS

Disposal system domain environmental factors are features and processes occurring within that spatial and temporal domain whose principal effect is to determine the evolution of the physical, chemical, biological and human conditions of the domain that are relevant to estimating the release and migration of radionuclides and consequent exposure to man (see Layer 3).

The following categories are used:

2.1 Wastes & engineered features - features and processes within these components;

2.2 Geological environment - features and processes within this environment including, for example, the hydrogeological, geomechanical and geochemical features and processes, both in pre-emplacement state and as modified by the presence of the repository and other long term changes;

2.2 Surface environment - features and processes within this environment, including near surface aquifers and unconsolidated sediments but excluding human activities and behaviour, see 1.4 and 2.4;

2.4 Human behaviour - the habits and characteristics of the individual(s) or population(s), e.g. critical group, for which exposures are calculated, not including intrusive or other activities which will have an impact on the performance of the engineered or geological barriers, see 1.4.

Interactions between FEPs in the different categories of environmental factors may be very important.

LAYER 3. DISPOSAL SYSTEM DOMAIN: RADIONUCLIDE/CONTAMINANT FACTORS

Radionuclide factors are the processes that directly affect the release and migration of radionuclides in the disposal system environment, or directly affect the dose to members of a critical group from given concentrations of radionuclides in environmental media.

The following categories are used:

3.1 Contaminant characteristics - the characteristics of radio-toxic and chemo-toxic species that might be considered in a post-closure safety assessment;

3.2 Release/migration factors - the processes that directly affect the release and/or migration of radionuclides in the disposal system domain;

3.3 Exposure factors - processes and conditions that directly affect the dose to members of the critical group, from given concentrations of radionuclides in environmental media.

The boundaries between the different layers and categories are subjective and will depend on individual analysts' concepts and extent of models. This should not prevent a self-consistent assignment of FEPs within the ISAM FEP list itself or when mapping project FEPs to the ISAM FEP list.

TABLE 3. THE ISAM FEP LIST IN CLASSIFICATION SCHEME ORDER (ADAPTED FROM [19])

0	**ASSESSMENT CONTEXT**
0.01	Assessment endpoints
0.02	Timescales of concern
0.03	Spatial domain of concern
0.04	Repository assumptions
0.05	Future human action assumptions
0.06	Future human behaviour (target group) assumptions
0.07	Dose response assumptions
0.08	Assessment purpose
0.09	Regulatory requirements and exclusions
0.10	Model and data issues
1	**EXTERNAL FACTORS**
1.1	**REPOSITORY ISSUES**
1.1.01	Site investigation
1.1.02	Design, repository
1.1.03	Construction, repository
1.1.04	Emplacement of wastes and backfilling
1.1.05	Closure, repository
1.1.06	Records and markers, repository
1.1.07	Waste allocation
1.1.08	Quality control
1.1.09	Schedule and planning
1.1.10	Administrative control, repository site
1.1.11	Monitoring of repository
1.1.12	Accidents and unplanned events
1.1.13	Retrievability
1.2	**GEOLOGICAL PROCESSES AND EFFECTS**
1.2.01	Orogeny and related tectonic processes at plate boundaries
1.2.02	Anorogenic and within-plate tectonic processes (Deformation, elastic, plastic and brittle)
1.2.03	Seismicity
1.2.04	Volcanic and magmatic activity
1.2.05	Metamorphism
1.2.06	Hydrothermal activity
1.2.07	Erosion and sedimentation

1.2.08	Diagenesis and pedogenesis
1.2.09	Salt diapirism and dissolution
1.2.10	Hydrological/hydrogeological response to geological changes
1.3	**CLIMATIC PROCESSES AND EFFECTS**
1.3.01	Climate change, global
1.3.02	Climate change, regional and local
1.3.03	Sea level change
1.3.04	Periglacial effects
1.3.05	Glacial and ice sheet effects, local
1.3.06	Warm climate effects (tropical and desert)
1.3.07	Hydrological/hydrogeological response to climate changes
1.3.08	Ecological response to climate changes
1.3.09	Human response to climate changes
1.3.10	Other geomorphological changes
1.4	**FUTURE HUMAN ACTIONS**
1.4.01	Human influences on climate
1.4.02	Motivation and knowledge issues (inadvertent/deliberate human actions)
1.4.03	Drilling activities (human intrusion)
1.4.04	Mining and other underground activities (human intrusion)
1.4.05	Un-intrusive site investigation
1.4.06	Surface excavations
1.4.07	Pollution
1.4.08	Site Development
1.4.09	Archaeology
1.4.10	Water management (wells, reservoirs, dams)
1.4.11	Social and institutional developments
1.4.12	Technological developments
1.4.13	Remedial actions
1.4.14	Explosions and crashes
2	**DISPOSAL SYSTEM DOMAIN: ENVIRONMENTAL FACTORS**
2.1	**WASTES AND ENGINEERED FEATURES**
2.1.01	Inventory, radionuclide and other material
2.1.02	Waste form materials, characteristics and degradation processes
2.1.03	Container materials, characteristics and degradation processes
2.1.04	Buffer/backfill materials, characteristics and degradation processes
2.1.05	Engineered barriers system, characteristics and degradation processes

2.1.06	Other engineered features materials, characteristics and degradation processes
2.1.07	Mechanical processes and conditions (in wastes and EBS)
2.1.08	Hydraulic/hydrogeological processes and conditions (in wastes and EBS)
2.1.09	Chemical/geochemical processes and conditions (in wastes and EBS)
2.1.10	Biological/biochemical processes and conditions (in wastes and EBS)
2.1.11	Thermal processes and conditions (in wastes and EBS)
2.1.12	Gas sources and effects (in wastes and EBS)
2.1.13	Radiation effects (in wastes and EBS)
2.1.14	Nuclear criticality
2.1.15	Extraneous materials
2.2	**GEOLOGICAL ENVIRONMENT**
2.2.01	Disturbed zone, host lithology
2.2.02	Host lithology
2.2.03	Lithological units, other
2.2.04	Discontinuities, large scale (in geosphere)
2.2.05	Contaminant transport path characteristics (in geosphere)
2.2.06	Mechanical processes and conditions (in geosphere)
2.2.07	Hydraulic/hydrogeological processes and conditions (in geosphere)
2.2.08	Chemical/geochemical processes and conditions (in geosphere)
2.2.09	Biological/biochemical processes and conditions (in geosphere)
2.2.10	Thermal processes and conditions (in geosphere)
2.2.11	Gas sources and effects (in geosphere)
2.2.12	Undetected features (in geosphere)
2.2.13	Geological resources
2.3	**SURFACE ENVIRONMENT**
2.3.01	Topography and morphology
2.3.02	Soil and sediment
2.3.03	Aquifers and water-bearing features, near surface
2.3.04	Lakes, rivers, streams and springs
2.3.05	Coastal features
2.3.06	Marine features
2.3.07	Atmosphere
2.3.08	Vegetation
2.3.09	Animal populations
2.3.10	Meteorology
2.3.11	Hydrological regime and water balance (near surface)
2.3.12	Erosion and deposition

2.3.13	Ecological/biological/microbial systems
2.3.14	Animal/plant intrusion leading to vault/trench disruption
2.4	**HUMAN BEHAVIOUR**
2.4.01	Human characteristics (physiology, metabolism)
2.4.02	Adults, children, infants and other variations
2.4.03	Diet and fluid intake
2.4.04	Habits (non-diet-related behaviour)
2.4.05	Community characteristics
2.4.06	Food and water processing and preparation
2.4.07	Dwellings
2.4.08	Wild and natural land and water use
2.4.09	Rural and agricultural land and water use (incl. fisheries)
2.4.10	Urban and industrial land and water use
2.4.11	Leisure and other uses of environment
3	**RADIONUCLIDE/CONTAMINANT FACTORS**
3.1	**CONTAMINANT CHARACTERISTICS**
3.1.01	Radioactive decay and in-growth
3.1.02	Chemical/organic toxin stability
3.1.03	Inorganic solids/solutes
3.1.04	Volatiles and potential for volatility
3.1.05	Organics and potential for organic forms
3.1.06	Noble gases
3.2	**CONTAMINANT RELEASE/MIGRATION FACTORS**
3.2.01	Dissolution, precipitation and crystallisation, contaminant
3.2.02	Speciation and solubility, contaminant
3.2.03	Sorption/desorption processes, contaminant
3.2.04	Colloids, contaminant interactions and transport with
3.2.05	Chemical/complexing agents, effects on contaminant speciation/transport
3.2.06	Microbial/biological/plant-mediated processes, contaminant
3.2.07	Water-mediated transport of contaminants
3.2.08	Solid-mediated transport of contaminants
3.2.09	Gas-mediated transport of contaminants
3.2.10	Atmospheric transport of contaminants
3.2.11	Animal, plant and microbe mediated transport of contaminants
3.2.12	Human-action-mediated transport of contaminants
3.2.13	Food chains, uptake of contaminants in

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

To make the list applicable to a wide range of near surface waste disposal concepts, many of the FEPs have rather general names. The scope of each FEP is defined within a glossary (Appendix C), which the user should also examine. Each glossary entry consists of three parts:

- A definition, which defines the scope of the FEP in a general way and may include a technical definition if necessary;
- Comments, which give more specific remarks on FEPs or issues that might be discussed under this FEP name. The comment is optional; and
- Specific examples and key concepts of the FEPs related to the particular FEP. This list can be updated with time to as new FEPs related to near surface disposal systems are encountered. Not all FEPs from the ISAM FEP list have examples in the glossary.

The entries for the ISAM FEP list glossary have been developed to be consistent with the IAEA Radioactive Waste Management Glossary [21].

The ISAM FEP list has already proved to be useful. It was used in all three of the ISAM Test Cases for a range of purposes and at differing levels of detail.

4.3.4. Scenario generation in the ISAM Test Cases

Scenario generation approaches were defined and applied in all the ISAM Test Cases. These approaches varied according to each test case's assessment context and time available to perform the scenario analysis. The focal point of all three approaches, however, was the ISAM FEPs list, which has been applied for different purposes and at differing levels of detail. The scenario generation approach developed and applied for each ISAM test case is discussed in Volume II. Similarly, the three FEPs lists used for safety assessment of RADON, vault and borehole test cases. ISAM FEP list has been used by several countries in their national programmes; a number of these national analyses are summarized in Appendix B. The approaches are discussed below.

Vault Test Case

The approach adopted for the Vault Test Case (VTC) is summarized below and illustrated in Fig. 5. The approach comprises of the following elements:

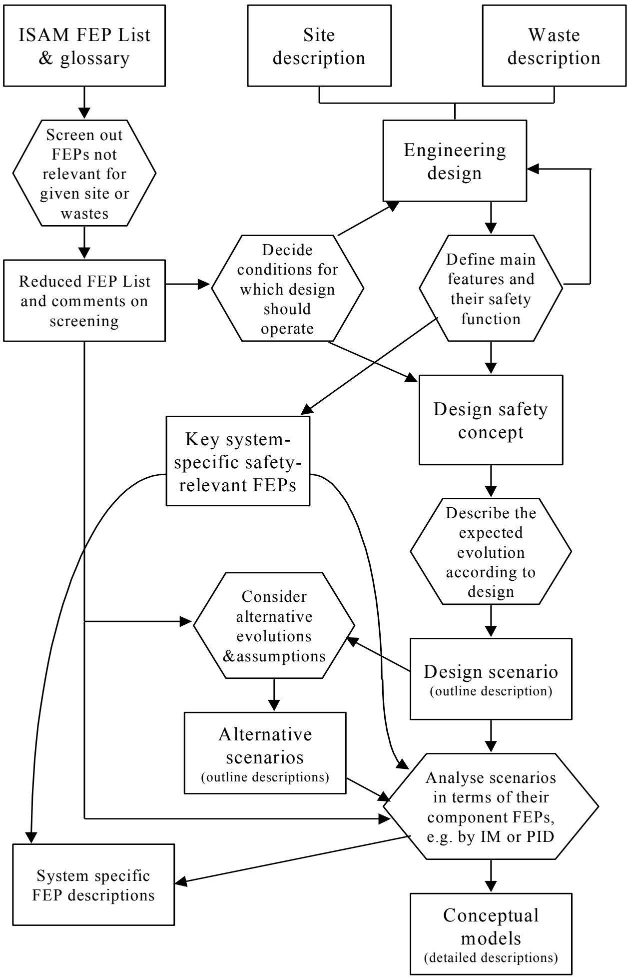

FIG. 5. The Vault Test Case Scenario Generation Approach.

- Carry out an initial screening of the ISAM FEP list on the basis of the assessment context and system description. Record the justification for excluding any FEPs from further consideration.

The VTC Group decided to identify a limited number of representative scenarios rather than comprehensively identify every possible scenario.

- Focus initially on one reference scenario termed the 'Design Scenario', which represents how the system might be expected to evolve assuming the design functions as planned. This design scenario approach was adopted because the facility assessed in the VTC was still in the planning stage. If the Design Scenario were not to yield acceptable results, it would be unlikely that development of the disposal facility would proceed with the current design. It is important to recognize the difference between the Design Scenario (how the system will evolve assuming everything goes according to plan) and a 'normal' or 'central' scenario (how the system is most likely to evolve).
- Decide the status of external, scenario generating FEPs for the Design Scenario.
- Identify the safety-relevant features and associated safety functions for the Design Scenario.
- Develop a description for the Design Scenario. This includes estimates of the expected lifetime/performance of the identified safety-relevant features and their safety functions.

- Identify alternative scenarios at a high level by revisiting the screened ISAM FEP list, especially focusing on the external FEPs, and select which alternative scenarios should be assessed in detail.
- Decide the status of external FEPs for each Alternative Scenario to be assessed.
- Identify safety-relevant features and associated safety functions for each Alternative Scenario to be assessed.
- Develop a description for each Alternative Scenario. This includes estimates of the expected lifetime/performance of the identified safety-relevant features and their safety functions.

Once the Design and Alternative Scenarios have been described, their FEPs and FEP interactions can be analysed in more detail to allow the development of associated conceptual models.

Initial FEP screening

Prior to an initial screening of the ISAM FEP list, the assessment context and system description documentation were reviewed to identify points for further clarification and increase participants' understanding of the disposal system. At this stage that it was only necessary to record a simple 'yes' if a FEP should be included. For excluded FEPs, the justification for the decision was recorded. In some cases, this may require a modification to the assessment context in an iterative process to ensure the context and the justification for screening decisions are in agreement.

a. Design scenario

Development of the design scenario

Two options for the next stage of the scenario generation process were considered:

- Review the screened FEPs list and break it down into more detailed, lower level FEPs; and
- Generate scenarios down to an appropriate level of detail and then feed lower level FEPs into the ISAM FEP list.

Given the resource constraints, it was decided to focus on a limited number of illustrative scenarios rather than developing a more comprehensive approach that identified all possible scenarios in a systematic manner. A functional analysis approach was used to develop the Design Scenario, which represents 'how you would expect the disposal system to evolve assuming the design functions as planned'.

For the purposes of the Vault Test Case, the Design Scenario was developed with constant present day external FEPs, although it is noted that the approach does not necessarily require external FEPs to be constant, e.g. climate change may be included in the scenario if this is very likely to happen at some point[2]. The list of external factors in the ISAM FEP list was

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[2] The prediction of climate change over hundreds or thousands years is not possible with any degree of confidence. Because of this, one of the American Regulatory documents [45] established that the future climate change can not be used in the safety assessment of near surface repositories in the USA. Nevertheless, consideration of the possible climate changes may be important for certain safety assessments and climate change is often included in most FEPs lists (e.g. the ISAM FEP list). Therefore, some assessments have considered the effects of climate change (see for example [147]).

reviewed to decide the conditions to be fixed for the purpose of defining the safety functions. All decisions were recorded.

The main safety-related features and their safety functions were recorded. It was noted that single features might have several safety functions. Furthermore, these different functions might operate over different time scales. For example the cover over the disposal facility can act as a barrier to intrusion as well as an infiltration barrier. Its role as a physical barrier to intrusion might exist long after its role as an infiltration barrier has failed.

Description of the design scenario

By considering the lifetime/performance of the safety related features and their safety functions the Design Scenario description was developed. Only a largely qualitative, high level description of the temporal evolution of the system was required based on questions such as ‘why’, ‘when’ and ‘how’. In the development of the Design Scenario, it was found important to have a good definition for the design. It was noted that if the design is well specified, the design scenario and alternative scenarios could be relatively easily defined. If the design is poorly defined, then the scenarios are more difficult to specify and there needs to be greater iteration between the scenario and design work.

b. Alternative scenarios

Once the Design Scenario had been developed, there was a need to go through the key assumptions and decide if there was a need to develop alternative scenarios. This was done by comparing each category of external FEP in the ISAM FEP list against the Design Scenario. These external FEP were considered to be scenario-generating FEPs, i.e. changes in their status were considered to result in the generation of additional scenarios. In contrast, differences in the internal FEPs were considered to result in different conceptual models associated with the same scenario, rather than different scenarios. If the Design Scenario did not satisfactorily cover the range of possible conditions for external FEPs in a category, then an alternative scenario was developed. This process was iterative. To help the screening of the resulting scenarios, probability, uncertainty and consequence were used as screening criteria. Table 4 lists the criteria that were used to screen the possible alternative scenarios.

Although four alternative scenarios were identified, only one alternative scenario was selected for the purpose of the ISAM Test Cases for development due to resource constraints. Given the potentially high consequences of human intrusion and the relatively high occurrence probability of human intrusion over the timescales of concern into a near surface disposal facility, it was decided to develop the Human Intrusion Scenario. For this purpose the external FEPs were reviewed for the scenario and the results recorded. The external FEPs for repository issues, geological processes and effects, and climate processes and effects remained the same as for the Design Scenario, whereas those relating to future human actions were modified to account for human intrusion.

TABLE 4. SCREENING CRITERIA FOR POSSIBLE ALTERNATIVE SCENARIOS

Importance of consequence	Probability	Knowledge		
		Certain	Uncertain	None
Important	High	Consider	Investigate	Investigate
	Low	Investigate	Investigate	Investigate
Not important	High	Screen out	Check	Check
	Low	Screen out	Screen out	Check

The main safety related features were reviewed together with the design scenario description to produce a high level, qualitative description of the Human Intrusion Scenario. The description outlined the expected temporal evolution of the system and its safety-related features, i.e. a high level description of the evolution of the system under human intrusion conditions.

RADON test case

The basis of the approach adopted by the RADON Test Case is illustrated in Fig. 6 and is comprised of the following elements.

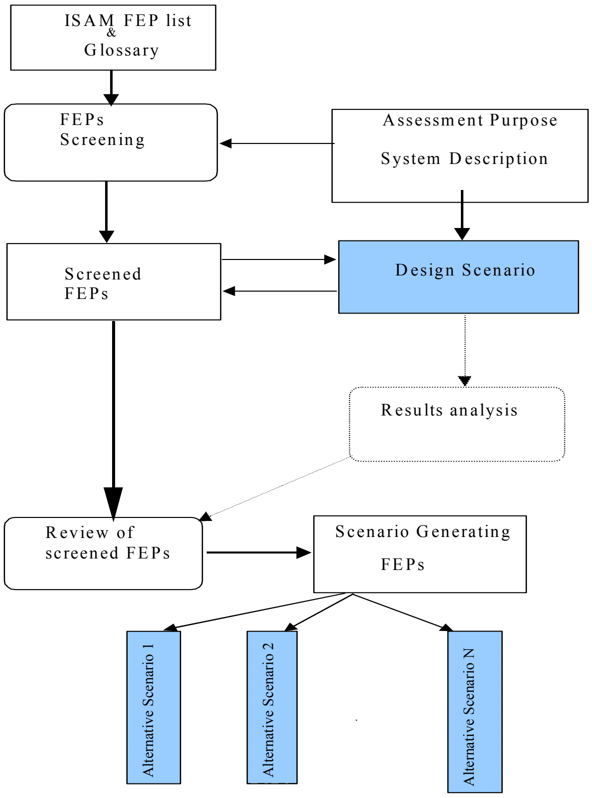


FIG. 6. The RADON Test Case Scenario Generating Approach.

- Screen the ISAM FEP list on the basis of the assessment context and system description. Record the justification for excluding any FEPs for further consideration. Identify additional FEPs related data to be obtained, clarified or substantiated.
- Develop and agree a simplified Design Scenario as the main case of the safety assessment. In common with the Vault Test Case, the Design Scenario is considered to represent how the system might be expected to evolve assuming the design functions as planned.
- Obtain and check necessary data, screen FEP list, and review Design Scenario. Compare FEPs involved in the Design Scenario against the screened FEP list.
- Make preliminary calculations on Design Scenario. Identify safety-relevant FEPs. Screen unrecorded FEPs and select scenario-generating FEPs.
- Identify a limited number of representative alternative scenarios rather than comprehensively identify every possible alternative scenario by revisiting the screened ISAM FEP list, especially focusing on the external FEPs.

a. FEPs screening

An initial screening of the ISAM FEP list was conducted using expert judgement. Information from the assessment context and system description was used as input to the screening process. Four categories of excluded FEPs were identified based on the following criteria.

- FEPs that are clearly not relevant to the assessment. There should be no argument about the exclusion of these FEPs. An example of this category of screened FEP for the RADON Test Case is the exclusion of FEPs associated with discharge to a marine environment.

- FEPs that are not relevant because of the chosen assessment context. These FEPs might potentially be important in the future, if other assessment contexts are applied. An example is collective dose, which is not relevant because the current assessment context only requires consideration of individual dose.

- FEPs that are not considered to be important. The lack of importance may be the result of the type of disposal system considered, or because other FEPs have been judged to be more important for overall system performance. Inclusion in this set of FEPs is more judgmental than the first two exclusion categories.

- FEPs that are not considered because there is no information about them, and for which it is unreasonable to expect information to be available for the assessment. Inclusion in this set of FEPs is the most judgmental of the four.

The results of this process were recorded, including a justification for excluding the various FEPs.

An additional step was taken in screening the FEPs in which similar FEPs were combined together. This step supposed that an expert keeps in mind preliminary set of important scenarios or preliminary procedure of FEPs use.

The next step in the process was to link the screened FEPs into a coherent structure capable of being analysed. Effectively, this step involves developing a Process System Model and identifying the External FEPs acting on it. Formal approaches have been proposed for this step, which are intended to address increasing requirements on justification and traceability.

Approaches that have been described in the literature for this step include: lists and tables; influence diagrams [22]; and the interaction matrix approach [23, 24].

For the RADON Test Case, the process system model was developed using professional judgement since time constraints did not allow more formal methods to be used. This procedure highlighted some important uncertainties relating to the system description and even the assessment context. It was decided to continue the assessment procedure recognising that it was a first iteration and additional data could be collated for use in future iterations.

c. Design scenario

The Design Scenario for the RADON Test Case was selected to represent a reasonable future evolution of the disposal system. This future evolution has been chosen to be the one that most closely resembled the current situation at the disposal facility. It was not considered to necessarily represent the "most probable" future evolution of the system, no judgement was made about the likelihood of occurrence of the scenario. The scenario considered that the engineering barriers functioned according to their design and assumed no evolution of the geosphere or biosphere due to factors such as climate change. The Design Scenario provided a high level description of the evolution of the engineering barriers and near field and should included a brief description of most probable pathways and interaction between the geosphere and biosphere.

d. Review of screened FEPs

From the list of screened FEPs, the following scenario-generating FEPs were identified.

- Enhanced degradation (no credit taken for the engineered barriers);
- Erosion - accretion;
- Flooding associated with high precipitation;
- Subsidence;
- Biotic intrusion;
- Drilling (human intrusion with intrusion and post-intrusion dose);
- Surface construction and site development (human intrusion including road construction with intrusion and post-intrusion dose, house building with intrusion and post-intrusion dose, use of vault as house foundation); and
- Societal change.

e. Alternative Scenarios

Alternative scenarios were identified after the Design Scenario was defined. Ideally it would be helpful if some preliminary results from the Design Scenario could be obtained prior to the identification of the Alternative Scenarios, especially when significant uncertainties are present in its description. However, in practice the alternative scenarios often have to be identified before results from the Design Scenario are available – this was the case with the RADON test case.

Some Alternative Scenarios were defined using the list of scenario generating FEPs, obtained from reviewing the screened FEPs list and using scenarios often considered in the assessment of near surface disposal facilities, independent of the scenario generation method implemented for safety assessment. Such scenarios can be divided into three main groups:

- Undisturbed performance (leaching, groundwater, gas generation);
- Naturally disturbed performance (erosion, bathtubbing, earthquake, earth creep, frost heave, plant and animal intrusion); and
- Inadvertent intrusion (construction, agriculture).

All these cases should in general be considered for both on-site and off-site human residence.

Combining these "generic" scenarios with the scenario generating FEPs identified above, the following alternative scenarios were identified.

- Variations of the Design Scenario without human intrusion for on-site and off-site situations with: leaching to and transport in groundwater and subsequent discharge into river and use by humans.
- Variations of Design Scenario without human intrusion for on-site and off-site situations with: leaching to and transport through unsaturated zone into aquifer and subsequent discharge into wells and use by humans for domestic and agricultural purposes; biotic intrusion could be included;
- Human intrusion scenarios resulting in exposure of intruders and off-site dwellers that farm on the contaminated land. Surface construction and site development (e.g. drilling with intrusion and post-intrusion dose, road construction with intrusion and post-intrusion dose, house building with intrusion and post-intrusion dose, use of vault as house foundation);
- Flooding associated with high precipitation;
- Erosion-accretion; and
- Societal changes.

These scenarios were considered to cover all previously discussed features of the disposal system and a review of the literature showed that such results are in accordance with references concerning the assessment of near surface disposal facilities. It should be noted that the bathtubbing scenario, which is often analysed in previous assessments, was excluded after initial screening calculations. It turned out that infiltration was less than outflow and the bathtubbing effect was unlikely to occur.

Borehole Test Case

In the assessment context for the Borehole Test Case, it was stated that one of the purposes of the safety assessment was to evaluate the borehole disposal concept under specific site and land use conditions. The site conditions involved the implementation of the borehole disposal concept in saturated and unsaturated condition in a semi-arid environment. Two land use conditions were considered: the continuation of current land use patterns, characterized by small farms and agricultural activities to the extent supported by the local climate; and reversion to traditional human behaviour, characterized by hunter-gatherer land uses.

With these conditions as part of the assessment context, it was considered possible to follow a simplified approach to scenario development and justification. The following two exposure scenarios were defined by expert judgement on the basis of the assessment context:

- Member of public (farmer) with an abstraction well (with variants on distance of well from disposal borehole); and
- Member of public (hunter-gatherer) eating termites.

In addition to these two land-use based scenarios, a third scenario was added for consideration, namely:

— Inadvertent human intrusion.

b. Screening of the ISAM FEPs list

The main scenario generation effort was directed towards providing an audit trail of factors to be considered in the analysis of these scenarios. This was achieved through the screening of the ISAM FEP list and use of a source-pathway-receptor analysis (Fig. 7). This analysis allowed the source of radionuclides to be identified for each scenario (i.e. the disused sealed source in the disposal borehole), the various pathways from the source to the receptor to be identified, and the target (i.e. the exposed humans) to be identified.

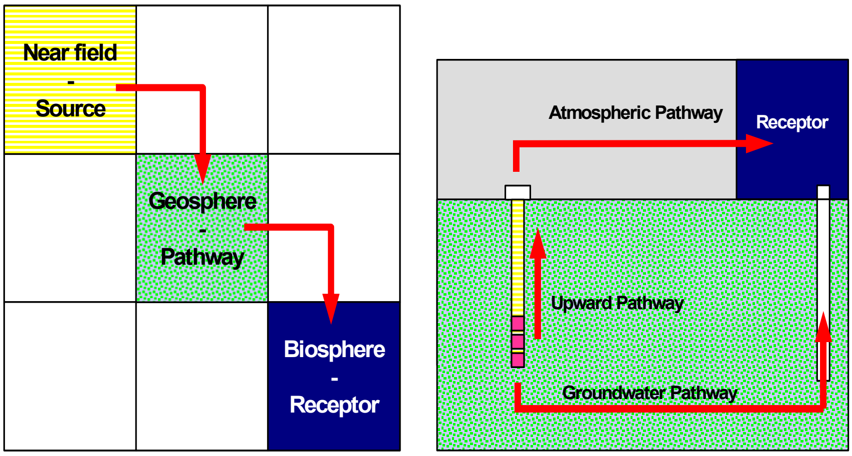


FIG. 7. Schematic Representation of the Source-Pathway-Receptor Analysis for the Borehole Test Case

4.4. LESSONS LEARNT AND CONCLUSIONS

(a) **Scenario Development:** It is now common practice in post-closure safety assessments to address uncertainties in the future evolution of a disposal system through the development and application of scenarios. Scenario generation is a key component of the safety assessment for several reasons:

(i) Scenarios provide the context in which safety assessments are performed. One cannot assess the long term performance of a radioactive waste disposal facility without considering future conditions of the site.

(ii) Scenarios influence model development and data collection efforts.

(iii) Scenarios provide an important area of communication between disposal facility developers, regulators and others with an interest in the safety of the disposal facility.

(iv) Scenarios are a very important aspect of confidence building for the post-closure safety assessment of radioactive waste disposal facility and therefore also a focal point of independent reviewers of the assessment.

(b) **Terminology:** It is important to provide a clear definition of terms used such as "scenarios" and "FEPs". Finding a single definition for "scenario" suitable for all assessments can be difficult. It is important to ensure that the definition used for an assessment is consistent with the purpose and scope of the assessment, as well as the approach followed to generate the scenarios. Similarly, providing a single definition of a feature, event or process (FEP) suitable for all assessments is equally difficult. For example a physical phenomenon can often be thought of as a feature, event, or process depending on the temporal and spatial scale on which it is viewed. It also depends on how the FEP is represented in the model used to evaluate a safety case. However, in ISAM the term "FEP" is still preferred because of its common use in assessment literature.

(c) **Systematic Scenario Generation Framework:** It is important to adopt a systematic approach to scenario generation that allows the underlying assumptions to be clearly identified and documented which provides a formal basis for scrutiny of the logic of the underlying assumptions leading to the safety assessment. This helps to provide assurance that the assessment has effectively addressed all potentially relevant FEPs and taken account of the ways in which combinations of these FEPs might produce qualitatively different scenarios. A systematic scenario generation approach should fulfil a number of basic functions. In particular, the approach should ensure:

(i) Completeness – taking care to ensure the selected scenarios provide an appropriately comprehensive picture of the system, its possible evolutionary pathways, and associated critical events to allow the robustness of the system to be investigated.

(ii) Transparency - including the documentation of the application of the approach (e.g.); and

(iii) Comprehensiveness – all possible FEPs which can significantly influence the disposal system and the migration and fate of radionuclides should be considered.

(iv) Relevant future evolutions are described;

(v) Critical issues are identified; and

(vi) Robustness of the system is investigated.

Note, however, that more than one method can be used to generate and justify scenarios; there is no single approach that such always be used in all assessments. It is important to ensure that to the approach selected is consistent with the overall objectives of the assessment as described in the assessment context. Thus the method used to generate scenarios can depend on the assessment context.

(d) **The ISAM FEPs list:** A common element in many scenario generation methodologies is the initial construction of a comprehensive list of Features, Events and Processes that could directly or indirectly influence the disposal system and the migration and fate of radionuclides within the system.

(i) The FEPs list plays a pivotal role in most scenario generation approaches, although its application may vary from assisting in site selection, as a check list, to facilitating model development, to guiding site characterization programmes, to generating a comprehensive set of exposure scenarios. *FEPs should be appropriately screened using expert judgement or predetermined screening criteria.* Approaches in the literature describe screening criteria based on probability, consequence, or some combination of the two. Regardless, of the approach used, *documenting the screening processes is necessary for traceability, transparency and confidence building.*

The NEA FEPs list was adopted and revised to be suitable for near surface disposal facilities, thus forming the ISAM FEPs list. The current version of the ISAM FEPs list has been developed with the intent to be comprehensive; initial evaluations of the list have not identified any obvious gaps in its comprehensiveness. It is also intended to be well structured to allow easier use. The ISAM FEPs list should serve as a very good starting point to identify site- specific features, events and processes for real sites.

(ii) The ISAM FEPs list is very similar to the NEA list, which has been extensively reviewed for completeness for geological systems. To some extent, the confidence in the NEA FEPs list derived from these reviews transfers to the ISAM FEPs list. Some of the FEP definitions and comments associated with the FEPs have been altered to be more representative of near surface conditions. Experience with both specific near surface disposal facilities and FEPs lists developed and applied in the ISAM Test Cases has been used in the development of the ISAM FEPs list.

(iii) The ISAM FEPs list consists of high level FEPs that could influence the behaviour of the disposal system. To facilitate model development it is often necessary to subdivide these high level FEPs into lower levels. The FEPs included in the ISAM FEPs list are very useful for this purpose.

The ISAM FEPs list is grouped into two distinct sets of FEPs:

— Internal FEPs, referring to FEPs that are associated with phenomena built into the system model under consideration; and

— External FEPs, referring to FEPs that are treated as affecting the system from the outside, but which are not intrinsically built into the system model. External FEPs can be regarded as boundary conditions or forcing functions for the system model.

(g) **FEP Screening and Expert Judgement:** If needed*, the ISAM FEPs* list can be reduced to satisfy site specific needs. It can also be enlarged if needed, but this is less likely, given the attempts to make the list comprehensive. Site specific and context specific conditions may reveal that some of the FEPs are redundant and consequently may be eliminated from the list for further consideration, using expert judgement and/or pre-determined screening criteria. Clearly defined screening criteria are necessary, of which the following can serve as examples:

(i) Physically implausible given the timescale of the assessment (e.g., orogeny and volcanic activity);
(ii) Physically implausible given the site context (e.g., geothermal effects);
(iii) Rate or probability of occurrence is small relative to other FEPs (e.g., large meteorite impact);
(iv) Global disaster (e.g., extreme global warming creating a tropical/desert climate);
(v) Included elsewhere (e.g., human impacts on climate change);
(vi) Excluded by regulatory guidance (e.g., technological development); and
(vii) Excluded by assessment context (e.g., species evolution) effect on the repository.
(viii) Effect on the repository.

Regardless, of the approach used, documenting the screening processes is necessary for traceability, transparency and building confidence.

(f) **FEP Representation and FEPs Interactions:** Several tools can be used to visually represent FEPs and their interactions in a logical, traceable and systematic way. These tools include tables or more visual representations, such as fault or event trees, Process Influence Diagrams, flow diagrams, and interaction matrices. Interaction matrices were widely used in the ISAM project. Most participants felt that interaction matrices are a useful tool for clarifying scenarios and conceptual models, and in documenting assumptions made in their development. However, it is emphasized that there is no one technique that is the best available for this function; each technique has particular strengths and weaknesses.

(g) **Types of Scenarios:** In most assessments, a single reference scenario is developed for initial consideration and alternative scenarios are then developed to investigate the impact of scenarios that differ to a lesser or greater extent from the reference scenario. Indeed in some cases, the alternative scenarios can be seen as little more than sensitivity analysis of the reference scenario. The reference scenario is often, but not always, considered to be the most likely scenario for the given safety assessment; however, it is usually considered to be a benchmark scenario against which the impact of alternative scenarios can be compared. Terms such as normal evolution, base case, central have been used in a variety of assessments instead of the term reference. Similarly terms such as altered evolution and deteriorated evolution have been used instead of alternative. The key issue is to ensure that any terms that are used to describe the different types of scenario in an assessment are defined and their purpose clearly explained. .

In ISAM, the term **Design Scenario** was chosen for the reference scenario. The Design Scenario represents how the system might be expected to evolve assuming the design functions as planned. It is generally devoid of consideration of major disruptive events and processes; only gradual degradation is usually considered. The scenario defined in this way becomes the benchmark against which alternative scenarios are measured. It should not be misconstrued to be the “most likely” or “best estimate” scenario.

With the Design Scenario appropriately defined and evaluated, it becomes a useful reference to assess the significance of **alternative scenarios**. The Design Scenario addresses a single representation of the future evolution of the system. Questions related to alternative possible climate or geological changes or related to a change in human behaviour are still unanswered. The consideration of alternative assumptions about external FEPs and their implications for the system leads to alternative evolutionary behaviour of the system; these alternative future histories are referred to as alternative scenarios. Generally, a limited number of external FEPs will be judged to be of greatest concern with respect to safety. By identifying the influences of these external FEPs to be key perturbations to the Design Scenario, these FEPs can be identified as scenario-generating FEPs, in that they lead to the formation of specific alternative scenarios. These scenarios are then evaluated to determine the effect on system behaviour.

5. FORMULATION AND IMPLEMENTATION OF MODELS

5.1. INTRODUCTION

Model formulation and implementation has often been conducted as a largely informal process in which assumptions and decisions were poorly documented. However, the models are important to the defensibility and transparency of a safety assessment, and are frequently the focus of attention for independent reviewers. Therefore, as with other steps in the safety assessment approach, there is a need to make the process of formulating and developing models formal, defensible, and transparent to independent review. In particular, it is important for the assessor to document:

- The identification of the various processes affecting the release, migration and fate of radionuclides and decide which processes are most important;
- The selection of appropriate models, tools and data to represent the processes; and the justification of the choice of the models, tools and data, for example through the use of more detailed analyses, experimental data, or expert judgement.

The process of conceptual model development, mathematical abstraction, and implementation using computer tools is shown in Fig. 8, as Element 4: Formulate and Implement Models. The process is expressed in more detail in Fig. 7 and Section 5.

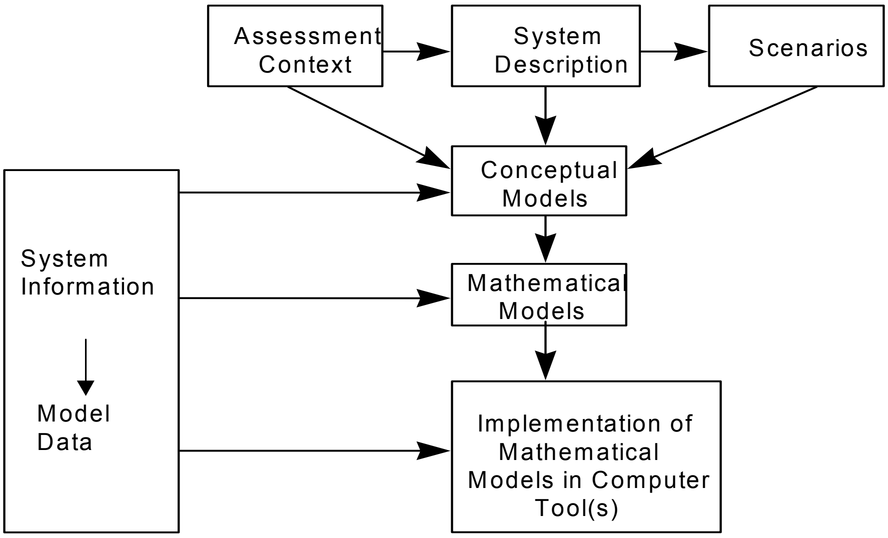


FIG. 8. The Model Formulation and Implementation Process.

This section summarized the work undertaken on approaches that have been used to formalize the process of model development and implementation. In particular, approaches to conceptual and mathematical model development are discussed in Section 5.2 and 5.3, respectively, the data for the model formulation and implementation are discussed in Section 5.4, whilst the implementation of the models and data in computer tools is discussed in Section 5.5. The types of calculations are discussed in section 5.6. The types of calculations are discussed in Section 5.6 and key lessons learnt and conclusions are presented in Section 5.7.

5.2. DEVELOPMENT OF CONCEPTUAL MODELS

The development of conceptual models is a crucial phase of the safety assessment process in which various hypothetical scenarios are used to evaluate the performance of a radioactive waste disposal facility against a set of performance objectives (i.e., radiological dose to man). Safety assessment aims to demonstrate with reasonable assurance that future members of the public and the environment are protected from potential releases from the disposal facility. This demonstration involves the quantitative assessment of scenarios.

Conceptual models describe the features, events, and processes (FEPs) included in the in a scenarios. In other words, conceptual model describes qualitatively how radionuclides are: released from the disposal facility (near field or source term) into the accessible environment (biosphere) (sometimes directly, for example due to human intrusion, and sometimes via the geosphere, for example due to leaching of radionuclides into the geosphere); how they are transported in the geosphere and biosphere; and through what exposure pathways they lead to environmental contamination and/or dose to man (see for example Fig. 9 and Fig. 10).

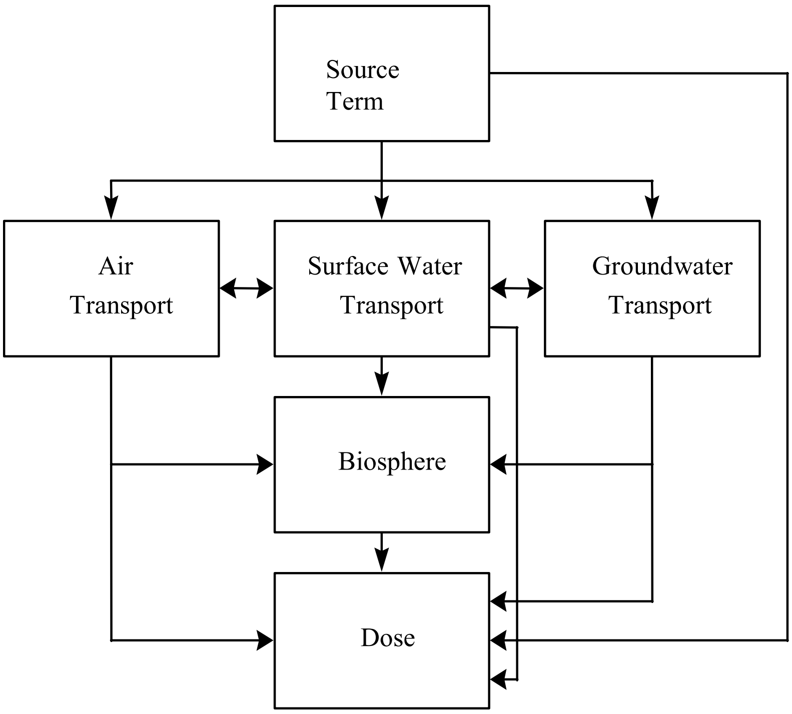


FIG. 9. Example Conceptual Model of Radionuclide Release, Transport and Exposure.

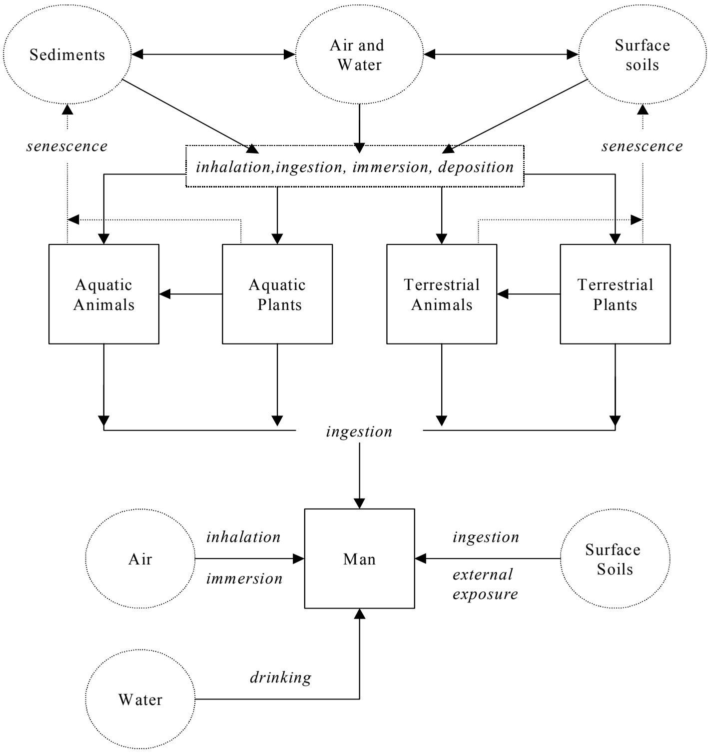


FIG. 10. Conceptual Model of Biosphere Pathways.

The quantitative analysis of consequences for the scenarios are performed using mathematical models that are derived from the conceptual models. The performance evaluation process in which conceptual models and scenarios are developed and refined over the course of the evaluation is described below.

A conceptual model can be defined as “a set of qualitative assumptions used to describe a system or subsystem for a given purpose. At a minimum, these assumptions concern the geometry and dimensionality of the system, initial and boundary conditions, time dependence, and the nature of the relevant physical and chemical processes. The assumptions should be consistent with one another and with existing information within the context of the given purpose” [20].

A description of the scope of the model is necessary in order to record the assumptions under which it has been developed and the situations to which it applies. This in turn is important in ensuring fitness for purpose and avoiding inadvertent use of the model outside its intended area of applicability.

For the scenarios that are to be quantitatively assessed, it is important that the conceptual model is amenable to mathematical representation. The model should have enough detail to allow appropriate mathematical models to be developed to describe the behaviour of the system and its components. This description should be sufficient to provide an estimate of the performance of the system over time, at a level of detail that is appropriate to the assessment context and stage of iteration of the assessment.

More than one conceptual model may be consistent with available information for a scenario. Uncertainties in parameter values for a given conceptual model have been investigated extensively (see for example [25]). However, uncertainties arising from alternative conceptual models have until recently been largely ignored, even though these conceptual model uncertainties have the potential to give rise to the dominant uncertainties as demonstrated from the findings of the BIOMOVS II study (see for example [26]). An example involving the flow of water and the transport of radionuclides through a fractured rock mass is given in [27]. Figure 11 shows four alternative conceptual models for the rock mass permeability field. It has been suggested [27] that it is not appropriate to ask the generic question as to which of these, if any, is correct since the system is so complex and the extrapolations in time and space are so extensive that scientific validity is not achievable. Instead there is a need to ask whether the models are fit for purpose, such as for calculating the average flux of water through rock on a scale of tens of metres is within order-of-magnitude accuracy.

The biosphere is a heterogeneous medium and when developing conceptual models it is often convenient to divide it into sub-systems where discontinuities in the properties are found (for example air, water, soil and sediments, plants, animals, and man). Once released into air, water, soil, and sediments, radionuclides are taken up by plants, animals and man. Figure 9 shows a general biosphere conceptual model in which interactions of plants, animals, and man with the environmental media are identified. Plants and animals constitute the food-chain for man. Radionuclides reach man through the food chain by ingestion.

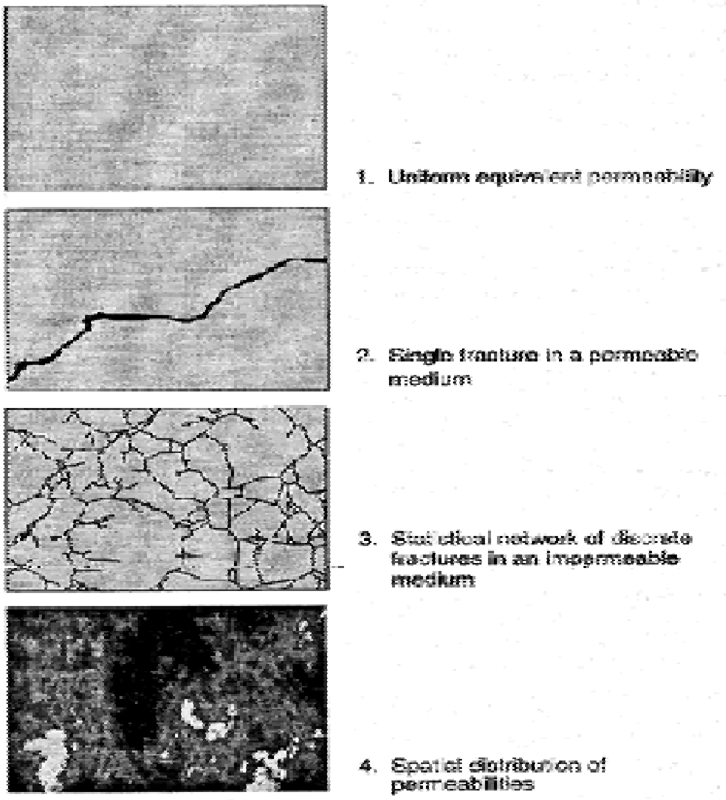


FIG. 11. An Example of Alternative Conceptual Models for Rock Permeability (from [28]).

A variety of approaches can be used to develop conceptual models for post-closure safety assessment for near surface disposal facilities. Three examples are given in Section 5.2.1 and additional ones are then given in Section 5.2.2.

5.2.1. Example approaches for conceptual model development

SACO approach

This approach is based on ideas initially developed in [27] and subsequently developed and enhanced in [29]. It has the advantage of allowing the rapid development of the conceptual model. However, it relies on the expert judgement and experience of the staff carrying out the assessment and therefore it not necessarily as transparent as other approaches.

In order to develop a conceptual model for a given scenario using the SACO approach, it is necessary to consider:

- The source of contaminants – i.e. the disposal facility;
- The release mechanisms – the processes affecting in the release of radionuclides from the source;
- The transport media - the media through which the radionuclides are transported;
- The transport mechanisms - the processes affecting the transport of radionuclides;
- The exposure media - the media in which humans are exposed to the radionuclides; and
- The exposure mechanisms - the processes resulting in the exposure of humans to the radionuclides.

The first step is to identify the release, transport and exposure media by reviewing the relevant FEPs associated with each scenario. This allows the identification of the key release, transport and exposure media, although no links are made at this stage between the media.

Once this first step has been completed, the mechanisms by which the associated release, transport and exposure may occur are considered for each scenario. Two strategies can be used based on information derived from each scenario:

- The deductive strategy starts with the consideration of how release events might occur, then considers the possible transport and exposure mechanisms, and finally considers the associated impacts; and

- The inductive strategy starts with the consideration of the impacts and considers the exposure and transport mechanisms which might have caused the impacts. Finally the associated release mechanisms are considered.

Both strategies can be used together for example [30] uses both approaches when attempting to identify release, transport and exposure mechanisms. FEPs previously identified in the scenarios identification and justification step of the assessment approach can be used as a check list.

Table 5 and Fig. 12 illustrate the application of the approach to a leaching scenario considered in [29].

TABLE 5. CONTAMINANT RELEASE MECHANISMS, TRANSPORT MEDIA AND MECHANISMS, AND HUMAN EXPOSURE MECHANISMS A LEACHING SCENARIO

Contaminant Release Mechanisms	Transport Media	Contaminant Transport Mechanisms	Human Exposure Mechanisms
Leaching	Waste Geosphere Well (irrigation and drinking water) Soil Crops Cows Atmosphere (dust)	Advection Dispersion Water abstraction for irrigation and drinking water Foliar interception Root uptake Adsorption Ingestion of water, pasture and soil by cows Leaching Erosion	Ingestion of water, crops, and animal produce Inhalation of dust External irradiation from soil

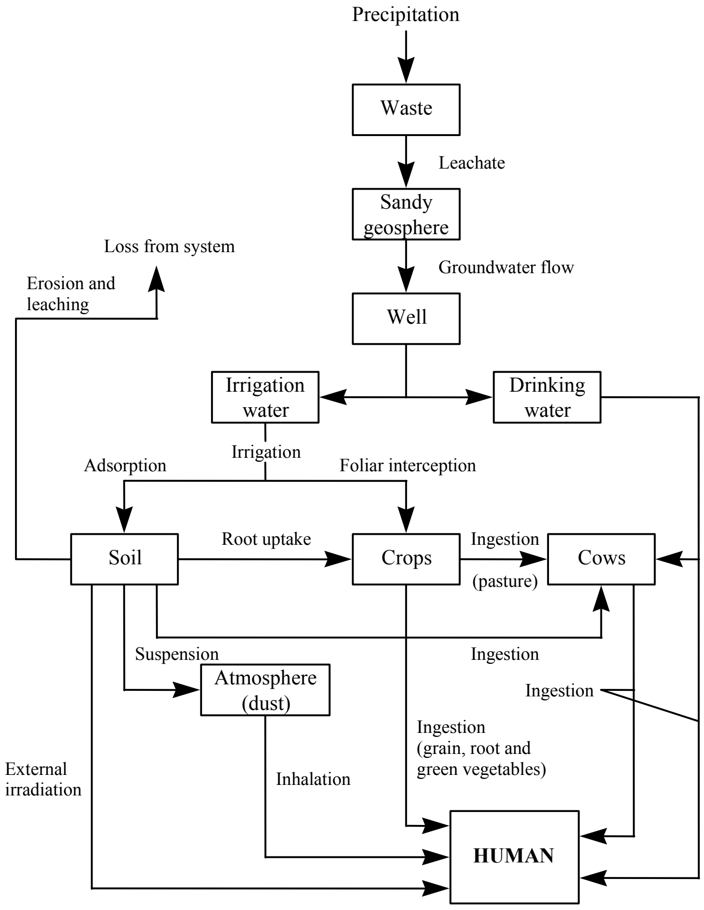


FIG. 12. Conceptual Model for a Leaching Scenario.

Interaction matrix approach

The Interaction Matrix approach is based on ideas developed in BIOMOVS II [31] and subsequently developed and enhanced in a number of studies such as [32 and 33]. The use of the Interaction Matrix was developed in the context of rock engineering systems [34] and applied in a number of studies considered in [35]. It allows the graphical representation of system interactions through the use of formalized procedures. However, there is still reliance on expert judgement, albeit recorded, and it is data intensive and can be time consuming.

The approach starts with a top down approach to dividing the system into constituent parts. This can be done without direct reference to a FEP list, since, at later stages in the assessment, the matrix and the FEP list contents can be audited against each other. The main components are identified and listed in the leading diagonal elements (LDEs) of the matrix. The interactions between the LDEs are then noted in the off-diagonal elements (ODEs). This allows FEP interactions and pathways to be mapped, which is an important step in developing and defining a conceptual model and in the logical progression to a mathematical model. Moreover, the systematic process of examining how the system components relate to one another may help to identify new, previously unrecognized relevant characteristics of the system.

Figure 13 illustrates the procedure with a 2 x 2 matrix and also demonstrates the clockwise convention for recording interaction/influence direction. When using the Interaction Matrix approach the convention is to allocate ODEs in the direction of contaminant migration. In this way, contaminant migration pathways and the associated exposure pathways and exposure groups can be traced and translated into the conceptual model. Each transfer of contaminant from LDE to another LDE via an ODE can then be represented by a mathematical formalization and incorporated into the mathematical model.

Component A 1,1	Influence of A on B 1,2
Influence of B on A 2,1	Component B 2,2

FIG. 13. Example 2 x 2 Interaction Matrix.

When considering the interactions it is important to ensure that they are direct interactions and to identify which element is the cause and what is the effect. More than two diagonal elements can be involved in describing a single process. A connected chain of interactions through the matrix is called a pathway. It is also possible to have loops, e.g. A → B → A, which preferably should be stable loops with the effect diminishing after a number of iterations.

Two or more iterations of Interaction Matrix development can be undertaken if time and resources allow. In this iterative process, all possible interactions between the LDEs will be included in the first iteration. Then with second and, if necessary, subsequent iterations the ODE interactions would be refined so that finally only the significant ones for inclusion in the conceptual model remain. Alternatively, a single iteration can be undertaken. In this case the Interaction Matrix will be developed with the aim of defining the conceptual model within one interaction. This can be practical if experience already exists concerning the system being modelled, since robust arguments for screening of FEPs will already be available.

The Interaction Matrix approach allows FEP interactions and pathways to be mapped, which is an important step in developing and defining a conceptual model and in the logical progression to a mathematical model (see for example Figs 14 and 15).

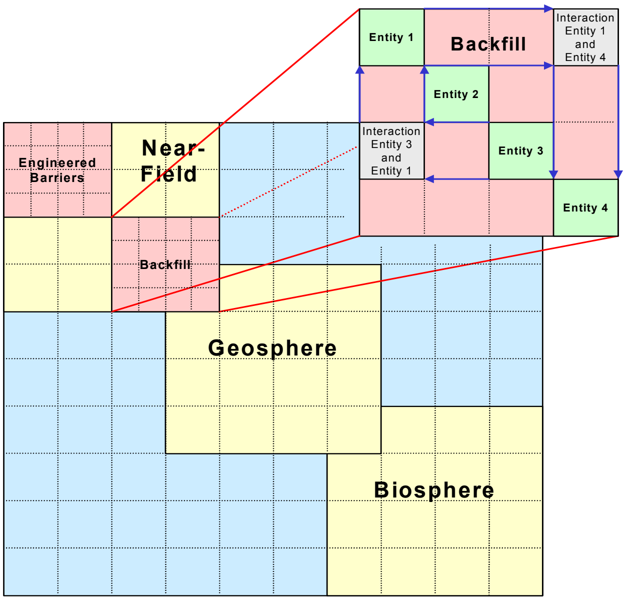


FIG. 14. An Example Hierarchical Interaction Matrix of a Disposal System.

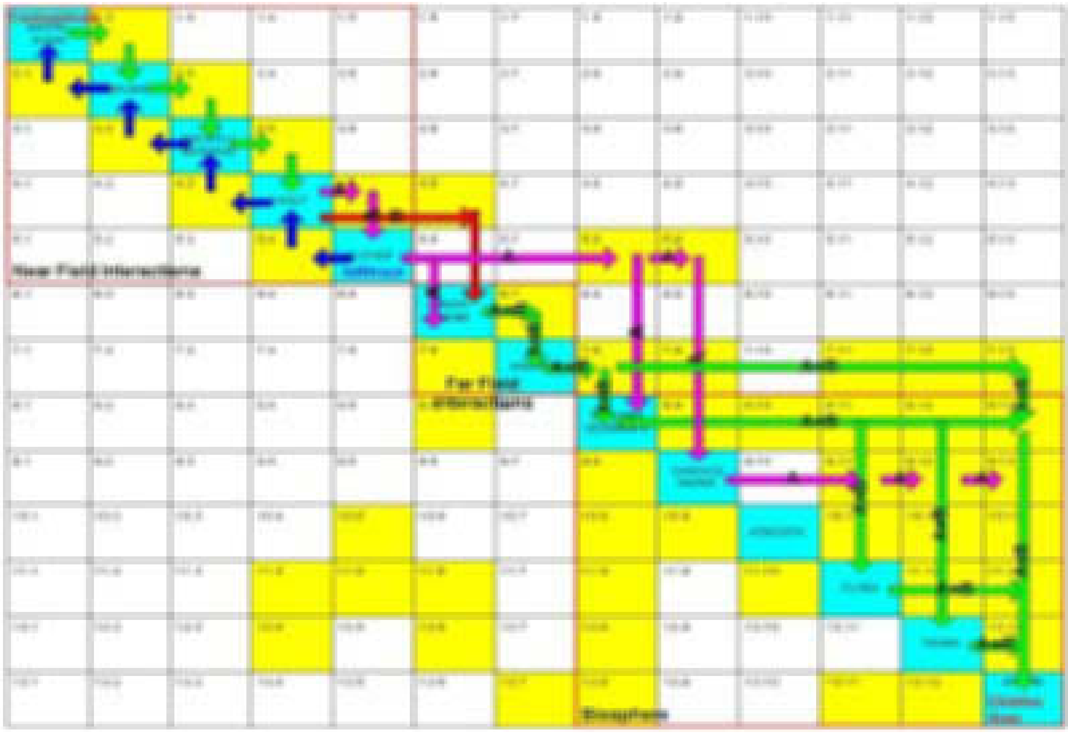


FIG.15. Example of Interaction Matrix for the Normal Evolution Scenario considered in [35] (A-bathtubbing, B – groundwater sub-scenario, A+B – transport pathways common to bathtubbing, and groundwater sub-scenario).

Influence diagram approach

This approach allows identifying the interaction between FEPs in a logic and systematic way. It is also useful to analyse where the external factors have an effect on the disposal system, helping in the definition of scenarios.

In Influence Diagrams, FEPs are represented by boxes and interactions between FEPs are illustrated by arrows showing the influence direction. The number of arrows between two factors will be equal to the number of influences between them. Only direct influences should be represented in the Influence Diagram. An example of its use is given in the SITE-94 Project and Fig. 16 [22].

The main steps to build the Influence Diagram can be summarized as follows:

- Definition of the system barriers and placing of them in the Influence Diagram;
- Selection of FEPs relevant to the defined system. The FEPs can be sorted in FEPs belonging to the system and those external to the system, i.e. external FEPs (EFEPs) or scenario initiating FEPs;
- Representation of the system FEPs in boxes. If a FEP is relevant for several disposal components, then it should be represented by one box for each of the disposal components. The factors are arranged in the diagram in such a way that the factors related to the barriers are sited in the top, the factors related to the radionuclide transport in the bottom and those which describe physical and chemical properties or conditions in the barrier in the middle of the diagram;
- Identification and representation of the influences between selected FEPs. Each influence in the diagram is marked with a unique code. There are no restriction on the number of influences between two FEPs; and
- Documentation of FEPs and influences. A more comprehensive description of each FEP and influence is needed to clarify the representation.

The Influence Diagram should not include large scale events that would alter the system since these events modify the system features, and it would be necessary to produce an Influence Diagram for the system before and after the event (as would be the case with the Interaction Matrix approach). Therefore, the Influence Diagram will only include features and processes and their influences. Processes-processes influences should be avoided, since the fact that the processes do not influence each other directly. Influences of this type should be broken in F-P or P-F influences.

The development of Influence Diagrams is an iterative process. It may be found that two FEPs can be combined into only one or that a FEP can be split into more than one to obtain an improved representation of the system. New influences between FEPs can be identified. The influences can also be classified using a significance scale. This can be used to build a reduced Influence Diagram by removing the influences with a lower significance than a defined level A schematic description of a reduced Influence Diagram is included in Fig. 16.

FIG. 16. Part of the Process System Influence Diagram Developed for SITE-94.

5.2.2. Example conceptual models

Some important pathways to be evaluated for an undisturbed performance of a site, for which conceptual models need to be developed, are identified in Table 6 [36]. These pathways apply during the institutional control period when site maintenance and monitoring help ensure that the facility performs as intended. The period after the institutional control period when the site is no longer maintained, site performance will be disturbed by natural processes such as cover erosion, waste form and container decay, degradation of engineered barriers, and subsidence and flooding. Some generic pathways identified in [36] for the disturbed performances of a disposal site are listed in Table 7.

TABLE 6. EXAMPLE PATHWAYS FOR UNDISTURBED PERFORMANCE OF SITE (AFTER [36])

Pathway	Source	Air	Ground-water	Surface water	Soil	Land plants	Land animals	Aquatic plants	Aquatic animals	Man
1	*		*							*
2	*		*		*					*
3	*		*			*				*
4	*		*				*			*
5	*		*	*						*
6	*				*	*				*
7	*		*			*	*			*
8	*		*	*					*	*
9	*		*		*	*	*			*
10	*		*	*				*	*	*

TABLE 7. EXAMPLE PATHWAYS FOR DISTURBED PERFORMANCE OF SITE (AFTER [36])

Pathway	Source	Air	Ground-water	Surface water	Soil	Land plants	Land animals	Aquatic plants	Aquatic animals	Man
1	*									*
2	*	*								*
3	*		*							*
4	*			*						*
5	*	*			*					*
6	*	*				*				*
7	*				*	*				*
8	*		*		*				*	*
9	*		*			*				*
10	*	*				*				*
11	*			*	*					*
12	*					*				*
13	*			*		*				*
14	*			*				*		*
15	*	*			*	*				*
16	*	*				*	*			*
17	*				*	*	*			*
18	*		*		*	*				*
19	*		*			*	*			*
20	*			*	*	*				*
21	*			*		*	*			*
22	*			*				*	*	*
23	*	*			*	*	*			*
24	*		*		*	*	*			*
25	*			*	*	*	*			*

As discussed previously when developing a conceptual model it can be helpful to consider:

- The source term;
- The transport media;
- The transport mechanisms; and
- The exposure mechanisms.

Each of these elements is discussed in turn below.

Source term

Source term refers to both the radionuclide inventory at the closure of the disposal facility, and the time-series of releases from the facility. The discussion in this section will be limited to the conceptual model of releases from the facility to the immediate environment. Such releases can occur through numerous pathways during the natural evolution of the facility, dependent on the location of the disposal cells (above-grade, below-grade, or below the water table), and the characteristics of the waste forms, waste containers, and the engineered barriers.

Figure 17 shows the types of releases that can occur at a near surface disposal facility, depending upon whether the radionuclides are dissolved in water, are in gaseous form, or are attached to solids.

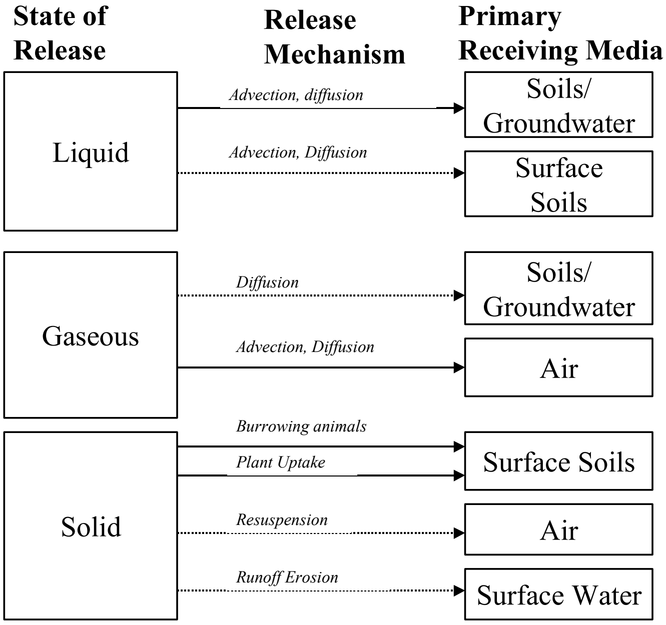


FIG. 17. Example Release Mechanisms.

- **Liquid**: Once the waste containers and engineered barriers no longer act as a barrier to water contacting the waste, radionuclides can be released into the water and transported from the disposal facility by advection, dispersion and diffusion. If the disposal units are located above the water table then releases will occur into the unsaturated (vadose) zone and contaminated water migrates down into the saturated zone. If the disposal units are below the water table, releases occur directly into groundwater. In arid climates, upward liquid advection can also be an important mechanism in moving radionuclides through the unsaturated zone above of the facility. The solid arrows in Fig. 17 show the dominant release mechanisms during the initial undisturbed phase of the facility.

- **Gaseous**: Volatile radionuclides can be released by diffusion into atmosphere and groundwater. Gaseous advection can also release volatile radionuclides into atmosphere.

- **Solid**: Burrowing animal activity may bring radionuclides attached to the soil particles into the surface soils. When the structural integrity of the facility has been lost, and the closure cover has eroded, thus exposing the waste, two further solid release mechanisms can be considered: wind erosion will suspend particulates into air from the contaminated surface soils and exposed waste; and precipitation induced runoff and erosion will carry radionuclides into surface waters. Plant uptake also can move significant quantities of radionuclides to the surface soils, especially after the institutional control is over (no maintenance) and native plants inhabit the site.

The long term performance of the engineered elements of the disposal system and of the waste containers and waste forms should be evaluated in order to decide which features and elements and release mechanisms to include in the release models. For a relatively short period following the closure when the disposal system functions as intended, there might be no particulate emissions into air, or releases to surface waters, and releases to surrounding unsaturated zone and groundwater may be at tolerable rates (Table 6). However, degradation of the integrity of the engineered barriers will eventually lead to accelerated releases to multiple media through multiple pathways (see Table 7).

Data pertinent to the development of the source term conceptual models are summarized in Table 8.

TABLE 8. EXAMPLE DATA REQUIRED FOR SOURCE TERM CONCEPTUAL MODEL DEVELOPMENT

Category	Data types
Climate	Precipitation Temperature Radiation Wind Relative Humidity Evapotranspiration
Soils and Vegetation	Soil depth Soil stratigraphy Soil structure Soil texture Particle Size distribution Porosity Fractures Soil-water characteristics Pressure, soil moisture measurements Hydraulic conductivity Infiltration measurements Plant types Plant rooting depths and density
Engineered barriers	Closure cover design elements Geotechnical properties of cover materials Hydraulic properties of cover materials Design elements of liners, vaults, units Geotechnical properties of these elements Hydraulic properties of these elements Properties of backfill materials Geochemistry Corrosion rates for metal components Rates of degradation of concrete
Containers	Type of containers Geometry of containers Burial depths of containers Material properties of containers Void space Corrosion and degradation rates
Waste Forms	Types of waste forms Stabilization Geochemistry of waste forms Degradation rates

Liquid Releases

Estimation of liquid releases from a near surface disposal facility is a complex problem. By necessity, the conceptual model for release idealizes how releases occur because the interaction of the engineered facility with natural site conditions cannot be known with reasonable certainty over the long term. A logical and convenient way of developing the source term conceptual model for liquid releases is then to consider the idealization of four major groups of inter-related processes shown in Fig. 18:

- Water flow;
- Container/barrier degradation;
- Releases from the waste forms; and
- Radionuclide transport within the facility.

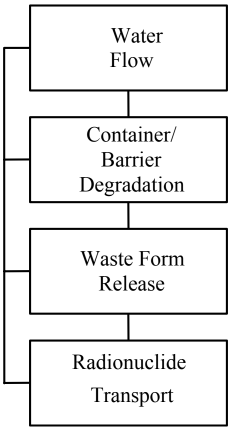


FIG. 18. Elements of a Near Field Liquid Release Conceptual Model.

These processes are discussed in the following sub-sections. In assessing them, it is important to consider the geochemical environment of the disposal units in determining the solubility limits, distribution coefficients, diffusion coefficients, and corrosion rates, considering the evolution of the geochemistry of the units over the assessment compliance period. Chemical parameters such as pH, redox potential, ionic strength, buffer capacity, chemical composition, speciation, and complexation are to be assessed for changing site and facility conditions over time. If initial analysis shows that acceptable performance relies on solubility limits and retardation due to sorption, site specific geochemical analysis is required, especially when initial parameters for releases have been developed using data from other disposal systems. Geochemical analysis should also be performed when the facility design calls for conditioning the environment within the disposal units in order to retard releases by means of specialized backfill materials of high buffering property, or concrete formulations.

Water flow

An important element of the source term analysis is the determination of the amount of precipitation water entering the facility and the amount of water contacting the waste. The waste forms, and the waste containers will delay the contact of water with the waste, and the engineered barriers to infiltration (closure cap, concrete vaults, etc.) will deter entry of water into the facility for a limited period. Degradation of waste forms, containers, and engineered barriers will eventually result in gradually increasing contact of waste with infiltrated water, and dissolution of more and more radionuclides into the water, forming leachate. The radionuclides in leachate will then migrate from the facility by advection, dispersion, and diffusion. Geochemistry of the facility will either enhance the migration from the facility or substantially delay it.

Site hydrologic conceptual model (Fig. 19) for a disposal facility above the water table should account for all processes affecting the amount of water entering the facility (infiltration), the amount of water passing through the disposal units and the soil column below (drainage), and the amount of water reaching the water table below (recharge). For a disposal facility below the water table, there is a need to consider the infiltration into the facility and the exfiltration out of the facility. These water flow need to be considered on a site specific basis and with due regard being paid to the effects of the engineering components on flow.

At most facilities, downward liquid flux will determine not only how much radionuclide leachate is generated and moved to the water table but how fast. Therefore, its site specific determination is essential.

The site conceptual model should be based on an evaluation of the categories of site and facility data given in Table 8.

For example, closure covers are designed to minimize water contacting waste, limit releases to the environment, and avoid exhumation of the waste. Conceptual model for the facility should discuss the details of the design of these barriers, and include all the assumptions supporting the inclusion or exclusion of design elements for the safety assessment.

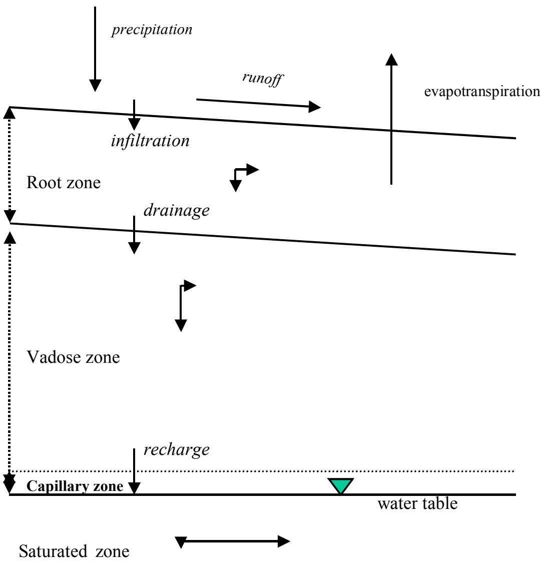


FIG. 19. Hydrological Conceptual Model for Unsaturated Conditions.

The conceptual model for flow can be highly idealized, accounting for only those processes sufficient to derive a range of steady-state downward fluxes (or a distribution) reflecting the variability of the current climate. A first assessment of the potential influence of climate change can be performed by supposing either an increased or decreased infiltration (wetter or dryer climate) for different periods of the compliance time frame such as 1,000 or 10,000 years.

Flux estimates should be based on modelling for site conditions and climatic variables covering a representative historic period, supplemented with field observations and tests (i.e., lysimeter, trace tests), and laboratory determination of soil-moisture characteristics of core samples taken from the site. If such data are not available at the site vicinity, surrogate data from hydrological similar areas can be used.

Degradation of containers and barriers

Containers provide isolation of the waste for a limited time. Eventually they will degrade due to chemical and physical processes occurring within the containers and within the disposal unit and water will contact the waste. Materials for containers loose their integrity because of the effects of chemical and physical processes occurring within the containers and within the specific disposal unit environment.

Materials used for containers include cardboard, plywood, carbon steel, stainless steel, fibre-reinforced concrete, polymer-impregnated concrete, high-density polyethylene, etc. A cautious conceptual model for source term may take no credit for containers since the lifetime of containers may be very uncertain. However, for containers made up from corrosion resistant metals, detailed corrosion models may be developed for estimating the time to failure. Such models can consider both the internal corrosion due to specific waste forms, and the external corrosion due to specific geochemistry of the in-situ environment of the disposal units.

Two types of container failure that can be considered for source term modelling [37].

— **General failure** is modelled by specifying a time to failure during which no water contacts the waste and beyond which the container no longer acts as a barrier to water. The time to failure can be estimated as the container thickness divided by a corrosion rate. Corrosion rates should ideally be developed based on data from specific disposal unit environment. However, most often such data are not easily obtained. Therefore, databases such as the United States National Bureau of Standards (NBS) [38] can be consulted.

— **Localized failure** accounts for container degradation. The portion of the area of the container that fails due to pitting corrosion can be formulated as a function of material type and pH [37]. To simplify the complex task of accounting for each container in a disposal facility containing numerous types of containers, a range of failure times for a representative number of container classes can be assessed.

The source term conceptual model should account for the structural integrity of the engineered **barriers** and their hydraulic performance over the long-term. Flow of water and gases through barriers, which are mostly made up of concrete can be treated as a porous media flow, or as a fracture media flow when cracks and joints develop in concrete elements over time. Therefore, conceptual model should consider the changing properties of concrete elements (structural stability as well as hydraulic properties) over time. Evaluation of the degradation of reinforced concrete, widely used in disposal facility design, then becomes an important task in assessing the long term performance of the facility.

Many factors affect concrete degradation, including chemical attack, physical stress, and microbial action. Chemical attack processes include sulphate attack, calcium hydroxide leaching, alkali-aggregate reaction, salt crystallisation, and metal corrosion. Degradation caused by physical stress is due to freezing and thawing, wetting and drying. Microbial action includes the effects of sulphur-oxidising and nitrifying bacteria and heterotrophic organisms. These factors cause concrete properties to change with time: surface degrades; rebar corrodes, and cracks develop and propagate to surface; calcium hydroxide leaching changes bulk properties of concrete; live and dead loads cause progressive cracking and ultimate failure. Continued degradation finally returns concrete toward its original soil constituents -- sand and gravel.

Release of radionuclides from waste forms

Conceptual models for source term can include the following three mechanisms for release of radionuclides from waste forms [39].

— Rinse release or wash-off occurs when water removes or washes radionuclides from the surface of the waste form. This release mechanism is appropriate for surface contaminated waste consisting of laboratory trash, clothing, plastics, etc.

— Diffusional release occurs when the release is limited by diffusion through a porous waste form such as cement-stabilized waste form.

— Dissolution release occurs when the release is controlled by the corrosion rate of a metal waste form, such as activated metals.

The releases may be retarded by sorption, represented by an element-specific distribution (sorption) coefficient, for waste forms where radionuclides are bound or sorbed onto a surface (i.e., ion-exchange resins used for their sorption properties.). Releases may also be limited by elemental solubility limits established for the particular geochemistry of the disposal unit.

Development of a source term model for a particular facility should consider the waste forms and waste types of the disposed inventory, and the release mechanisms that are appropriate given the characteristics of the site and the engineered barriers. The conceptual model may be simplified by grouping waste containers and waste forms and waste types, and assuming releases for each group to occur by one or more release mechanisms described above. The conceptual model should also address the degradation of the waste forms in determining release rates over long times.

Geochemistry of the facility environment

The source term conceptual model should consider the geochemical environment of the disposal units in determining the solubility limits, sorption coefficients, diffusion coefficients, and corrosion rates, considering the evolution of the geochemistry of the units over the assessment compliance period. Chemical parameters such as pH, redox potential, ionic strength, buffer capacity, chemical composition, speciation, and complexation are to be assessed for changing site and facility conditions over time. If initial analysis shows that acceptable performance relies on solubility limits and retardation due to sorption, site specific geochemical analysis is essential, especially when initial parameters for releases have been developed using data from other disposal systems. Geochemical analysis should also be performed when the facility design calls for conditioning the environment within the disposal units in order to retard releases by means of specialized backfill materials of high buffering property, or concrete formulations.

Radionuclide transport

Advection, dispersion, and diffusion are the processes by which radionuclides are transported away from the waste forms. The evaluation of these processes in the highly heterogeneous and dynamic environment of the disposal facility is a difficult task. A typical facility may contain multiple disposal units with multiple waste forms and containers, and engineered barriers. The engineered elements loose their integrity over time, and the hydraulic and geochemical performance of the facility likewise changes over time. Therefore, a simplified conceptual model of near field transport may be formulated, retaining only those features and processes that allow for a conservative assessment.

The releases from the facility may be only via diffusion when water flow through the facility is quite small. When a significant quantity of water passes through the facility, then it is important to estimate the amount of dilution that takes place in the disposal units before radionuclides reach the facility boundary. Various conceptualisations of the amount of dilution due to dispersion have been formulated. In one extreme, the facility can be treated as a single unit in which the radionuclides released from the waste forms are completely mixed (infinite dispersion). The other extreme is to assume no dispersion. Since neither case would provide a realistic accounting of dispersion that takes place in the facility, a more realistic conceptual model considers the facility as a series of multiple numbers of fully mixed units.

Gaseous releases

Radionuclides that are volatile or can be present in volatile molecules such as ^{3}H, ^{14}C, ^{85}Kr, ^{222}Rn, and ^{129}I can be released from the near surface disposal facilities into the atmosphere by diffusion and advection. These radionuclides can be present in disposed waste in various forms: ^{3}H and ^{14}C can be present in dry solids, dry active waste, sorbed aqueous liquids, activated metals, and animal carcasses. Various processes including microbial degradation of waste forms, oxidation/reduction reactions, and leaching and volatilisation result in generation of these gaseous radionuclides in the disposal units (Fig. 20). ^{85}Kr, which is disposed as gas in sealed containers, will be released upon container breakdown. ^{222}Rn is present as a daughter product in waste containing ^{226}Ra, ^{230}Th, ^{234}U and/or ^{238}U.

Complex conceptual models for gaseous releases can be formulated considering the waste forms, the integrity of the containers, the waste form release mechanisms (microbial, aerobic, anaerobic, radiolytic), and the geochemistry of the disposal unit environment (i.e., partitioning of radionuclides in gaseous and liquid forms). While diffusion can transport gaseous radionuclides upward or downward, advective gas transport is upward toward the ground surface and into the atmosphere. Advective transport or barometric pumping occurs by the gas pressure gradient created by changing atmospheric pressure. When the atmospheric pressure is low, there will be an upward gradient to drive gases out of the soil into the atmosphere. The reverse situation occurs under high atmospheric pressure conditions. However, a net upward flux is believed to exist, which results in gaseous releases to the atmosphere. Diffusive transport is reported to dominate gaseous releases from intact closure covers [40]. The United States Nuclear Regulator Commission (USNRC) formulated diffusion-based release methods to derive radon flux from uranium mill tailings covers [41].

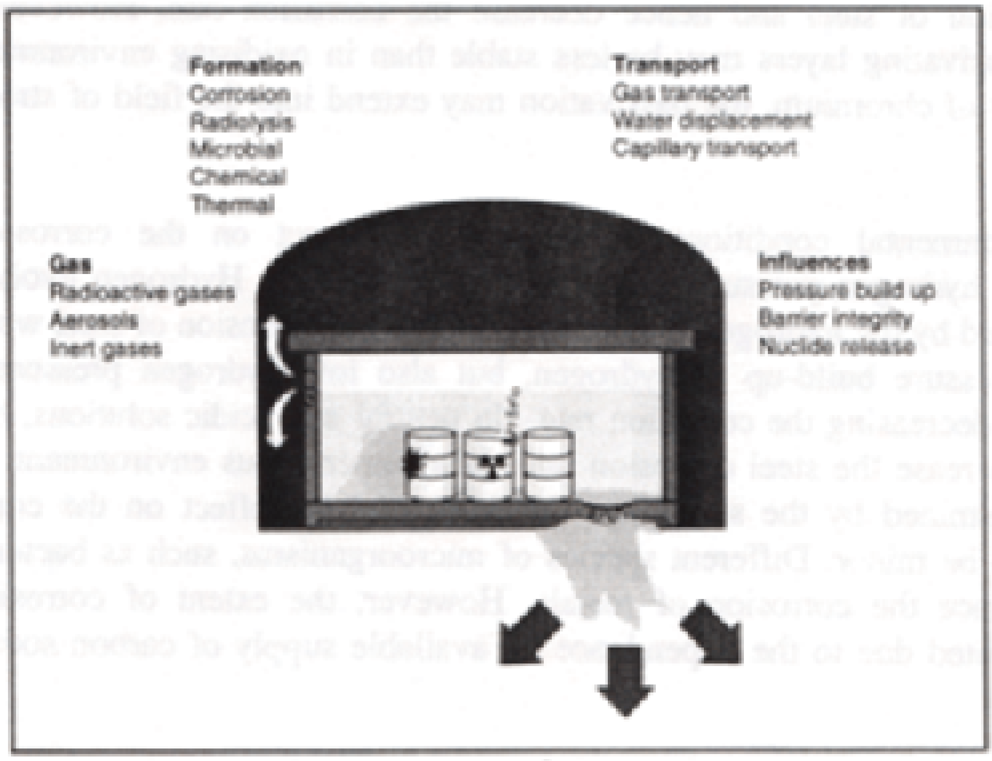


FIG. 20. Gas Generation and Transport Mechanisms for a Waste Facility.

The evaluation of gaseous releases can be performed considering a conservative conceptual model in which the whole volatile radionuclide inventory in the disposal unit facility is assumed to be available for release (released from the waste form into pore air space), and a one-dimensional diffusion is assumed to transport them through the unit near field to the atmosphere. Gaseous radionuclides move in response to a concentration gradient in pore air. In order to maximize the flux through the system, the concentration of radionuclide in air at the ground surface is assumed to be zero.

5.2.3. Solid releases

Plant uptake

Plant uptake can be a potential pathway of release of radionuclides from a near surface disposal facility to the land surface during the post-closure period when disposal facility is no longer maintained. Native plant species may be established at the site, resulting in root intrusion into the waste. Plants will absorb radionuclides dissolved in pore water through their roots, and transport them within the plant to the above ground biomass. When plant biomass decays, radionuclides will be dispersed into the surface soils. This process can lead to accumulation of certain long-lived radionuclides in surface soils.

The rate of water uptake of plant root depends on rooting density, soil conductivity and the difference between average soil-water suction and root suction. Usually the uptake rate is higher in the upper layer of the soil where the root density is higher (Fig. 21). The absorption of nutrients and metals into roots and their transmission up the roots are more complex: different chemical, biological and physical processes (i.e., plant metabolism, soil type and texture, soil moisture, soil pH) affect the plant uptake.

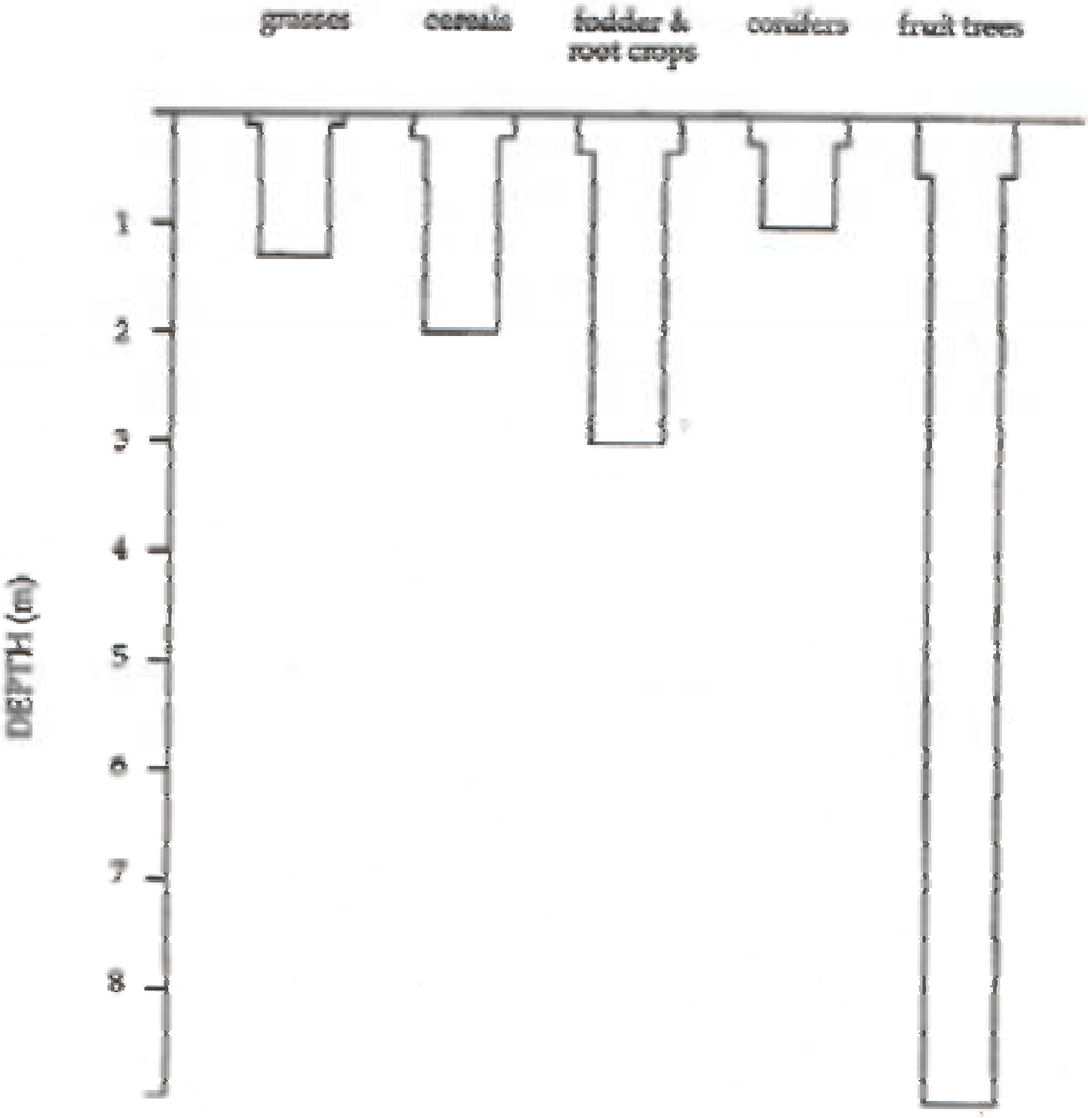


FIG. 21. Typical Active (expanded area) and Typical Maximum Rooting Depths for Various Plant and Trees in United Kingdom Conditions (after [42]).

A generic conceptual model for plant uptake can be formulated considering (1) plant rooting characteristics (depth distribution and density), (2) plant/soil concentration ratios of radionuclides, and (3) plant biomass production and turnover. The concentration ratio (CR) (plant/soil concentration ratio) provides a simple empirical model for the complex uptake process. CR can be defined as the ratio of the activity per unit mass of dry above ground biomass to the activity per unit mass of dry soil. CR model assumes that plant and soil concentrations are linearly related, and element specific. The release of radionuclides to the surface soils is assumed to be through the above ground plant biomass production and turnover.

Plant ecology, climate, and soils of the site should be known in order to develop a site specific conceptual model of plant uptake. Plant communities that might prevail at the site during the period of evaluation should be identified. Plant succession at the site under both current climatic conditions and changing climatic conditions should be considered. To avoid cumbersome analysis, plant species in these plant communities can be grouped into trees, shrubs/subshrubs, herbaceous perennials, and annuals. Rooting depths and densities for each group of plants should be developed. CR values are related to site specific conditions and are shown to be highly variable [42]. For some radionuclides (i.e., Cs) native plants are shown to have higher CR values than both agricultural plants and non-native plants [43]. Biomass production is also highly variable. For long term assessments, the conceptual model may assume that annual rate of litterfall, which releases radionuclides to the soil, is equal to annual rate of productivity.

Burrowing animals

Burrowing activities of animals are known to move contaminants from near surface disposal facilities to land surface. Animals burrow in the ground for shelter, nesting, storage, and foraging. Burrowing animals include mammals (i.e., rodents such as the ground squirrel, and the pocket gopher), invertebrates (ants and termites), reptiles (snakes, lizards), and birds (burrowing owls).). Burrows for shelter can extend to depths greater than 1.0 m, and extend to even greater depths for foraging activities. Rodents dig underground tunnels, bring the soil up to the ground surface, and deposit it around burrow openings. Gopher tunnels can range from 0.5 to 60 m. Gophers can excavate 800 to 16,000 kg soil ha^{-1} y^{-1}. Figure 22 shows typical burrowing depths and estimated removal rates of soil for a range of other animals. Termites have been observed as deep as 6 m in the arid southwest of the USA and 70 m in West Africa.

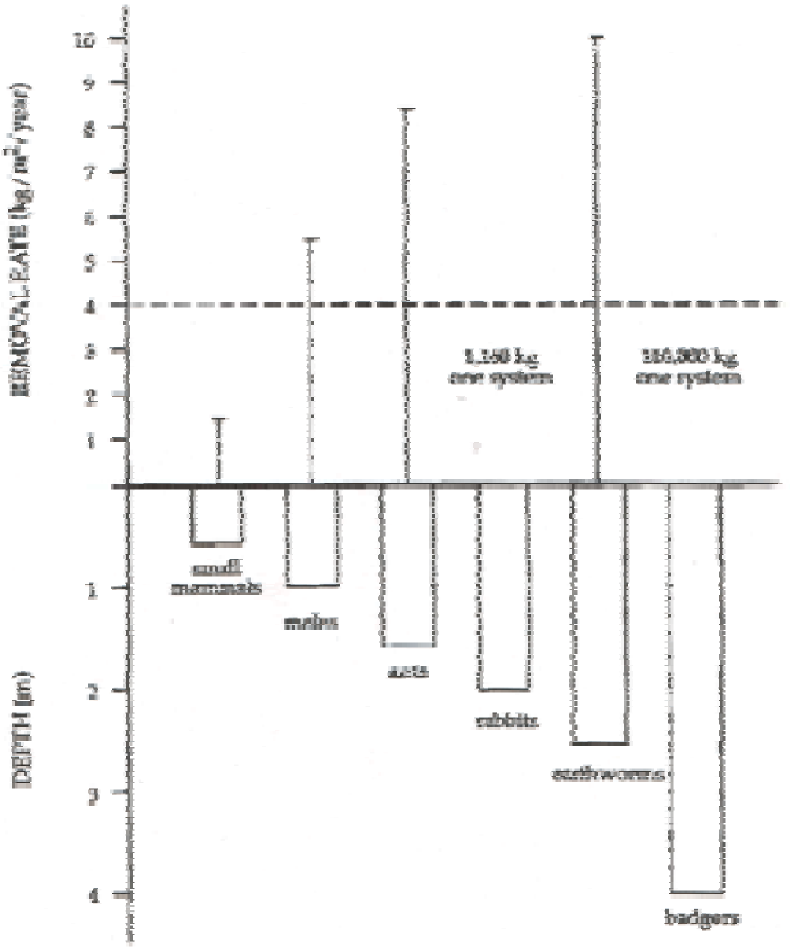


FIG. 22. Typical Burrowing Depths and Estimated Removal Rates of Soil for a Range of Burrowing Animals (after [43]).

The conceptual model for releases of radionuclides due to burrowing animals (bioturbation) needs to be developed based on information on burrowing animal types, their excavation rates and the depth of activity below the ground surface.

Resuspension

Resuspension, which refers to removal of contaminants from a surface and placing it in the atmosphere, can be a significant release mechanism at near surface disposal facilities. In arid or semi-arid sites especially, resuspension can release significant amount of soil particles that are contaminated with radionuclides brought to the surface by plant uptake, bioturbation, or liquid advection. In addition, resuspension can become a significant pathway at arid sites during the post-institutional control period when the closure cover might be eroded and the waste is potentially exposed.

Resuspension is a complex process, which can be modelled considering various processes and initiating events at a particular site, such as the physical and chemical nature of the surface and materials and their age, wind magnitude and duration, and other physical disturbances. Although conceptual models of erosion due to wind stress, which considers the physics of particle interactions and the forces between them, has been developed, they are not suitable for long term assessments. Instead, simple models have been formulated, which allow estimates of air concentrations due to resuspension to be made based on an empirically derived factor: resuspension factor or resuspension rate. Air concentration is simply expressed as this factor times the radionuclide concentration in surface soils. Another conceptual model, which has been widely used, is the mass loading model in which the air concentration is expressed as the dust concentration in the air times the concentration of radionuclide on the dust particles. Although these conceptualisations of resuspension are simple, site specific determination of the parameters is not often simple to undertake, and instead literature values are used.

Run-off errosion

Erosion of contaminated soils and exposed waste due to sporadic occurrence of precipitation-runoff events can result in the release of radionuclides from near surface disposal facilities. The erosion process is a complex one. Its site specific determination can be made based on data on climatic variables (precipitation depth-duration-intensity), the physical and chemical characteristics of the waste and soils, and the vegetation cover. Erosion has been classified as (1) sheet erosion (wearing away of a thin layer on the surface), (2) rill erosion (removal of soil by small channels or rills), (3) gully erosion (removal by large channels and rills), and (4) channel erosion (erosion occurring in channels). Erosion at a disposal site may start as sheet erosion; but rills, gullies, and channels may develop over the surface over time, leading to accelerated rates of erosion.

Physically based models have been formulated for erosion process, which consider how the soil particles are dislodged from the surface by the impact of the raindrops and how they move in the moving water by suspension, creep, and saltation. Although such models can be used to estimate long term erosion rates based on long term historic or synthesized time-series of storm events, the use of models based on simple empirical factors have proven to be more useful in such long term assessments. An annual erosion rate can be estimated assuming erosion is a multiplicative function of several factors such as rainfall factor, soil erodibility factor, slope-length and gradient factor, and management factors. These physically based models can provide conservative estimates of erosion.

Human intrusion

For the purposes of most safety assessments, it is usually assumed that human intrusion occurs at some time following closure of the disposal facility and loss of institutional control of the site, i.e. once society has lost the memory of the existence of the disposal facility. During operation of the facility and any subsequent period of institutional controls, either active or passive, it is assumed that a variety of measures will be in place to ensure that human actions do not adversely impact the safety of the disposal system.

Even if deliberate (intentional) human intrusion does occur prior to loss of institutional control, it is usually assumed that the intruders are aware of the waste and the consequences of disturbing the disposal facility and so take measures to limit the potential impacts, for example by minimising the contact time with the waste. Furthermore, if the actions are intentional, the intruders will have to bear their responsibility and consequences. However, it should be recognized that third parties might unwittingly be exposed to radionuclides as a result of deliberate intrusion by others. It also notes that, whilst it is widely accepted that the society that creates radioactive waste should bear the responsibility for developing a safe disposal system that takes into account future societies, the current society cannot protect future societies from their own actions if the latter are forewarned of the consequences.

Human intrusion is therefore usually considered to be inadvertent (unintentional), i.e. it occurs because the location of the disposal facility is unknown, its purpose is forgotten, or the consequences of the intrusion are unknown. At the same time the NEA states that “actions in which the disposal system is inadvertently disrupted should be considered” [44].

Human intrusion into the near field is often assumed to result from drilling of boreholes (for example due to site investigation, groundwater exploration/extraction, and mineral exploration) and/or direct excavation (for example for building construction, road construction, and railway construction). Such intrusions could result in any barriers above the waste being breach and the removal of contaminated material from the near field into the biosphere and the subsequent exposure of humans. Even if the intrusion does not result in the immediate breaching of barriers and/or removal of contaminated material, it could nonetheless have a significant impact on the future integrity of near field.

Regulations for LLW disposal in near surface facilities acknowledge the risk posed by the radionuclides remaining in the disposal facility after the institutional control is ended and the site is accessible by public. Any future member of public may carry on activities over the disposal grounds and inadvertently can come into direct contact with the radioactive waste. Regulations aim to protect the inadvertent human intruder by various means:

- By limiting disposal only to waste classified to be suitable for disposal in shallow land disposal;
- By providing features (intrusion barriers) in the facility design to deter intrusion; and
- By evaluating inadvertent human intrusion (IHI) scenarios against specific performance objectives for IHI.

An example of the treatment of human intrusion is the United States Nuclear Regulatory Commission Regulation (US NRC 10CFR) [44], which developed waste classification for the disposal of commercial low-level waste by evaluating generic IHI scenarios. Class A, B, and C waste is defined with special requirements for waste form and containers and depth of burial for Class B and C waste. Greater than Class C waste are not allowed for disposal in near surface facilities. Class A waste includes low concentration of radionuclides in waste forms requiring no stabilisation, and is usually segregated from Class B and C waste for disposal. The waste includes contaminated protective clothing, paper, and laboratory trash. It is assumed that within 100 years, radionuclides will decay to harmless levels to the inadvertent intruder. Class B waste, which contain higher concentrations of radionuclides, includes resins and filters from nuclear power plants. Waste form must be stabilized for 300 years to protect the intruder. Class C waste, which contains the highest concentrations of radionuclides, includes nuclear reactor components, sealed sources, and high activity industrial waste. The waste requires stabilisation for 300 years, and requires deeper disposal to protect the intruder. The facility design may require intruder barriers. Because of this waste classification system, which is derived from an evaluation of IHI scenarios, licensing of commercial LLW facilities in the USA does not require site specific evaluation of IHI. On the other hand, the US Department of Energy requires site specific evaluation of IHI for the disposal of defense related LLW in the USA, because defense waste is quite heterogeneous and not easily classifiable with generic scenarios across all DOE disposal sites. USDOE orders established performance objectives for the inadvertent human intruder: the effective dose equivalents received by individuals who inadvertently intrude into the facility after the loss of institutional control must not exceed 100 m.rem y^{-1} for continuous exposure and 500 $mrem.y^{-1}$ for a single acute exposure. The generic scenarios developed and used in the USA are summarized below.

Intruder-construction

In this scenario, an intruder inadvertently moves on the site to construct a house on the disposal facility after the institutional control period is over. The intruder contacts the waste during a specified period while constructing a basement for a house. A specific amount of waste and cover and backfill material for the facility is excavated during the operation. Exposure occurs through two pathways:

— Direct gamma exposure;
— Inhalation of contaminated dust.

This scenario is evaluated for short term (acute) exposure performance objective.

Intruder – discovery

This scenario, a variant of the intruder-construction scenario, occurs when the intruder stops the construction activities upon discovery of unusual circumstances at the site. It is evaluated similar to the construction scenario, with shorter exposure duration.

Intruder – agriculter

The agriculture scenario is an extension of the construction scenario. In addition to constructing a house on the facility where the intruder lives, the intruder is assumed to engage in agricultural activities on a specific sized garden plot containing contaminated soil and waste excavated during the house construction. Agricultural activities include cultivation of crops and grazing of domestic animals. The intruder drills a well nearby the facility or uses surface water contaminated with releases from the facility. Water is used for drinking and irrigation. A portion of the intruder’s diet includes vegetables, meat, and milk produced on the garden.

Agricultural activities result in contamination of air (suspension of contaminated soil particles), contamination of surfaces of plants and water (deposition), and bioaccumulation in the food chain. Plant residue recycles the radionuclides back to the soil.

The exposure to the intruder occurs through the following pathways:

- Direct contact with contaminated waste and surfaces;
- Direct contact with contaminated soil;
- Immersion in contaminated air and water;
- Inhalation of contaminated air;
- Inhalation of contaminated air in house;
- Ingestion of contaminated soil, water, vegetables, meat and milk, and eggs.

This scenario, which is evaluated against a chronic performance objective, usually results in a bounding IHI dose that is used to set waste concentration limits.

Drilling

In this scenario, the intruder drills a well, mostly for water, at the top of the facility, and brings drill cuttings from the waste zone into the surface. Drilling is assumed to penetrate through any waste form, engineered barrier, and reach any depth of burial. Amount of waste containing radionuclides brought to the surface depends on the drilling method (mostly involve the use of water and slurry) the drill core diameter, the thickness of the waste zone, and the time of intrusion after the closure of the facility. The exposure pathways include inhalation of resuspended contaminated particles, and direct exposure to gamma radiation. Drilling scenario is evaluated against an acute performance objective.

Post-drilling

The post-drilling scenario is a variant of the agriculture scenario, evaluated for chronic exposures. The intruder engages into agricultural activities in a garden plot nearby the facility. In this scenario, drill cuttings including waste are assumed to be mixed into the garden soil, instead of the waste from the basement construction of the agriculture scenario discussed previously. Like the agriculture scenario, this scenario is evaluated for a chronic IHI performance objective.

Transport media

Radionuclides may spread into one or more environmental media – e.g. groundwater, surface water, air, soil – upon their release from the facility, depending upon the characteristics of the site the facility and its evolution. Advection, dispersion, and diffusion are the mechanisms that transport the radionuclides in these media. Radionuclides are also transferred from one medium to another by various means, with each transfer resulting in further dilution of the waste concentrations through dilution and dispersion. Dose to a human receptor occurs through one or more exposure pathways appropriate to each medium, and through the food chain.

The conceptual model should describe each transport medium, evaluate transport rates and directions, assess the inter-media transfer rates, and account for all physical, chemical, and biological processes impacting these rates. The residence time and mobility of a radionuclide in a medium is dependent on the characteristics of the medium, as well as on all processes. Conceptual models should provide the arguments supporting the exclusion of processes or simplifications of these processes. Existing information on media characteristics may be supplemented with field investigations, tests and monitoring of the appropriate media at the disposal site for at least a few years prior to the construction and operation of the facility. Data obtained from monitoring of environmental media during the operation, and post-closure period of the facility help refine or modify the conceptual model for subsequent iterations of the safety assessment.

Extensive and comprehensive treatises on modelling contaminant transport are available in a variety forms and at a variety of levels of sophistication [46–51]. Consequently, a comprehensive review of the subject is not provided here. Instead, the focus is on aspects of transport that are particularly important for conducting safety assessments. In safety assessment analyses, transport of radionuclides have to be projected over long periods of time and space, frequently with relatively modest amounts of available information.

Groundwater

Groundwater is an important mediator to be evaluated for most near surface disposal facility safety assessments (Fig. 23). Groundwater forms part of the hydrological cycle and originate (with the exception of connate water) from atmospheric precipitation. The flow of water in the subsurface is governed by piezometric gradients and the hydraulic conductivity of the rock mass. A water saturated rock mass that is able to store and transmit water is known as an aquifer. There are basically two different types of aquifers. The first category is primary aquifers that are formed by loose sand such as sediments or alluvium, in which porous flow takes place. The other type is known as secondary aquifers that contain fractures or a combination of fractures and pores known as fractured-porous aquifers. The driving force behind groundwater flow under natural conditions is generally caused by differences in the topography that leads to gradients in hydraulic head. Within all types of aquifers, zones with a higher hydraulic conductivity exist, which forms preferential pathways for groundwater flow and radionuclide transport.

Movement of subsurface contaminants is influenced by the processes of groundwater flow, dispersion, diffusion, radioactive production and decay, and geochemistry (solubility and sorption) and the relative importance of these processes is site and contaminant specific.

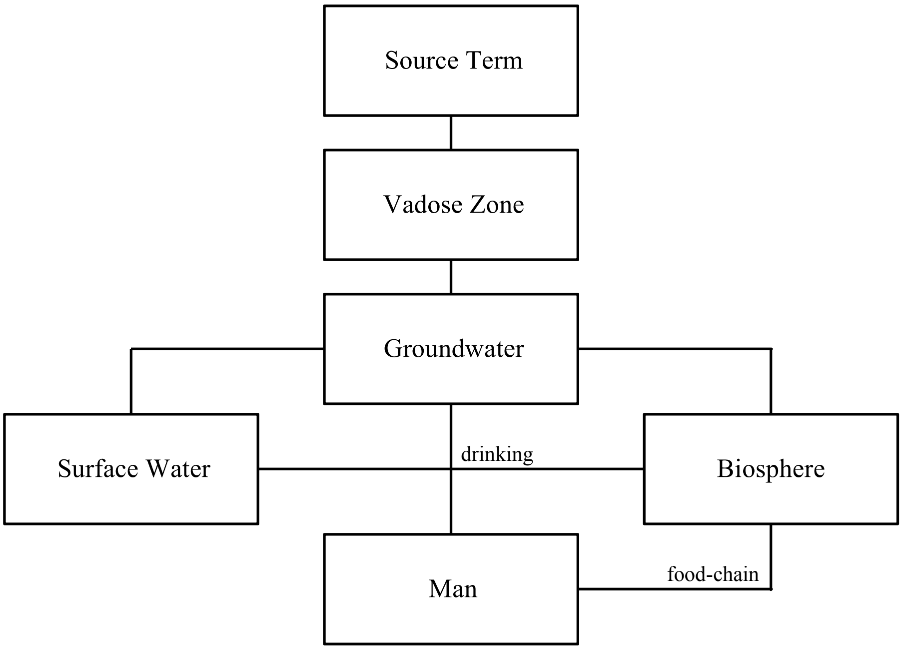


FIG. 23. Liquid Release Conceptual Model.

Radionuclides released from the facility are transported in groundwater by advection, dispersion, and diffusion. If the disposal units are located below the water table, a radionuclide plume will develop, with its longitudinal axis along the direction of flow and a small lateral and vertical spread. If the disposal units are located above the water table, the conceptual model for groundwater should account for the fate and transport of radionuclides in the unsaturated zone. Downward advection usually is the primary mechanism for migration of radionuclides through the unsaturated zone to the water table. With its low moisture content, and low unsaturated hydraulic conductivity, unsaturated (vadose) zone is usually acts as a natural barrier to migration of radionuclides to groundwater. On reaching the water table, radionuclides will be diluted due to mixing, and a plume will develop, predominantly in the lateral direction of the groundwater flow. Exposure to a human receptor occurs through drinking water pumped from a well intercepting the radionuclide plume. Additional human exposure pathways result when the well water is also used for irrigation and watering of domestic animals: ingestion of contaminated plants, and meat, milk, and eggs.

If groundwater discharge occurs through seeps and springs to the surface, or into surface water bodies within the compliance boundary of the facility, a receptor using water from the spring or the receiving water body (i.e. a lake, or river) for domestic and agricultural activities should also be evaluated in the conceptual model.

The conceptual model for the groundwater media should provide a detailed description of relevant media characteristics and list all the simplifying assumptions made concerning the fate and transport of radionuclides released into the groundwater. Data typically required for conceptual model development for the groundwater conceptual model are given in Table 9.

TABLE 9. EXAMPLE DATA REQUIRED FOR GROUNDWATER CONCEPTUAL MODEL DEVELOPMENT

Type	Parameters
Geology	Lithology Stratigraphy Structure Fracture density, aperture, width in both unsaturated and saturated zones
Hydrogeology	Groundwater system boundaries Aquifers, and confining units Recharge and discharge zones Hydraulic characteristics of the unsaturated zone: soil moisture, pressure, porosity, bulk density, saturated hydraulic conductivity Hydraulic characteristics of the saturated zone: conductivity, porosity Specific yield, and specific storage of aquifers Potentiometric surfaces of aquifers: well water levels Vertical gradients between aquifers
Geochemistry	Water chemistry of unsaturated and saturated zones sorption, precipitation, complexation, redox
Well	Size and Depth of screen Pumping Rate

In addition, design features of the receptor well (depth, screen interval, size of the casing), and pumping rate should be identified in the conceptual model. Pumping will enhance the potential gradient toward the well, and accelerate the advective transport. Under natural conditions, diffusion may be the only mechanism for transport of radionuclides released into a groundwater with flat water table, and negligible pore-water velocity. However, advective transport should be considered when pumping establishes a gradient toward the well. Ignoring pumping in such a case will result in underestimating the well water concentrations and the timing of the peak concentration. Additionally, radionuclide concentrations in water pumped from the well may be smaller if pumping captures only a portion of the contaminant plume.

At sites with highly variable water table close to the bottom of the disposal units, the conceptual model may not account for transport through the unsaturated zone, leading to a conservative analysis. For long term assessments, it is often sufficient to assume a steady-state flow field, with steady-state recharge. In the initial phase of an assessment, transport can be assumed to occur with a one-dimensional downward advection in the unsaturated zone, and with one-dimensional advection and one or two-dimensional dispersion in the saturated zone.

The significance of transport through preferential pathways such as animal burrows, root channels, and fractures in the unsaturated zone, and of groundwater transport through fractures, and high-permeability lenses and channels should also be considered in developing the conceptual model.

Surface water

Surface water pathways should be evaluated at sites where a receiving surface water body is located near the site, since it could be used by humans. Radionuclides released from the facility may enter such a surface water body by storm runoff (overland flow) carrying radionuclides dissolved in water and attached to sediments, by discharge of contaminated groundwater through seeps and springs, and by dry and wet deposition from air. For below ground facilities, only the discharge of groundwater may be significant. Storm runoff and deposition by air can become important pathways only if the waste is exposed because of an eroded cover or the collapsed of an above ground facility. Radionuclides received in the surface water body will be diluted, depending on the amount of mixing, which takes place in the receiving water.

Dissolved radionuclides may further partition onto suspended sediments, or the bed sediments. Resuspension from bed sediments into the water column may also occur.

Often, a simplified calculation can be performed to assess the significance of the surface water pathway. If found significant, more detailed transport in surface water may be conceptualized. Such an analysis will require data on channel or lake geometry (water depth, channel width), flow rates, stratification, geochemistry, and sediment characteristics of the water, dispersion, and the characteristics of the incoming seep or spring.

Air

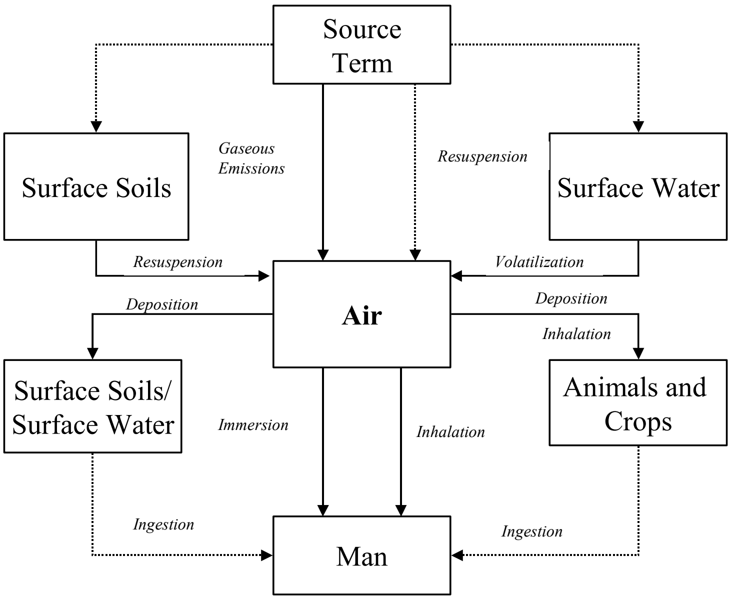


FIG. 24. Example Conceptual Model for Atmospheric Pathways.

Conceptual model for air transport pathways (Fig. 24) should be developed by evaluating the following information:

- — Wind direction, frequency, duration, and magnitude;
- — Atmospheric stability classes, function of surface wind velocity, degree of insolation and cloud conditions of the day;
- — Precipitation (annual, seasonal);
- — Deposition rates;
- — Topography, features of the terrain as barriers to air flow; and
- — Nature of the source: point source, area source, or volume source; height of the source above ground level.

The relevance of each in a assessment process be identified taking into account the scale of time of interest and the order of magnitude of the transport process from one subsystem to another one (e.g. from near field to far field).

The transport time inside the subsystem needs also to be estimated. If the time scale of the transport inside the subsystem is some orders lower than the order of the time scale of interest in the assessment, the subsystem is considered to have uniform concentration, although time dependent. In this situation the subsystem is named as compartment.

Transport mechanisms

Several phenomena occur that serve to transport contaminants to the accessible environment through groundwater (Table 10) and key processes are summarized below. It should be recognized that contaminants of concern in safety assessment are generally considered to be dissolved ionic species in aqueous solution. This assumption results from the nature of the waste acceptance criteria, with often precludes disposal of significant amounts of contaminated organic chemicals. As a result, phenomena associated with multiphase transport of non-aqueous phase contaminants are not discussed in this section.

TABLE 10. EXAMPLE FATE AND TRANSPORT PROCESS (AFTER [51])

Process	Definition	Impact on Transport
Mass Transport		
Advection	Movement of mass as a consequence of fluid flow.	Most Important way of transporting mass away from source
Diffusion	Mass spreading due to molecular diffusion in response to concentration gradients.	An attenuation mechanism of second order in most flows systems where advection and dispersion dominate.
Dispersion	Fluid mixing due to effects of unresolved heterogeneity in the permeability distribution.	An attenuation mechanism that reduces contaminant concentration in the plume. However, it spreads to a greater extent than predicted by advection alone.
Physico-chemical processes		
Radioactive Decay	Irreversible decline in the activity of a radionuclide through a nuclear reaction.	An important mechanism for contaminant attenuation when the half-life for decay is comparable to or less than the residence time of the flow system. Also adds complexity in production of daughter products.
Sorption	Partitioning of a contaminant between the water and mineral or organic solids in the system.	An important mechanism that reduces the rate at which the contaminants are apparently moving. Makes it difficult to remove contamination at a site.
Dissolution/ precipitation	The process of adding contaminants to, or removing them from, solution by reactions dissolving or creating various solids.	Contaminant precipitation is an important attenuation mechanism that can control the concentration of contaminant in solution. Solution concentration is mainly controlled either at the source or at a reaction front.
Acid/base reactions	Reactions involving a transfer of protons (H^+).	Mainly an indirect control on contaminant transport by controlling the pH of water.
Complexation	Combination of cations and anions to form a more complex ion.	An important mechanism resulting in increased solubility of metals in water, if adsorption is not enhanced. Major ion complexation will increase the quantity of a solid dissolved in solution.
Hydrolysis/ substitution	Reaction of a halogenated organic compound with water or a component ion of water (hydrolysis) or with another anion (substitution).	Often hydrolysis/substitution reactions make an organic compound more susceptible to biodegradation and more soluble.
Redox reactions (biodegradation)	Reactions that involve a transfer of electrons and include elements with more than one oxidation state.	An extremely important family of reactions in retarding contaminant spread through the precipitation of metals.
Biologically mediated mass transfer		

Biological transformations	Reactions involving the degradation of organic compounds, whose rate is controlled by the abundance of the micro-organisms and redox conditions.	Important mechanism for contaminant reduction but can lead to undesirable daughter products.

Sorption

Sorption, as it is customarily treated in safety assessment, is general and includes contributions from all heterogeneous reactions of dissolved contaminants with solid surfaces: both chemisorption and physisorption, precipitation, as well as ion exchange and isomorphic substitution. These effects are lumped into a single linear sorption factor, the K_d in many safety assessments. The reasons for this are (1) computer codes for solving coupled geochemical effects with transport are intensive computationally and often not suitable for use as an assessment level tool, and (2) existing geochemical databases and modelling constructs are not sufficiently reliable to justify the additional modelling detail. Consequently, despite the simplistic nature of the K_d concept, it is generally considered to represent the most appropriate approach for modelling sorption in the framework of a safety assessment. However, some assessments have used more detailed geochemical codes for assisting in the interpretation of geochemical processes.

K_d is generally defined as the ratio of the concentration of sorbed contaminant with respect to the concentration in solution adjacent to the solid. The most common assumption used in safety assessment is that the ratio is constant across the range of application. Since solid concentrations are commonly expressed as mass or activity per mass of soil, and fluid concentrations are commonly expressed as mass or activity per unit fluid volume, the unit on K_d is volume per mass (e.g. ml g^{-1} or m^3 kg^{-1}).

Of greater interest for safety assessments is how to justify K_ds used in an analysis. Sorption capabilities of a medium can be expected to vary both spatially and in time in unknown ways. Furthermore, many radionuclides of interest have the potential to change valence states and chemical speciation under different groundwater chemical conditions. As a result, caution should be applied when choosing a K_d to be used in an assessment model.

A common misconception is that applying low K_ds for the near field and geosphere to an assessment is universally a conservative assumption. This is not always the case, for example when pathways other than the groundwater pathway are important, for instance if erosion or intrusion is analysed. In this case, high near field K_ds can lead to higher exposures when the waste is exposed at the surface. A further case is when a parent radionuclide produces progeny of higher radiotoxicity. For example ^{238}U, whose progeny include ^{226}Ra, ^{222}Rn, and ^{210}Pb. Assigning a low K_d to ^{238}U in this case will allow the ^{238}U to migrate from the system before significant ingrowth of decay products can occur. By contrast, a high K_d will retain ^{238}U in the system, resulting in higher calculated concentrations of the more highly radiotoxic isotopes.

Advection

Advection (sometimes called convection) is the transport of dissolved contaminants by the bulk movement of flowing water. In the context of safety assessments, movement of water is usually considered to be due only to hydraulic forces. Consequently, the hydraulic head gradient is usually the primary motive force for advectively driven contaminant transport.

Although, when considering advective flow in the unsaturated zone, there is also a need to consider the moisture content of the unsaturated zone.

The rate of advective transport is usually described by a water velocity. The velocity needed in transport analyses is the pore water velocity given by a function of the total porosity and the Darcy velocity. An empirical modifier can be introduced to account for the fact that not all the porosity is available for transport [50]. In unsaturated soils, it is customary to assume that advective velocity is modified by the reduction in specific area through which the flow occurs by taking account of the moisture content of the zone.

Diffusion

Diffusion is a fundamental mechanism for transport of dissolved ionic species. Diffusion is caused by random thermal movement of the molecules. This causes a transport of contaminants from areas with high concentration to areas with low concentration. The rate of transport depends on how large the difference in concentration is over a given distance (the concentration gradient) and the pore structure of the material. The influence of the pore structure is described by a material constant - the diffusivity. The difference in diffusion behaviour between various chemical compounds is usually relatively small. The most common representation for transport via diffusion is Fick's first law, which says that a diffusive flux for a contaminant is linearly proportional to its concentration gradient. For diffusion of conservative tracers (those that do not chemically interact) in porous materials, the diffusion coefficient is commonly assumed to represent an "effective" diffusion coefficient that includes the alteration of the diffusion rate by the porosity and the tortuous diffusion path. When chemical sorption is included in the diffusion coefficient, it is known as the "apparent" diffusion coefficient. Mathematically, the apparent coefficient can be shown to include linear sorption effects.

It should be emphasized that the expression of Fick's Law is only a simplified expression that neglects non-ideal solution behaviour, non-linear dependency on the gradient, and cross-component fluxes. As a practical matter, these influences are usually ignored in safety assessments. Of greater importance is the necessity for defining effective diffusion coefficients for each isotope and material of interest. Again, as a practical matter, intrinsic diffusion coefficients (diffusion coefficients measured in free water) are often used when specific data are unavailable. This approach tends to overestimate the contribution of diffusion to transport, since effective diffusion coefficients are less than intrinsic ones, frequently by many orders of magnitude. The conservatism of this approach depends on the particular circumstances of the analysis, and no generalization can be made. Intrinsic diffusion coefficients are sometimes used in conjunction with semi-empirical equations that incorporate the effects of porosity and tortuosity on the effective diffusion coefficient [51]. Use of such approaches can lead to improve estimates of the effective diffusion coefficient, but caution should be exercised in choosing the parameters in these equations, since they cannot be measured.

Diffusion in natural barriers is of importance when the water flow rate is very small or non-existent. For example diffusion can contribute significantly to the transport through low permeability materials such as clays. Diffusion into parts of the geosphere with immobile water may also contribute significantly to the retardation of radionuclides. This is a very important retention mechanism in the case of radionuclide transport in fractured rock where the radionuclides can diffuse from the fracture into the rock matrix.

Dispersion

Dispersion is the term applied to the observed spreading of contaminants in an advective velocity field. It can arise from: radionuclides being transported by several paths with different transport times; and differences in flow velocities within a single transport path. In geological media, dispersion due to the presence of multiple flow paths often dominates. Dispersion occurs in direction of flow (longitudinal dispersion) and perpendicular to flow direction (transverse dispersion).

Dispersion has several effects on radionuclide transport:

- A sharp pulse of radionuclide release will be spread out often causing a reduction in the peak concentration;
- A radionuclide may reach a discharge point much earlier than the mean travel time - this is of great importance for radionuclides that decay during their travel through the geosphere; and
- The radionuclide may spread out over a larger area.

It has become conventional in the groundwater transport literature to describe dispersion as the sum of two physical effects (in such cases the combined dispersion term is often referred to as “hydrodynamic dispersion”. The first effect is molecular diffusion (see Section 5). The second effect is known in the literature as “mechanical dispersion”, and is ascribed to the different local velocities that a contaminant will experience while travelling the tortuous flow path that a tracer follows during movement through the porous soil.

The concept of mechanical dispersion is an approximate approach to representing the velocity variations that are not explicitly accounted for in the transport model. That is, it is an informational effect, and the degree to which it is included in the model is dependent on the amount of resolution used in the model. To illustrate this concept, consider the treatment of dispersion in transport through a pipe developed in [52] and [53]. In this treatment of dispersion of free-flowing water in a pipe, the velocity field can be derived exactly: the parabolic Poiseuille flow profile. Taylor-Aris dispersion theory uses the information about the microscopic flow field to provide a mathematical link between the macroscopic average flow velocity and the spreading behaviour of the contaminant carried by the fluid. If one uses a microscopic representation of the flow field, there is no need to invoke the concept of mechanical dispersion. It is only when the velocity field is averaged over some volume that dispersion is needed to account for discrepancies between predicted contaminant spreading based on the averaged velocity and the real behaviour of the system.

Similarly, dispersion in porous media represents the relationship between the macroscopic observable velocity, and the spreading due to velocity variations at a smaller scale than the one on which the average velocity is defined. The difference between the conditions studied by Taylor and Aris and the needs of groundwater modellers is that the nature of the velocity variations can never be known in groundwater systems. It is of both theoretical and practical interest to note that the dispersion used in analysing transport should decrease as the flow model becomes increasingly complex. Consequently, it was found that when using extremely detailed knowledge of the flow field available in the Twin Lakes Tracer Test it was possible justify using small dispersivities [54].

The most common representation of dispersion is to treat it mathematically identically to molecular diffusion. The theoretical literature suggests that the dispersion coefficient can be a second-order tensor. In practice, however, data to support the tensorial nature of the dispersion coefficient is unavailable. These aspects of the dispersion coefficient are universally neglected in practical safety assessments.

This approach to representing dispersion, sometimes called Fickian dispersion because of the similarity to Fick's first law, is equivalent to assuming that the unknown velocity variations are randomly distributed about a mean value, such that the velocity variations take on a Gaussian (normal) statistical distribution. This approach represents an extreme extrapolation of Taylor-Aris theory. It is justified to some extent by observations of transport in columns containing uniform sediments, but is of dubious applicability in any real field situation. Nevertheless, it is almost universally applied in many practical cases, with the justification that no other information is available.

In an additional extrapolation of the form of Taylor-Aris theory, the dispersion coefficient is suggested to be linearly proportional to velocity.

Decay and ingrowth of radionuclides

Radioactive decay is an important process for the reduction of radionuclide concentrations during the transport from the facility into and through the geosphere (assuming that there is no ingrowth of the radionuclide from a parent). Many radionuclides have half-lives much shorter than their transport time in groundwater and will thus decay before reaching the biosphere in significant concentrations. Other radionuclides have half-lives that are so long that the decay during the transport through the geosphere to the biosphere is negligible.

Radionuclides that are part of a decay chain need specific consideration for a number of reasons. First, the decay products may be radioactive isotopes of elements with different physical and chemical characteristics, e.g. different sorption capabilities (for example that the decay of Th isotopes to their progeny is often important as the decay products tend to be more soluble and mobile than the parent) and so could have different transport characteristics. Second, for certain decay chains, there can be a long-time period required for a parent and its daughter to reach secular equilibrium and so both might need to be explicitly considered. Third, whilst short-lived daughters might not need to be explicitly considered for groundwater transport calculations per se, they might significantly contribute to the radiological impact of groundwater releases (for example ^{210}Pb) and so need to be accounted for in the estimated flux of radionuclides from the geosphere to the biosphere.

Exposure mechanisms

The main human exposure routes for radionuclides are:

- Ingestion — which refers to intakes of contaminated fluids and food and the inadvertent ingestion of contaminated materials (e.g. soil and dust);
- Inhalation — which refers to intakes of contaminated air (i.e. solid particulates, vapours and gases); and
- External exposure — which refers to irradiation by radionuclides located outside the body.

The ingestion and inhalation pathways result in internal exposure. External exposure is potentially important for radionuclides that emit penetration radiation (gamma and beta). Humans living in a contaminated environment can receive a radiological dose via a multitude of exposure pathways (see for example Fig. 25) depending on the characteristics of the

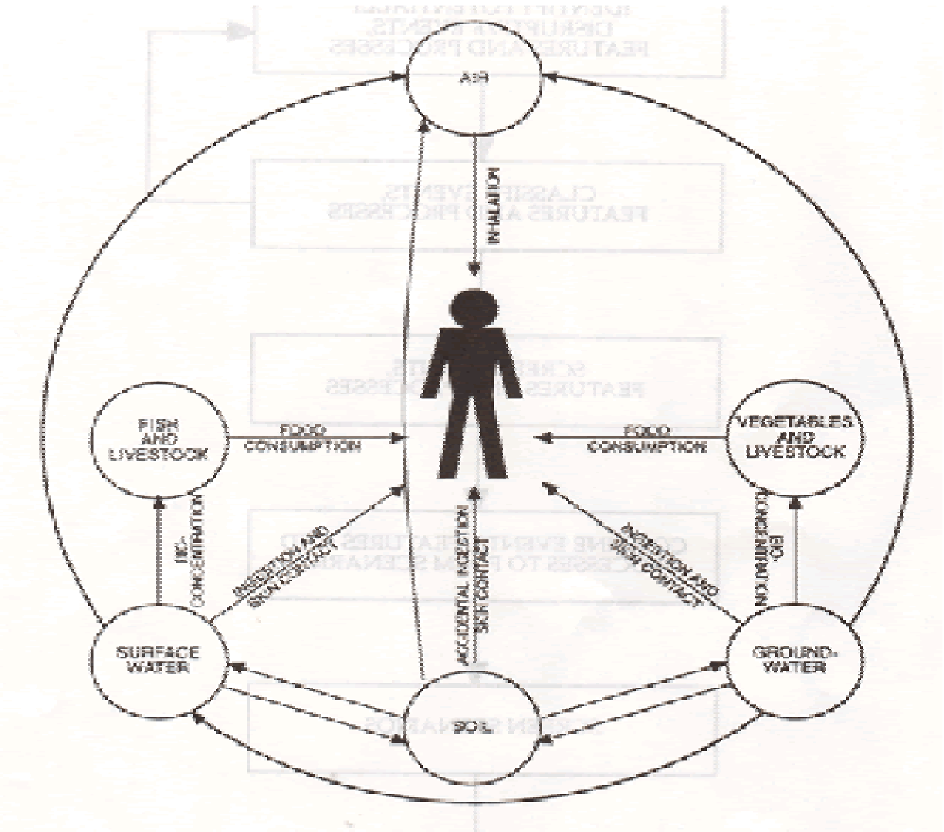


FIG. 25. Example Exposure Pathways for Humans (after [55]).

release, the biosphere media, and the human habits. Assumptions also have to be made concerning the particular behaviour of the individuals or populations for whom a calculation of health impact is required. Of special interest are the assumptions for the behaviour of groups whose exposure is representative of the highest that may be expected, commonly referred to as the critical group.

For the groundwater release, exposure of a human can occur for example through drinking groundwater pumped from a well intercepting the radionuclide plume. Additional human exposure pathways can result when the well water is also used for irrigation and watering of domestic animals and crops, resulting in the ingestion of contaminated plants, and meat, milk, and eggs. If groundwater discharge occurs through seeps and springs to the surface, or into surface water bodies a human using water from the spring or the receiving water body (i.e., a lake, or river) for domestic and agricultural activities can also be evaluated in the conceptual model.

The conceptual model of exposure from contaminated surface water may include the following pathways:

- Ingestion of water;
- Irrigation of crops and watering of livestock, leading to bioaccumulation in plants and domestic animals;
- Ingestion of meat, milk, and eggs contaminated with surface water;
- Direct contact with water (i.e., swimming);
- Exposure to contaminated sediments exposed during dry conditions of the surface water body; and
- Ingestion of fish.

The exposure pathways for dose to man for the atmospheric pathways can be:

- Inhalation;
- Immersion;
- Plant and animal uptake leading to ingestion pathway for man; and
- Ingestion of soil.

In addition to the calculation of exposure of humans, consideration in some assessments is being given to the impact of exposure on non-human biota. For example the FASSET [56] programme of the European Commission has the aim of providing a reference set of models, dosimetric factors, etc., for generic organisms and ecosystems.

The quantification of the exposure is one of the main steps in the safety analysis process. As part of the process it may be also important to consider the background concentration of the radionuclide in the environment.

5.3. DEVELOPMENT OF MATHEMATIAL MODELS

Mathematical models translate the assumptions of a conceptual model into the formalism of mathematics, usually represented by sets of coupled algebraic, differential and/or integral equations with appropriate initial and boundary conditions in a specified domain. These equations are solved to give the temporal and spatial dependence of the quantities of interest (such as radionuclide concentrations in media and doses to humans).

5.3.1. Types of models

Mathematical models are required for two primary purposes:

- to describe the evolution of the disposal system (e.g. the chemical evolution in the near field, and the impact of climate change on the disposal system); and
- to describe the transfer of radionuclides through the evolving disposal system.

The particular mathematical representation of a conceptual model will depend on the assessment context and on the understanding of the ways in which FEPs can be interpreted in modelling terms. There is a hierarchy of models depending on the degree of simplification.

At the most detailed level, research models are used to build an understanding of certain processes and structures such as sorption of radionuclides onto engineered and natural barrier materials. The aim of research modelling is to build an understanding of issues of importance. This can be done by analysing the results of experiments or by using models to investigate the effects of interactions between various processes and structures.

At the other end of the spectrum lies assessment models, that can be used to represent individual components of the disposal system (e.g. near field) and/or the entire disposal system. They usually have a simplified geometry, structure and representation of processes due to computational and data constraints arising from the need to carry out a large number of calculations for sensitivity analysis and uncertainty analysis, and to evaluate various design options. For example, assessments of radionuclide transport in fractured rock are usually carried out using one-dimensional models, or networks of such models, despite the fact that three-dimensional codes are available. Research models are often used to support and justify the necessary simplifications required for assessment models.

The distinction between research and assessment models is somewhat blurred; there is a continuum of models. Certainly, as the understanding of the system is developed, it may become necessary to employ more detailed models to ensure that the system is adequately represented. However, the models should be simple enough to be compatible and commensurate with available data; otherwise, they could result in greater uncertainty rather than improved accuracy. Expert judgement can be used to ensure a proper balance between using simple models and existing data and more detailed models that may need data that are not readily available. This does not preclude the use of more complex models of parts of the system to improve the understanding of the phenomena involved, although the use of such models should be consistent with aims of the wider assessment. Reference [4] gives an example involving the use of sophisticated finite element groundwater codes to assess hydrological boundary conditions and temporal variability of water levels if physical characteristics or groundwater monitoring suggest the need to understand changes in the system at a detailed level.

5.3.2. Model simplification

Several factors can affect the complexity of the models used (see Fig. 26). Some level of simplification is generally required, even for research level codes, in order to translate the concepts of a conceptual model into mathematical terms. This simplification can take several forms, i.e.:

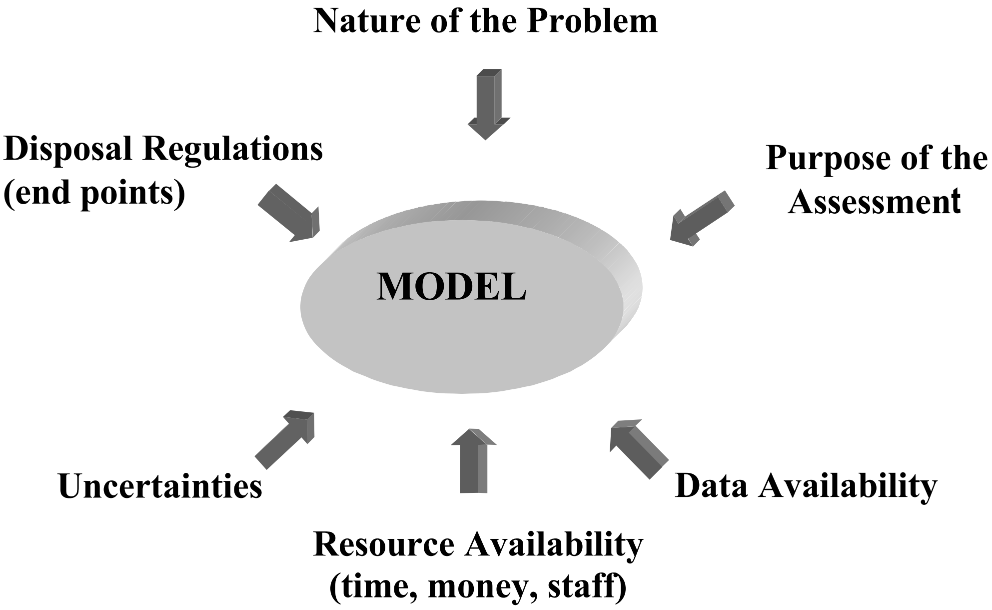


FIG. 26. Factors Affecting Model Complexity.

- Simplification of the geometry or structure, for example considering transport in only one dimension or the medium to be homogeneous and isotropic.
- Omission of processes and interactions or the simplification of their description, for example neglecting kinetic terms in chemical reactions.
- Simplifications, such as the exclusion of non-linear relationships, may be set by the preferred solution method for the model.

The process of producing simplified models is often not particularly rigorous and can introduce unquantified uncertainties and biases. Important aspects can be lost in the simplification process, and, for this reason, the reduction is often undertaken in such a way that it produces a conservative result. It is therefore important that any such simplifications should be clearly documented and their impacts on the mathematical model noted.

In practice, the mathematical representation of the process system will often be based on an empirical understanding of the system-level effect of more detailed processes. It is important to recognize where a particular mathematical model, perhaps described in terms of a single empirical factor, in fact represents a combination of different FEPs that may have been identified within the conceptual model. Where this is the case, care needs to be taken to avoid double-counting the effects of certain processes or, conversely, the inadvertent exclusion of potentially relevant FEPs. These simplifications relating to the representation of particular effects or processes, can potentially lead to a revision of the FEPs to be included within the mathematical model.

Sometimes, it can be convenient to develop a mathematical model that is consistent with existing computer tools rather than developing a new tool to implement the model. When this approach is taken, it is important to ensure that any associated limitations, such as the exclusion of certain FEPs identified in the scenario and conceptual model development processes, are adequately documented.

5.3.3. Initial and boundary conditions

As noted at the start of Section 5.3, differential equations are equations that can be used to describe the evolution of a system over time. In order to solve such equations its necessary to provide information on external influences on the system and the state of the system at the initial time. This information is referred to as the boundary or initial conditions. Different boundary and initial conditions will lead to different solutions of an equation. This additional information together with the differential equations defines an individual problem. Usually this additional information includes specifications of:

- The geometry of the domain where the physical phenomena takes place with possibly parts of the boundary being at infinity;
- Values of all important physical coefficients; and
- Initial conditions which describes the initial state of the domain.

Also, to be sure that the mathematical problem corresponds to the physical reality modelled, the solution must exist, be uniquely determined and should depend continuously on the data to ensure stability, so that a small variation of data results in a small change in the solution.

There are three types of boundary conditions as follows.

- Specified values — values of head, concentration, or temperature are specified along the boundary sometimes as a function of time (known also as a Dirichlet condition);
- Specified total flux — flow rate of water, contaminant mass, or energy is specified perpendicular to the boundary. A no-flow (impermeable) boundary is a special case of this type in which the flux is zero (known also as the Neuman condition); and
- Specified disperse flux — the flow rate is related to both the normal derivative and the value.

All type of boundaries conditions cited can be represented as function of time. In addition, each contaminant must have its own set of boundary conditions. Different boundary conditions can be used over different regions in the modelled domain. For example, for a contaminant, one boundary could have a specified total flux, while another boundary could have a specified concentration.

Selection of the boundary and the associated initial conditions is an important aspect of defining the conceptual model of the system. The choice of boundary conditions will affect the model results. For example, consider a problem with vertically downward flow. Selecting a zero concentration at the bottom boundary would lead to the maximum flux out of the system. However, it would not accurately calculate the concentrations at (or near) the boundary. Similarly, specifying a zero flux boundary condition will maximize the concentration at the boundary, but will not accurately represent the flux. At the boundary used to represent the ground surface, it is usually best to specify zero flux. This prevents mass from entering or leaving the system. Use of a zero concentration boundary condition will simulate mass exiting through the surface.

The flow and transport analysis conducted for near surface disposal systems is commonly subdivided into unsaturated-zone modelling and saturated-zone modelling. The purpose of this subdivision is to provide both mathematical and conceptual simplicity and clarity. However when this subdivision is made, a boundary condition must be specified at the interface between the two zones. There are several options that can be considered:

- If dispersion and diffusion are neglected, transport can be modelled using a first order partial differential equation, and no boundary condition is needed at this interface (a boundary condition is still needed at the ground surface). To use this approach, one could at best argue that it would tend to be conservative, at least for long-lived radionuclides. For short-lived radionuclides, this approach may not be conservative since the effect of dispersion is not modelled.

- The boundary condition can be specified to be zero concentration. Physically, this condition represents discharge into a rapidly moving aquifer, which carries contaminants away from the boundary quickly. This approach can be argued to be conservative for calculating flux (it maximizes the dispersive flux), but is inappropriate for evaluating concentrations at the interface.

- The unsaturated zone/aquifer boundary condition can be specified such that the gradient of concentration equals zero. This assumption physically relates to a case in which advective transport dominates at the boundary. Many groundwater transport codes use this assumption, and it is frequently not subject to much scrutiny. However, in low to moderate Peclet number problems, it is not physically appropriate. One can argue that it provides a less conservative condition to flux than would the zero concentration condition. It is not clear what effect the boundary condition has on the conservatism of the overall analysis.

- The conceptual model for the system can simulate the unsaturated zone using an infinite or semi-infinite domain. This approach is equivalent to ignoring the presence of the water table, but evaluating what occurs at the plane anyway. Physically, this approach corresponds most closely to discharge into an aquifer that has a strong downward component of velocity in the neighbourhood of the discharge. In general, this is not a good representation of the physical system;

- The unsaturated flow and transport fields can be coupled to aquifer flow and transport fields, and continuity mass conditions can be applied. This is mathematically correct approach, and constitutes dividing the system in a different manner than the way described above. However, due to its high data and computer resource requirements, this approach is frequently impractical for safety assessments.

It is clear that, except for the last option, all of these approaches have some component to them that is not physically correct in general, but which may be appropriate in individual cases. Therefore it is important to ensure that safety assessment is performed by using consistent set of codes.

5.3.4. Solution approaches

A variety of solution methods for the equations of radionuclide transport are commonly applied in safety assessment modelling. These are discussed below. The differences between the solution methods generally represent either a balance between modelling efficiency and complexity or between correctness and conservatism. In principle, a single general solution technique could be used for all safety assessment modelling needs. However, such a general solution typically can be cumbersome, and can require large amounts of computer time to perform solutions for the long time periods needed for safety assessment. As a result, a variety of simple numerical, analytical, and semi-analytical solutions have been used in safety assessments.

Analytical solutions

Analytical methods can provide exact solutions to the differential equations describing flow and transport of fluids. However, solutions have only been developed for simple cases involving homogeneous or uniform spatial domain, steady flow, one-dimensional advection, and one to three dimensional dispersion (see for example Appendix D). When the assessment domain has complex boundary conditions, and heterogeneous and anisotropic material properties, a more rigorous analysis can only be performed using numerical models.

Analytical models have two main advantages [57]:

- When site characterization data are sparse and uncertain, these methods provide screening level assessments for the initial phase of the iterative assessment process; and

- Coupled with Monte Carlo simulations these methods provide for a fast means of sensitivity and uncertainty analysis. If the assessment shows compliance for all realisations, more detailed modelling may not be necessary. If this is not the case then the results of the sensitivity analysis can be used to select a more refined approach.

Models using analytical solutions are often used to verify the more complex models, and assist with the laboratory column studies.

Analytical solutions for transport analyses broadly fall into two categories:

- Solutions in which dispersion is included in the transport equation; and
- Solutions in which it is not included.

If dispersion is not included in the transport equation, the governing equation for transport reduces to a first-order partial differential equation (or coupled system of equations in the case of decay chains), which can be solved by the method of characteristics. In essence, these solutions displace the contaminant in space and time through the geosphere, with concentrations only modified by decay, ingrowth and reactions. If dispersion is included in the transport equation, solutions of the resulting second-order partial differential equation result from the applications of a variety of solution methods and approximations. Complex analytical solutions are available in the literature for transport of several member decay chains.

Semi-analytical solutions

Semi-analytical solutions are exact formal solutions to the differential equation that is used to represent transport. However, the complexity and form of the solution prevent their evaluation without numerical approximation. Semi-analytical solutions provide a more flexible modelling tool than the analytical methods for solving problems with multiple sources and sinks. However, they are limited mostly to solving advection-dominated transport problems. Semi-analytical solutions often result from the use of “Laplace” and other transform techniques. Three particularly useful semi-analytical techniques are summarized below.

— **Laplace transformation** reduces differential and integral equations to less difficult mathematical problems. The conditions of the initial equation are called the original space and the conditions of the transformed equation are called the image space (Fig. 27). The Laplace transformation of a given function f(x) is defined as:

$$L[\,f(x)\,] = F(s) = \int_0^{\infty} e^{-sx} f(x)\, dx \tag{1}$$

where

x is the spatial or temporal independent variable to be transformed into a parameter. The Laplace transformation is linear and does not impact other independent variables which are not transformed. After the problem is solved in the image space, the inverse or back transformation of the function F(s) into the original space must be carried out. In most practical problems the inverse L-transformation is difficult to perform. This transformation is defined by:

$$f(x)=L^{-1}\,[\,F(s)\,] = 1/(2.\pi.j).\int_{\Omega} e^{sx} F(s)\, ds \tag{2}$$

For a large number of special functions f(x), correspondence tables with solutions of previous equation are available. If no correspondence is available, a solution can usually be obtained only by numerical integration of Equation 2 (numerical L-back transformation).

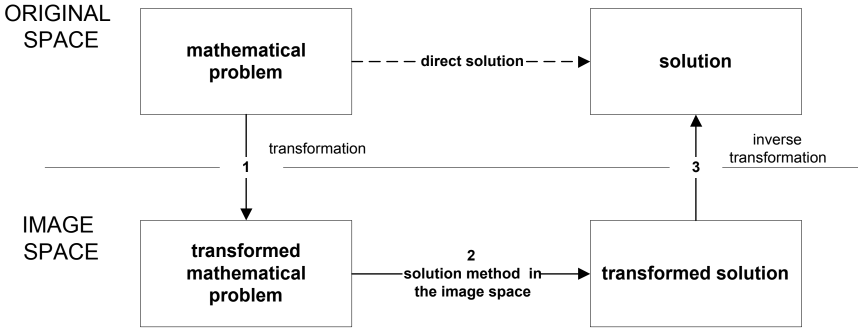


FIG. 27. Methodological Approach of Laplace Transformation.

- **Green's functions method** provides a general way to solve inhomogeneous differential equations of the form:

$$L(y) = f(x) \tag{3}$$

where

L is a differential operator on the dependent variable y, and f(x) is the inhomogeneity. In terms of the transport equation, y is the concentration C, L is the operator representing the time rate of change in y, advection, diffusion/dispersion, and radioactive decay, and f(x) is the source term. The Green's function, g, can be determined from the related differential equation:

$$L(g) = \delta(x-x') \tag{4}$$

where

δ is the Dirac delta function and g is the Green's function. If one can solve for the Green's function, the solution for the original differential equation is given by:

$$y(x) = \int_{-\infty}^{\infty} f(x')g(x-x')dx' \tag{5}$$

The Green's function approach is particularly useful for safety assessment applications because of the clear manner in which arbitrary and complex forcing functions can be treated. A number of useful Green's function solutions for groundwater transport analyses are described in [58]. However, the real value of this technique is in developing site specific and design-specific solutions for new problems. For instance, solutions for transport in unsaturated soils are simple to develop for a variety of source-term functions; these solutions are related to, but different from solutions given in [58].

The primary drawback to Green's function solutions is the simplicity of the underlying assumptions. The Green's function that forms the basis for the solutions given in [58] are for uniform, homogeneous, semi-infinite or infinite media with one-dimensional flow. In addition, a Green's function for transport of decay chains is not available; consequently, to analyse decay chains using this approach one must apply one of the approximate approaches described above.

- **The stream-tube approach** to modelling groundwater transport is a specialized approach that has been developed for safety assessments. The primary reason for the development of stream tube approaches was to develop a method that would allow rapid analyses over very long time periods. The basis for the stream-tube analysis is to define a one-dimensional region, within which the advective-dispersion equation can be solved analytically or semi-analytically.

Groundwater flow analysis is first used to define the flow paths. Stream tubes are defined based on the flow paths. Transport is considered to be one-dimensional within the stream tube, and transport is not considered to cross the stream tube boundary. A key to the stream tube approach is to define an appropriate size of the stream tube. For analyses directed toward compliance with an integrated discharge requirement, this is not an issue, since integrated discharge is not a function of the area through which transport occurs. However, dose is based on concentrations. Therefore, for dose-based standards, it is necessary to define the spatial extent of the stream tube by using the stream paths of groundwater and thereby estimate concentrations.

The Distributed-Velocity Method is described in [59]. This approach solves the advective-dispersion equation with a novel numerical method, which has the characteristic that the accuracy increases with increasing time step. It therefore allows long-duration safety assessment analyses quickly and efficiently. More recent developments in the Distributed Velocity Method are reviewed in [60].

Other stream-tube solution methods are available that incorporate dispersion as a distribution of velocities in the tube, treating the transport as a purely advective process [61].

Integral transform methods

Within the last two decades, the classical integral transform method gained a hybrid numerical-analytical structure, offering user controlled accuracy and quite efficient computational performance for a wide variety of *a priori* non transformable problems, including the non-linear formulations of interest in heat and fluid flow applications (see for example [62][63]). This approach has been used to solve problems with variable equation and boundary coefficients, moving boundary problems, irregular non-transformable geometries, difficult auxiliary eigenvalue-type problems, coupled problems, non-linear diffusion and convection-diffusion problems, boundary layer formulations and Navier-Stokes equations.

Besides being an alternative computational method in itself, this revived approach is particularly well suited for benchmarking purposes, in light of its automatic error control feature, retaining the same characteristics of a purely analytical solution. In addition to the straightforward error control and estimation, a useful aspect of this method is its direct extension to multi-dimensional situations, with only a moderate increase in computational effort with respect to one-dimensional applications. Again, the hybrid nature is responsible for this behaviour, since the analytical part in the solution procedure is employed over all but one independent variable, and the numerical task is always reduced to the integration of an ordinary differential system in one single coordinate.

More details concerning the approach are given in Appendix D.2.

Numerical solution techniques

Numerical solution techniques involve the translation of the differential equation into a system of equations that can be solved using a computer. The majority of computer codes developed since the 1960s to analyse groundwater flow and transport are numerical finite-element or finite difference solutions. In numerical approaches, the physical domain is partitioned into a discrete set of finite-sized regions. The governing differential equations are approximated in terms of the variables in that region and immediate neighbouring regions. This leads to a set of discrete equations that are solved by matrix inversion methods. Finite difference techniques expand the differential equation using local expansions while finite element techniques use integral techniques to approximate the differential equation. The differences between finite-difference and finite-element methods are well established, and are not considered in detail this report. The practical considerations that are most important for safety assessments are as follows:

— These methods can be adapted to arbitrary and complex sources and modelling geometries. Consequently, they are most appropriate for complex situations.

— Accuracy increases as the discretisation is made finer, both in space and time. Since safety assessment analyses are commonly carried out for many thousands of years, there is a conflict between computational effort and accuracy when using this method. This computational burden can become intense if full uncertainty analysis is conducted.

— When solving the discretised equations, spurious "numerical dispersion" is introduced into the solution, potentially making the solution inaccurate. Numerical dispersion is a function of mesh size and relationships exist for many situations which permit estimation of the numerical dispersion. For accuracy, the analyst should demonstrate that the value for the numerical dispersion is far less than for mechanical dispersion or molecular diffusion. One approach to evaluating the effect of numerical dispersion is to solve the transport equation using progressively finer discretisation meshes, until the analyst has confidence that the discretisation is fine enough. This also adds to the computational burden of the analysis. Often, concentrations at the monitoring point are several orders of magnitude less than in the source region. In these cases, numerical dispersion should be carefully estimated to insure accurate results.

— The development and use of these models require highly trained personnel.

Example mathematical models

Some example mathematical models associated with the conceptual models discussed in Section 5.2 are presented in this section and its associated appendix (Appendix E). Models for preliminary analysis as well as for in-depth analysis are discussed in the section and Appendix E. The compilation should not be seen as being exhaustive, it is provided to illustrate a variety of mathematical models that can be used in safety assessment.

Source term

Models that can be used to quantify the releases of radionuclides in liquid, gaseous, and solid forms from near surface disposal facilities are presented below. Estimates of releases from the facility over time can be made either simply by making conservative assumptions about processes and parameter values, often leading to a bounding analysis, or by performing a more complex analysis in which pertinent processes are simulated in detail using physically-based models, and more realistic parameter values. However, if a bounding analysis is sufficient to show compliance with performance objectives, a more detailed analysis may not be necessary.

Liquid releases

Consistent with the discussion of the conceptual models for liquid releases presented in Section 5.2, the range of models that can be used to estimate liquid release rates are discussed for water flow, degradation of containers/barriers, waste form releases, and the radionuclide transport.

Water flow in near field

The estimation of the near field water flow is an important element of near field modelling since it is the driving force for the release of radionuclides in the liquid phase (see Fig. 18). Its aim is to obtain the flow rate and the moisture content in the near field for each phase of the near surface disposal facility’s existence.

For disposal facilities in the **unsaturated zone**, the amount of water infiltrating the disposal facility cover, moving through the disposal units, and finally recharging the groundwater beneath the facility needs to be estimated. At most sites, an estimate of the one-dimensional downward steady-state flow rate (expressed as volume of water per unit area per year, which is equal to depth of water per year) is all that is required. For, preliminary estimates, a certain percentage of the average annual precipitation at the site can be assumed as the steady-state infiltration rate (or recharge rate). If the effect of the degradation of engineered barriers is to be considered, then the flow rate might be considered to be time dependent to reflect the changing state of the barriers. In arid environments, the impact of capillary rise resulting in the potential upward movement of contaminants might also have to be considered.

If more detailed analysis is required, rainfall-runoff models can be used to assess the hydrologic response of the engineered site over time, for example due to variations in climate or degrading facility conditions. Continuous simulation models of rainfall-runoff provide a detailed accounting of precipitation (rainfall and snow) falling on the land surface in terms of evaporation, transpiration, runoff, soil moisture storage, and drainage from the bottom of the root zone. Drainage rates thus can be simulated using historic records of precipitation. In order to arrive at long term estimates of infiltration and drainage rates, long sequences (20-30 years) of short duration precipitation data (15-minute or hourly amounts) should be used. If such long term data are not available, either data from hydrologically similar areas, or stochastically generated long term (100 to 1,000 years) climatic data series can be used as input. The annual statistics (mean, standard deviation, minimum, maximum) of the generated drainage rates can then used in the source term modelling.

Likewise, the hydrologic response of a disposal site and facility can be evaluated using an unsaturated zone (vadose zone) flow model. Such an evaluation can be performed in one- or two- or three dimensions, with climatic time-series of data (precipitation, evapotranspiration) imposed as the upper boundary condition to the model domain. With numerical models, the facility features (closure cover, vaults, liners, drainage systems, and backfill) can be represented as realistically as possible. Such an analysis, however, will prove to be time-consuming and costly because of the non-linear nature of the unsaturated zone hydraulic properties, and the difficulty of representing the engineered barriers. The results of such long term simulations can be averaged to provide a one- or two-dimensional flow field that can be used as the steady-state flow field for the source term modelling.

For a disposal facility in the **saturated zone**, groundwater flow modelling (see Appendix E), can also be used to provide estimates of steady-state downward flux rates for source term modelling. At sites where groundwater water-level measurements and hydraulic conductivity data exist, a steady-state saturated zone groundwater model can be calibrated, with recharge being the calibration parameter. The calibrated recharge value can then be used as the steady-state flux through the facility for the source term modelling.

Degradation of containers and barriers

Waste containers and engineered barriers provide containment of waste through closure cover, vaults, liners, backfill, etc. Water entry into the disposal units will be small until the engineered barriers degrade, and intact containers will delay entry of water into the waste forms until container decay. Therefore, the time to failure of the containers and barriers needs to be estimated for source term modelling.

Containers: As noted in, two types of failures of containers can be considered for source term modelling [36]:

— General failure — the output of the general failure model is the time at which failure occurs, t_f (y), and can be determined from:

$$t_f = d/u \tag{6}$$

where

d is the corrosion allowance thickness for the container (m);
u is the general corrosion rate (m y^{-1}).

General failure is modelled specifying a time to failure during which no water contacts the waste and beyond which container no longer acts as a barrier to water. The time to failure can be estimated as the container thickness divided by a corrosion rate. Corrosion rates should ideally be developed based on data from specific disposal cell environment. However, most often such data would not be easily obtained. Therefore, databases such as the United States National Bureau of Standards (NBS) [38] could be used.

— Localized failure — the portion of the area of the container that fails due to pitting corrosion can be computed with empirical equations such as the following taken from [37]:

$$A_{bc} = k\, t^n \tag{7}$$

where

A_{bc} is the breached surface area of the container (m^2);
k is the pitting parameter for specific container material and soil pH (m y^{-1});
t is the time (y);
n is the pitting parameter ($n < 1$) (m).

Considering the complexity of accounting for each container in a typical disposal facility containing numerous types of containers, a range of failure times for a small number of classes of containers can be assessed [37]. With such an approach, all containers in a given class can be assumed to fail at the same time.

Barriers: Models of concrete degradation are considered in terms of surface and bulk-attack mechanisms. Surface-attack mechanisms are initiated at the concrete surface and progress inward over time. Bulk-attack mechanisms modify the properties of the entire concrete component uniformly.

Most important surface attack mechanism is sulphate attack. The rate of degradation can be defined as:

$$R=E.\beta^2.c_o.C_e.D_i/[\alpha.\gamma.(1-\mu_c)] \tag{8}$$

where

R is the rate of degradation (m s^{-1})
E is Young’s module (Pa)
β is the linear strain caused by a mole of sulphate reacted in unit volume (m^3 mol^{-1})
c_o is the water sulphate concentration (mol m^{-3})
C_e is the concentration of sulphate as ettringite (mol m^{-3})
D_i is the diffusion coefficient of sulphate ions in water saturated cement (m^2 s^{-1})
α is the roughness factor for fracture path (-)
γ is the fracture surface energy of concrete (J m^{-2})

μ_c is the Poisson's ratio for concrete (-)

Calcium hydroxide leaching is the most notable bulk attack process. When the water is not saturated with calcium carbonate, the fractional release of $Ca(OH)_2$ can be calculated as:

$$C_a = I.C_p/(C_t.C_c) \tag{9}$$

where

C_a is the fractional water release rate of $Ca(OH)_2$ (y^{-1})
I is the percolation rate through the disposal facility ($m\ y^{-1}$)
C_p is the $Ca(OH)_2$ concentration in concrete pore solution ($mol\ m^{-3}$)
C_t is the concrete thickness (m)
C_c is the $Ca(OH)_2$ concentration in concrete ($mol\ m^{-3}$)

Other example equations describing the degradation of barriers are given in Appendix E.

Release of radionuclides from waste forms

— Rinse Release

A conservative approach to deriving releases from waste forms is to assume that radionuclides are rinsed or washed off of the surfaces of the waste forms by flowing water. The flux can be calculated as follows [64]:

$$J = C\ v\ \left(\frac{A_b}{A}\right) \tag{10}$$

where

J is the flux of radionuclide released ($Bq\ (m^2\ y)^{-1}$);
C is the concentration of the radionuclide in the pore water ($Bq\ m^{-3}$);
v is the pore water velocity ($m\ y^{-1}$);
A_b is the breached surface area of the waste form (m^2);
A is the surface area of the waste form (m^2),

Concentration in pore water is computed as follows, assuming solubility limitation:

$$C = M\ \frac{1-(C_s\ /C_{sat})}{\theta_w\ V} \qquad C_s < C_{sat} \tag{11}$$

where

C is the radionuclide concentration in the pore water at the end of the time step ($Bq\ m^{-3}$);
M is the activity of the radionuclide (Bq);
C_s is the radionuclide concentration at the beginning of the time step ($Bq\ m^{-3}$);
C_{sat} is the solubility limit ($Bq\ m^{-3}$);
θ_w is the water filled porosity of the waste form (-);
V is the volume of the waste form (m^3).

Mass balance should be computed at the end of each time step to compute the available mass.

The availability of radionuclides for release into pore water can be limited due to geochemical processes such as adsorption, absorption, adhesion, and ion-exchange. Rinse release model can be refined by incorporation into the above formulation a partitioning coefficient which accounts for all these processes helping to retard releases. However, reliable estimates of such radionuclide specific partitioning coefficients may prove difficult (Sullivan, 1993) [64].

Rinse model with partitioning can be formulated as following. Assuming that the amount of radionuclides in the waste decreases with time exponentially, the following expression can be written:

$$M(t) = M(0)\, e^{-(\lambda + \lambda_l)\, t} \tag{12}$$

where

M(t) is the activity of the radionuclide at time t (Bq);
M(0) is the initial activity of the radionuclide (Bq);
λ is the decay rate of the radionuclide (y^{-1});
λ_l is the leach rate of the radionuclide (y^{-1}).

The mass release, R (t), (Bq y^{-1}) can then be expressed as:

$$R\ (t) = M(t)\ \lambda_l \tag{13}$$

The leaching rate is expressed as the ratio of the amount released per time step to the amount remaining. Assuming that leaching of radionuclides which are partitioned into the pore water occurs by a steady-state infiltration or drainage through the waste, the following expression can be derived:

$$\lambda_l = \frac{q}{z\ (\theta_w + \rho_b\, K_d)} \tag{14}$$

where

q is the rate of drainage of water through the waste forms (m y^{-1});
θ_w is the water filled porosity of the waste form (–);
ρ_b is the bulk density of the waste form (kg m^{-3});
K_d is the waste form distribution coefficient (m^3 kg^{-1});
z is the height of the waste form (m).

The leaching rate can also be adjusted for the area of the waste form accessible to water.

— Diffusion Release

Under diffusion release conditions, analytical solutions for the release rate from the waste forms can be used to solve the diffusion equation with radioactive decay:

$$\frac{\partial C\ (x,t)}{\partial t} = D\ \Delta^2 C\ (x,t) - \lambda\ C\ (x,t) \tag{15}$$

where

C(x,t) is the concentration of radionuclide at time t within the waste form (kg m^{-3});
D is the waste form diffusion coefficient (m^2 y^{-1});
λ is the decay rate of the radionuclide (y^{-1});
x is the spatial location vector (–);
t is the time since container failure (y).

The initial condition is:

$$C\ (x,0) = C_0 \tag{16}$$

Solutions can be obtained for a variety of geometries for example semi-infinite, finite sized cylindrical, and rectangular [65]. The semi-infinite waste form model for release is:

$$CFR = \frac{2\,A}{V}\sqrt{\frac{D\ t}{\pi}} \tag{17}$$

where

CFR is the cumulative fractional release (–);
A is the surface area of the waste form (m^2);
V is the volume of the waste form (m^3).

— Dissolution Release

Releases from activated metals that undergo corrosion can be modelled as follows [66]:

$$R = u\ A\left(\frac{M(0)}{V}\right)\left(1 - \frac{C_s}{C_{sat}}\right)e^{-\lambda\,t} \tag{18}$$

where

R is the release rate of the radionuclide (Bq y^{-1});
u is the corrosion rate (m y^{-1});
A is the surface area of the waste form (m^2);
M(0)is the initial activity of the radionuclide (Bq);
V is the volume of the waste form (m^3);
C_s is the radionuclide concentration at the beginning of the time step (Bq m^{-3});
C_{sat} is the solubility limit (Bq m^{-3});
λ is the decay rate of the radionuclide (y^{-1});
t is the time (y).

Solubility-limited release models assumes an instantaneous release of radionuclides into solution until the solubility limit is reached. The model is expressed simply as:

$$C = C_{sat} \tag{19}$$

Radionuclide transport in near field

The simplest approach to modelling of raidonuclide transport through the near field is to assume that once a contaminant is released from the waste form, it is also released from the disposal facility. The simplicity, the lack of need for transport parameter data, and the general conservatism inherent in this approach make this method appealing. However, this approach predicts earlier releases from the facility and therefore, may substantially over predict release rates for most radionuclides (except for those than ingrow from a parent). For example, consider the case where the average transport time for a non-sorbing contaminant to move through the entire disposal facility is ten years, and the entire inventory is uniformly distributed through the facility and released upon container failure. If it is assumed that would be released instantly. On the other hand, accounting for transport would spread the release out over the ten year transport time. Thus, the peak release rate would be a factor of ten lower than the instantaneous release.

The next level of modelling complexity simulates transport through the facility by considering advection while ignoring dispersion and diffusion processes. A number of approaches can be used. One approach divides the facility into a number of mixing units. A mass balance is performed for each unit and the movement subject to advection, sorption, and decay is estimated (see for example [67]). Under appropriate conditions for waste form release rate (i.e. rinse release with partitioning or uniform release in time), analytical solutions can be obtained for an arbitrary distribution of sources [68].

Diffusion may be an important transport process when the engineered facility is performing as designed and limiting advection to very low rates. Dispersion may be important to the release process as it tends to spread the contaminant plume out around the average flow velocity. This can be particularly important for short-lived radionuclides which would decay prior to leaving the near field.

For many safety assessments, a one-dimensional transport model that assumes spatially uniform flow through the facility is often used. When localized effects (e.g. flow around containers, infiltration barriers, through cracks in the grout backfill and through the engineered barrier) are important, two- or three-dimensional models or fracture flow models may be necessary. These more detailed models may not lend themselves to assessment of thousands of different cases for simulation of long time periods. In this case, they may be used to provide justification for the selection of a flow rate that bounds the non-uniform flow effects.

Although short term transient effects are not used to model the transport in the facility, long term alterations in flow rates are often considered through step or ramp changes. These changes are used to represent the degradation of the engineered barrier in time. The release from the facility is quite sensitive to flow rate and changes in flow rate. A ramp change slowly alters the flow rate and therefore, spreads the release out in time. Step changes in flow rate, which are often as large as an order of magnitude, lead to estimations of large changes in release rates.

An alternative conceptualisation of changes in flow rates assumes that the disposal unit has two flow regions. The first region receives water flow at a rate determined by the intact barriers to flow. In the application of the model, this is often assumed to be a diffusion dominated region and the flow velocity is zero. The second region receives water flow at a rate determined without any barriers to flow. The fraction designated as region 1 and 2 change in time to simulate the degradation of the barriers.

Equations used to represent the processes of advection, dispersion, diffusion, decay and sorption considered above are described in the report.

Gaseous Releases

Radionuclides can be released from the disposal facility by gaseous diffusion through the air filled pore space of the waste, backfill material and the closure cover. The one-dimensional diffusion equation with decay can be written as:

$$\frac{\partial C_g(z,t)}{\partial t} = D_e \frac{\partial^2 C_g(z,t)}{\partial z^2} - \lambda \; C_g(z,t) \tag{20}$$

where

C_g is the concentration of the radionuclide in pore gas of radionuclide (Bq m^{-3});
D_e is the effective gas diffusion coefficient of the radionuclide in the porous medium (m^2 y^{-1});
λ is the decay rate of the radionuclide, (y^{-1}).

The equation of continuity is solved assuming steady-state conditions and two boundary conditions. First, the gas concentration is assumed to be zero at the cap-air interface ($z = x$). This is a conservative assumption that will maximize the concentration gradient and the flux density. At the waste-cap interface ($z = 0$), the concentration is assumed to equal the waste pore gas concentration. Gaseous radionuclides are assumed to be completely and immediately released to the pore space and to be lost by radioactive decay only. The loss by radioactive decay is assumed to be slow relative to changes in concentration in the cap. Therefore, the concentration profile is assumed to instantaneously reach steady state as the source term decays. The boundary conditions can be written as:

$$C_g\,(0,\ t) = C_g\,(0,\ 0)\ e^{-\lambda\ t} \tag{21}$$

$$C_g\,(x,\ t) = 0 \tag{22}$$

where

$C_g\,(0,0)$ is the initial pore gas concentration in the waste of the radionuclide (Bq m^{-3});
$C_g\,(x,t)$ is the soil pore gas concentration at cap-air interface ($z = x$) (Bq m^{-3});
t is the elapsed time since closure (y).

Assuming the boundary conditions above, a particular solution can be obtained (for steady state) as:

$$C_g\,(z,\,t) = C_g\,(0,\,0)\ e^{-\lambda\,t}\,\frac{\cosh\,\left\lfloor\left(\,x - z\,\right)\sqrt{\lambda_j\,/\,D_e}\,\right\rfloor}{\sinh\,\left(\,x\,\sqrt{\lambda\ /\,D_e}\,\right)} \tag{23}$$

The initial concentration in the waste pore gas is calculated assuming the entire inventory is released to the gas-filled pore spaces. For all nuclides other than ^3H, the pore gas concentration is given by:

$$C_g\,(0{,}0) = \frac{C_w(0)}{\theta - \theta_w} \tag{24}$$

where

$C_w(0)$ is the waste concentration of radionuclide at closure (Bq m^{-3});
θ is the total porosity of the waste form (–);
θ_w is the water filled porosity of the waste form (–).

The ^{3}H pore gas concentration is calculated assuming that the specific activity of ^{3}H in waste pore water is equal to the specific activity of vapour in the waste air-filled pore space. The concentration of the waste pore gas is given by:

$$C_{g,H3}(0,0) = \frac{C_{w,H3}(0)\, P_v\, Mw}{\theta_w R\, T\, \rho_{H2O}} \tag{25}$$

where

P_v is the vapour pressure of water(Pa);
Mw is the molecular weight of water(kg mol^{-1});
R is the gas constant (m^3 Pa /(mol K));
T is the absolute temperature (K);
ρ_{H2O} is the density of water (kg m^{-3}).

The atmospheric concentration directly over the cap was estimated assuming steady state mixing of the flux into a compartment. Assuming steady state mixing into a zone above the waste disposal site, the concentration of a gaseous radionuclide is given by:

$$C_a(t) = \frac{J\ (x,t)\sqrt{A_{df}}}{H\,U} \tag{26}$$

where

J(x,t) is the gas flux density (Bq (m² s)$^{-1}$;
A_{df} is the area of the disposal facility (m²);
$C_a(t)$ is the atmospheric concentration of gaseous radionuclide over the cap at time t, Bq m^{-3};
H is the height of the mixing zone (m);
U is the annual mean absolute wind speed (m s^{-1}).

Diffusion coefficients in air should be converted to an effective diffusion coefficient for use in porous media. Care should be taken to ensure that the selected effective diffusion coefficient is appropriate for the porous medium and the model assumptions. The definition of the flux density, J, and the concentration, C, are of particular concern, because they can be defined to include or to exclude the solid matrix of the porous medium. Effective diffusion coefficients commonly account for the effects of the increased path length and reduced cross-sectional area available for gaseous diffusion in porous media. Other effects that can be accounted for are adsorption of the gas by the porous medium, dissolution in pore fluids, and for high level waste, the effects of temperature.

The effective diffusion coefficient in a porous medium can be estimated as:

$$D_e = D_a \frac{\theta_a^{10/3}}{\theta} \tag{27}$$

where

D_e is the effective gas diffusion coefficient of the radionuclide in the porous medium (m^2 y^{-1});
D_a is the gas diffusion coefficient of the radionuclide in air (m^2 y^{-1});
θ_a is the air filled porosity of the porous medium (–);
θ is the total porosity of the porous medium (–).

The effective diffusion coefficient in a porous medium can also be calculated as:

$$D_e = 0.66\, D_a \tag{28}$$

where

D_e is the effective gas diffusion coefficient of the radionuclide in the porous medium ($m^2\ y^{-1}$);

0.66 D_a is the gas diffusion coefficient of the radionuclide in air ($m^2\ y^{-1}$);is the assumed geometrical factor value.

Solid Releases

Processes resulting in the release and transport of radionuclides from the near field in the solid phase are usually considered using scoping calculations, since there is rarely data available to support a more detailed model. Therefore the effect of colloids can be represented by varying sorption coefficients for relevant radionuclides, although detail models can be used.

The following source term model has been used for two human intrusion scenarios (on-site residence and road construction) [69]. The activity to which the on-site resident and intruder is exposed, A_i (Bq kg^{-1} of waste), is given by:

$$A_i = A_m\, e^{-\lambda t_1}\, dil \tag{29}$$

where

A_m is the initial concentration of the radionuclide disposed (Bq kg^{-1} (of waste));

λ is the decay rate of the radionuclide (y^{-1});

t_1 is the time before exposure starts (y);

dil is the dilution factor (–).

For an erosive release, the radionuclide concentration (C_{Soil}, Bq m^{-3}) in the source term can be calculated by assuming that it is the same as that in the waste:

$$C_{Soil} = M/V_{df} \tag{30}$$

where

C_{Soil} is the radionuclide concentration in the soil (Bq m^{-3});

M is the radionuclide inventory in the disposal facility (Bq);

V_{df} is the total disposal facility volume (m^3).

The source term is reduced as a function of time due only to radioactive decay.

Further examples of such scoping models for human intrusion and erosion are given in [70 and 71] and Volume II.

Work undertaken to develop a generic model of the uptake and accumulation of radionuclides by plants growing on near surface waste disposal sites in the United States of America is cited in [42]. The following model was proposed:

$$Q = \sum_{l=1}^{p} \frac{C\ CR\ B_l}{K_d} \tag{31}$$

where

Q is the quantity of the radionuclide taken up by a plant (Bq (ha y)$^{-1}$);

p is the total number of plants;

C is the concentration of the radionuclide in the soil water (Bq m^{-3});
CR is the concentration ratio of the radionuclide per unit mass of biomass to the activity per unit mass of dry soil (Bq kg^{-1} of biomass/Bq kg^{-1} of dry soil);
B_l is the total biomass of the plant (kg (ha y^{-1});
K_d is the soil distribution coefficient of the radionuclide (kg m^{-3}).

Transport media and mechanisms

Geosphere

The governing equation for groundwater flow that is often used is:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)=S_s \frac{\partial h}{\partial t}+W \tag{32}$$

where

h is the head (m);
K_x, K_y, K_z is the hydraulic conductivity in x, y, and z coordinates (m y^{-1});
S_s is the specific storage (m^{-1}); and
W is the general sink or source term (y^{-1}).

For homogeneous and isotropic media, the equation becomes:

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=\frac{S_s}{K}\frac{\partial h}{\partial t} \tag{33}$$

For a horizontal aquifer of constant thickness:

$$S = S_s\, b \tag{34}$$

$$T = K\, b \tag{35}$$

where

S is the storitivity or storage coefficient (–);
b is the aquifer thickness (m);
T is the transmissivity (m^2 y^{-1}).

The governing equation becomes:

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=\frac{S}{K}\frac{\partial h}{\partial t} \tag{36}$$

The head distribution over the problem domain can be obtained by solving these equations in one or two or three dimensions, with known S_s, or S, and T.

For unsaturated flow, the hydraulic head is expressed as:

$$h = P + z \tag{37}$$

where

P is the pressure head (m);

z is the gravitational head (m).

Solution of the governing equation also requires knowledge of the soil-moisture retention relationship, or the characteristic curves. Van Genuchten relationship is one of several such empirical relationships developed to define the soil moisture and pressure relationship in the unsaturated zone [72 and 73]:

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{\left[1 + (\alpha|\Psi|^{\beta}\right]^m} \tag{38}$$

where

θ is the soil moisture content (–);
θ_r is the residual soil moisture content (–);
θ_s is the soil moisture content in saturated conditions (–);
ψ is the suction pressure (m);

α, β. and m are empirical curve fitting parameters with $m=1-1/\beta$

The unsaturated hydraulic conductivity is expressed as:

$$K=K_sS^{0.5}\,[1-(1-S^{1/m})^m]^2 \tag{39}$$

where

K_s is the saturated hydraulic conductivity (m y^{-1});
S is the relative saturation.

The relative saturation is given by:

$$S=(\theta-\theta_r)/(\theta_s-\theta_r) \tag{40}$$

For the solution of transport of dissolved contaminants, most groundwater models first generate the head distribution over the problem domain using the flow equations. The pore water velocities are then computed using Darcy's law:

$$v_x = -\frac{K_x}{\theta_e}\frac{\partial h}{\partial x} \quad v_y = -\frac{K_y}{\theta_e}\frac{\partial h}{\partial y} \quad v_z = -\frac{K_z}{\theta_e}\frac{\partial h}{\partial z} \tag{41}$$

where

v_x, v_y and v_z are the pore water velocities (m y^{-1});
θ_e is the effective porosity (–).

The general advection-dispersion equation in two dimensions for unsaturated and saturated media is:

$$\frac{D_x}{\theta_e}\frac{\partial^2 C}{\partial x^2} + \frac{D_y}{\theta_e}\frac{\partial^2 C}{\partial y^2} - \frac{v_d}{\theta_e}\frac{\partial C}{\partial x} = R\frac{\partial C}{\partial t} + R\,\lambda\,C \tag{42}$$

where

x is the water flow axis;
y is the transverse axis;

θ_e	is the effective porosity (–) or in the case of unsaturated flow the water filled porosity (–);
C	is the concentration of the radionuclide in the water (Bq m^{-3});
v_d	is the Darcy velocity (m y^{-1});
D_x, D_y	are the hydrodynamic dispersion tensors of the radionuclide (m^2 y^{-1});
R	is the retardation factor of the radionuclide (–);
λ	is the decay rate of the radionuclide (y^{-1}).

Darcy's velocity is given by:

$$v_d = -K\frac{\partial H}{\partial x} \tag{43}$$

where

K	is hydraulic conductivity (m y^{-1});
$\frac{\partial H}{\partial x}$	is head gradient (–).

V_d/θ_e is the pore water velocity (v) used in Equation 41.

The retardation factor of the radionuclide is given by:

$$R = 1 + \frac{\rho_b K_d}{\theta} \tag{44}$$

where

ρ_b	is the dry bulk density of the medium (kg.m^{-3});
K_d	is the distribution coefficient (m^3 kg^{-1});
θ	is the total porosity of the medium (–).

The hydrodynamic dispersion tensors are given by:

$$D_x = \theta D_e + \alpha_L |v_d| \approx \alpha_L |v_d| \tag{45}$$

$$D_y = \theta D_e + \alpha_T |v_d| \approx \alpha_T |v_d| \tag{46}$$

where:

θ	is the total porosity of the medium (–);
D_e	is the molecular diffusion coefficient in the medium (m^2 y^{-1});
α_L	is the longitudinal dispersivity in the medium (m);
α_T	is the dispersivity in the medium (m);
v_d	is the Darcy velocity (m y^{-1}).

Biosphere

Mathematical models that have been developed to represent biosphere transport of radionuclides derived from near surface disposal facilities range in complexity from simple expressions to highly complex mathematical algorithms. The models can be split according to their degree of complexity in two categories.

— **Mechanistic models** describe processes in a physically realistic manner and are normally specific to a given process (e.g. erosion of soil). For example, in the case of erosion, they would calculate the flux of radionuclide from the source to the atmosphere, and then let this material be dispersed according to typical fluid motions. In most cases, mechanistic models are quite complicated and reflect the state of the art knowledge about the process. This often makes them specific, and not always applicable to a large range of processes. For example, UK Nirex has developed the SHETRAN code [74] to model the migration of radionuclides within a hydrological catchment area within three dimensions. Such codes tend to be resource intensive and their contribution to an assessment of a facility is restricted to increasing the understanding of certain processes which can then be incorporated into the more simplified code used for the assessment.

— **Transfer coefficient models** do not describe the physical processes in a detailed mechanistic way, but instead are based on measurements made of contaminants in two different media. The transfer coefficient is then inferred from these relationships. Although this approach is often not scientifically rigorous it considers many parts of a process implicitly, it is simple, and it is usually based on real data. Thus, it can be appropriate for assessment purposes especially given the considerable uncertainties associated with the future evolution of the biosphere.

The focus of the following section is on the transfer coefficient models since these are more widely applied.

Most of the transfer coefficient models are based on linear donor-controlled compartment models [75] and [76]. Such models assume that a system may be represented by breaking it down into compartments, each of which may represent a medium which is distinct from other associated media. It is assumed that, as soon as material (in this case radionuclides) enters a compartment, instantaneous mixing occurs so that there is a uniform concentration over the whole compartment. Each compartment should be chosen to represent a region of the environment for which this assumption is reasonable. Radionuclides in one compartment may be transferred to another by various processes. The transfer is described by transfer coefficients that represent the fraction of the activity in a particular compartment transferred from that compartment to another one in unit time. Radionuclides can also be lost from the system altogether (by radioactive decay).

The mathematical representation of the intercompartmental transfer processes takes the form of a matrix of transfer coefficients that allow the compartmental amounts to be represented as a set of first order linear differential equations. For the i^{th} compartment, the rate at which the compartment inventory changes with time is given by:

$$\frac{dN_i}{dt} = \left(\sum_{j\neq i} \lambda_{ji} N_j + \lambda_N M_i + S_i(t)\right) - \left(\sum_{j\neq i} \lambda_{ij} N_i + \lambda_N N_i\right) \tag{47}$$

where

N_i is the activity of radionuclide N in biosphere compartment i (Bq);
M_i is the amount of radionuclide M in biosphere compartment i (M is the precursor radionuclide of N in a decay chain) (Bq);
$S_i(t)$ is an external source term of radionuclide N to compartment i (Bq y^{-1});
λ_N is the decay constant for radionuclide N (y^{-1});
λ_{ji} is the transfer coefficient to compartment i from compartment j or to sinks (y^{-1}).

The solution of the matrix of equations given above provides the time-dependent inventory of each compartment. Assumptions for compartment sizes then result in estimates of concentrations in the corresponding media. The transfer coefficients can represent the single or multi-phase movement of radionuclides. Examples are provided in publications such as [70], [71,72, 73].

Exposure mechanisms

Concentrations in biosphere media

For the purposes of long term assessments of radioactive waste disposal, as opposed to the short term routine/accidental discharge assessments, concentrations of radionuclides in certain biosphere media (for example crops and animals) can often be assumed to be in equilibrium with their donor media and their concentrations are assumed to be a linear function of the concentration in the donor media. Therefore, they and their associated FEPs do not need to be modelled dynamically using the first order differential equation given in Section 5.3, instead this equilibrium assumption is sufficient. For example, the concentration in a crop grown in the soil can be assumed to be in equilibrium with the concentration in the soil and any irrigation water applied. This approach is valid because the processes affecting the concentrations in such media are rapid compared with those affecting concentrations in the donor media, particularly because of the long term nature of the release.

Thus it is helpful to distinguish between media for which the temporal variation of radionuclide concentration needs to be calculated using the first order differential equation given in Section 5 (i.e. dynamic media – the "primary media" in (Fig. 28), and those for which the radionuclide concentration is a linear function of the concentration in the dynamically modelled media (i.e. equilibrium media – the "secondary media" in Fig. 28). Data for the derivation of this linear function are often derived from models and monitoring of current day releases into the environment.

This approach has been used in a large number of biosphere modelling studies, for example [77] and [76]. Two specific examples are given below, based on [75], for the calculation of radionuclide concentrations in crops and aquatic.

The radionuclide concentration in the edible part of the **crop** ($C_{crop,}$ Bq kg^{-1} (fresh weight of crop) is calculated using the following equation:

$$C_{crop} = \frac{(F_{p2}CF_{crop} + F_{p1}Soil_{plant})C_s}{(1-\theta_t)\rho} \tag{48}$$

where

F_{p2} is the fraction of the internal contamination associated with the edible part of the plant at harvest that is retained after food processing has occurred (–);

CF_{crop} is the concentration factor from root uptake to the edible portion of the plant (Bq kg^{-1} (fresh weight crop)/Bq kg^{-1} (dry weight soil));

F_{p1} is the fraction of external soil contamination on the edible part of the crop retained after food processing (–);

$Soil_{plant}$ is the soil contamination on the crop (kg (dry weight soil) kg^{-1} (fresh weight of crop));

C_s is the radionuclide concentration in the soil compartment (Bq m^{-3}).

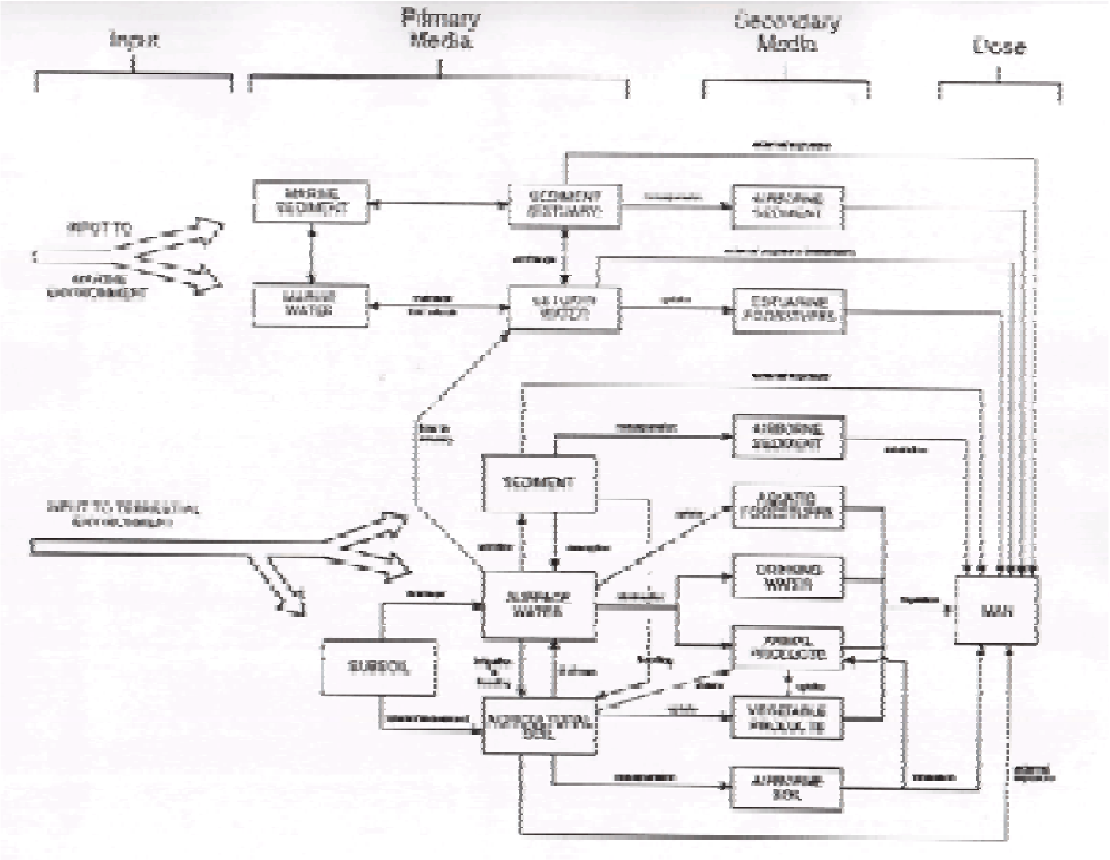


FIG. 28. Example Radionuclide Transport Pathways in the Biosphere and Associated Exposure Mechanisms (after [26]).

This particular model assumes that:

— the crop can be contaminated due to internal uptake of contaminants from the surface soil compartment into the crop via the roots (represented by the $\frac{CF_{crop}C_s}{(1-\theta_t)\rho}$ term);

— the crop can be contaminated due to external contamination of the crop due to deposition of re-suspended sediment from the surface soil compartment (represented by the $\frac{Soil_{plant}C_s}{(1-\theta_t)\rho}$ term);

— contamination can be lost due to food preparation (represented by F_{p1} and F_{p2} terms).

Extra terms can be added to represent other sources and losses of radionuclides such as contaminated irrigation water.

The radionuclide concentration of the **aquatic food** (C_{aqfood}, Bq kg^{-1}) is calculated using the following equation:

$$C_{aqfood} = FF_{Ls}C_{Ls}CF_{aqfood} \tag{49}$$

where

FF_{Ls} is the fraction of activity in the filtered lake water (–);
C_{Ls} is the radionuclide concentration in the surface water of the lake (Bq m^{-3});
CF_{aqfood} is the concentration factor for the aquatic foodstuff (Bq kg^{-1} (fresh weight of edible fraction)/Bq m^{-3} (filtered water)).

The FF_{Ls} term is calculated using:

$$FF_{Ls} = \frac{1}{1 + K_{dLb}\alpha_{Ls}} \tag{50}$$

where

K_{dLb} is the distribution coefficient for the lakebed sediment (m^3 kg^{-1});
α_{Ls} is the suspended sediment load in the surface water compartment of the lake (kg m^{-3})

Doses to Humans

Having determined radionuclide concentrations in the various media, it is possible to calculate the associated dose (D) using equations of the form:

$$D = C\,U\,DCF \tag{51}$$

where

C is the radionuclide concentration in the environmental media that acts as the source of contamination;
U is a use factor that describes the utilization rate of the media by human;
DCF is a dose conversion factor for the radionuclide and any shorted lived daughters[3].

In [76], the dose from a pathway p is expressed mathematically as:

$$D_p^{(N)}(t) = \sum_{i,\exp} E_p H_{\exp}^{(N)} P_{p,i} N_i(t) \tag{52}$$

where

D_p (N) is the effective dose (Sv y^{-1});
$N_i(t)$ is the amount of radionuclide in the physical media (Bq);
$P_{p,i}$ is the processing factor which transforms $N_i(t)$ into a concentration in pathway p;
E_p is an exposure factor for the pathway;
H_{exp} (N) is the dose per unit intake for radionuclide N.

Different approaches for the mathematical representation of the term $P_{p,i}$ are given in [76].

The dose calculations for safety assessment of near surface repositories practically are the same as usual methods of dose account for the public, estimated on recommendations the ICRP (for example [78–81]). The effective dose is usually used for safety assessment. According to the ICRP, the total dose (D, Sv y^{-1}) is sum of dose due to the external exposure (D_{ext}), the inhalation (D_{inh}) and the ingestion (D_{ing}) pathways:

---

[3] Daughter radionuclides with a half-life less than 25 days are often assumed to be in secular equilibrium with their parents. Their radiological effects, e.g., the dose per unit activity ingestion, are taken into account by adding them to those of their parents.

$$D = D_{ext}+D_{inh}+D_{ing}. \qquad (53)$$

Examples for ingestion, inhalation and external irradiation are given below based on [77]. Other examples are given in [75] and [76].

Ingestion

The annual individual dose from the consumption of a crop is given by:

$$D_{crop} = ING_{crop} DC_{ing} C_{crop} \qquad (54)$$

where

D_{crop} is the individual dose from consumption of the crop (Sv y^{-1});
ING_{crop} is the individual ingestion rate of the crop (kg y^{-1});
DC_{ing} is the dose coefficient for ingestion (Sv Bq^{-1});
C_{crop} is the radionuclide concentration in the edible part of the crop (Bq kg^{-1} (fresh weight of crop)).

The annual individual dose from the consumption of fish is given by:

$$D_{aqfood} = ING_{aqfood} DC_{ing} C_{aqfood} \qquad (55)$$

where

D_{aqfood} is the individual dose from consumption of the aquatic foodstuff (Sv y^{-1});
ING_{aqfood} is the individual consumption rate of the aquatic foodstuff (kg y^{-1});
C_{aqfood} is the radionuclide concentration of the aquatic food (Bq kg^{-1}).

Inhalation

The annual individual dose from the inhalation of dust, during occupancy of the soil compartment, is calculated for both normal and dusty conditions using:

$$D_{dust} = DC_{inh} BR\, O_s C_{airs} \qquad (56)$$

where

D_{dus} is the individual dose from the inhalation of dust (Sv y^{-1});
DC_{inh} is the dose coefficient for inhalation (Sv Bq^{-1});
BR is the breathing rate of the human in the soil compartment (m^3 h^{-1});
O_s is the individual occupancy in the soil compartment (h y^{-1});
C_{airs} is the radionuclide concentration in the air above the soil compartment (Bq m^{-3}).

External Irradiation

The annual individual dose from external irradiation from soil/sediment, during occupancy of the soil compartment, is given by:

$$D_{exsoil} = O_s DC_{exts} C_s \qquad (57)$$

where

D_{exsoil} is the individual dose from external irradiation from the soil (Sv y^{-1});
DC_{exts} is the dose factor for external irradiation from soil (Sv h^{-1}/Bq m^{-3});
C_s is the radionuclide concentration in the soil compartment (Bq m^{-3}).

Various modelling approaches are adopted for the simulation of the transfer of radionuclides through food chains. The most appropriate models to use depend on the particular application and on the desired endpoint of the assessment. Some models are designed to predict the time dependence of transfer or the total amount of activity transferred.

Multiplicative models use a series of factors to relate the levels of radioactivity in compartments to the food chain and human. The physical processes by which radionuclides are transferred through the food chains are very complex and it is often modelled by several compartments, each representing different parts of the food chain. Many dynamic compartmental models are used when the end point of the assessment relates to some parts of the food chain system. In other cases, the activity concentration in the food chain is derived assuming equilibrium with the abiotic compartments and constant transfers are used representing the transfer processes.

In BIOMOVS II TR12, the dose from a pathway p is expresses mathematically as:

$$D_p^{(N)}(t) = \sum_{i,\exp} E_p H_{\exp}^{(N)} P_{p,i} N_i(t) \tag{58}$$

where

D_p (N)	is the effective dose (Sv/y);
$N_i(t)$	is the amount of radionuclide in the physical media (Bq);
$P_{p,i}$	is the processing factor which transforms $N_i(t)$ into a concentration in pathway p;
E_p	is an exposure factor for the pathway;
H_{exp} (N)	is the dose per unit intake for radionuclide N.

Doses from human intrusion

As way of illustration, information is given below of the approach used in the USA to calculated doses from inadvertent human intrusion.

Intruder – Construction

The Intruder-Construction scenario assumes that an intruder constructs a house directly over a waste disposal site. The intruder is exposed to waste while excavating a basement for the house. The basement excavation is assumed to have a 200 m^2 base, to be 3 m deep, and to have 45 degree angled walls. Exposure was assumed to occur through inhalation of contaminated dust and external irradiation from contamination on the ground surface and resuspended in the air. The Intruder-Discovery scenario is the same as the Intruder-Construction scenario except that it is assumed to occur for a shorter time period. The time of the exposure is contracted because the intruder is assumed to leave the site when the waste is contacted and the hazardous nature of the site is realized.

The dose in the intruder-construction scenario is calculated as:

$$H = C_w \left[\sum_n \left(f_o f_d f_w f_s \right)_{air} PDCF\!-\!2 + \sum_n \left(f_o f_d f_w f_s \right)_{DG} PDCF\!-\!5 \right] \tag{59}$$

where

H	is the 50-year whole body dose equivalent (mSv y^{-1});
f_o	is the time delay factor;

f_d	is the site design and operation factor;
f_w	is the waste form and package factor
f_s	is the site selection factor for the air pathway (air) and external irradiation pathway (DG); and
PDCF	is the pathway dose conversion factor (Sv y^{-1} per Bq m^{-3}).

The time delay factor accounts for radioactive decay between disposal and the intrusion event and is calculated as:

$$f_o = e^{-\lambda t} \tag{60}$$

where

λ	is the radiological decay constant (y^{-1});
t	is the time elapsed between disposal and intrusion (y).

Intruder – Agriculture

The Intruder-Agriculture scenario is assumed to occur after the Intruder-Construction scenario. The Intruder-Agriculture Scenario assumes that the intruder lives in the house constructed on the site and produces agricultural products within the contaminated soil zone. In the intruder-agriculture scenario, the intruder is exposed through inhalation of contaminated dust, external irradiation from the ground surface and soil suspended in the air, and through ingestion of contaminated vegetables, meat, and milk. Consumption of contaminated groundwater was not included in the intruder scenarios, but was analysed separately. Groundwater pathway analysis often produces activity limits while intruder scenarios produce activity concentration limits. The dose in the intruder-agriculture scenario was calculated as:

$$H = C_w \left[\sum_n (f_o f_d f_w f_s)_{ait} \; PDCF{-}3 + \sum_n (f_o f_d f_w f_s)_{DG} \; PDCF{-}5 + \sum_n (f_o f_d f_w f_s)_{Food} \; PDCF{-}4 \right] \tag{61}$$

where

H	is the 50-year whole body dose equivalent (Sv y^{-1});
f_o	is the time delay factor;
f_d	is the site design and operation factor;
f_w	is the waste form and package factor;
f_s	is the site selection factor for the air pathway (air), external irradiation pathway (DG), and ingestion (Food) pathways;
PDCF	is the pathway dose conversion factor (Sv y^{-1} per Bq m^{-3}).

Drilling

In the post-drilling scenario an inadvertent intruder is assumed to drill through the disposal unit for the purpose of constructing a well, and all drilled waste is assumed to be mixed with native soil in the intruder's vegetable garden. The same pathways as in the agriculture scenario are considered except that the volume of waste mixed with the garden soil which is ten times inferior.

5.4. DATA FOR MODEL DEVELOPMENT

In the course of developing mathematical models, a list of parameters relevant to the calculation will be identified. Each of these, and their specific meaning within the context of the model, should be documented in order to provide a basis for establishing the necessary model input parameter databases. In order to allow the computer tools to be run, values for these input parameters need to be specified. Although data are particularly required following the development of the mathematical, as Fig. 8 shows, data are important at all stages of the model development process.

The quantity and quality of data required will depend on the purpose of the assessment and the stage in the life cycle of the disposal facility. Preliminary assessment will probably require only simple models using data that are readily available. While finalising the design and licensing certain stages of the disposal facility, the operator should support the application with an assessment based on large quantities of quality assured data describing the site, the design and the waste characteristics. Indeed, as part of the BIOMASS programme, work has been undertaken on the development of a formalized data protocol [82] (see Fig. 29). Although a quality assurance programme and procedures should be established and followed as early as possible in the process, it is recognized that a similar quantity and quality of data may not be necessary at an early stage in the design and scoping stages of the disposal facility.

An electronic database of parameter values can be useful for performance of safety assessment. For example, Ciemat (Spain) has developed the VALORA database [83], which stores information about the values, bibliographic sources and dependencies of parameters. It should be noted that the design of a parametric database is not a trivial issue due to the different possible dependencies of each parameter (for example on the radionuclide/element, and the transport media).

In specifying data, consideration should be given to the treatment of uncertainties associated with the parameter values. Uncertainties can arise due to a number of factors such as uncertainties in the measurement and derivation of values. There is also a need to consider any spatial and temporal variability of parameter values such as porosities and hydraulic conductivities. If the computer tools are to be used for probabilistic analysis (see Section 5), then parameter distributions need to be specified.

Below is information that has been collated for certain parameters commonly required by computer codes used in the assessment of near surface radioactive waste disposal facilities. It is presented here to illustrate the type of information and associated data that needs to be collated for an assessment. The list is not designed to be exhaustive, nor should the example data values given necessarily be seen as being recommended values. They are presented merely by way of illustration. Further example data are provided in the documentation of the ISAM Test Cases (Volume II). Information concerning data acquisition techniques used for a range of common parameters is given in Appendix G.

5.4.1. Near field data

Corrosion rate

The corrosion rate is the rate at which a waste drum corrodes, generally expressed as a loss if thickness of the drum per year.

In safety assessment studies corrosion rates of waste drums are used to determine the container lifetime. In the case of steel containers disposed in an anaerobic environment, the corrosion rate can also used to calculate the production of hydrogen by anaerobic corrosion. The corrosion rate of metals depends strongly on the chemical conditions in the waste repository such as pH, salinity, chloride concentration, the sulphate concentration, and oxygen concentration. Relevant data are provided in various references such as [38] and [84].

Release rate

The release rate is the quantity of a radionuclide or containment released per unit of time. It can also be expressed as the fraction of the initial or remaining inventory released per unit of time.

The release rate can thus be expressed in Bq y^{-1}, mol y^{-1} or y^{-1}. When it is expressed as a fraction, it is important to clearly indicate whether it is a fraction of the initial inventory or of the remaining inventory. The release fraction is in literature also sometimes indicated as ALF (annual leached fraction). Although the use of a release rate greatly facilitates the building of a source term model, it is very difficult to determine values for it. The value of the release rate will depend on the waste, the waste matrix, the packaging, the disposal facility and the climate conditions. Therefore no general values can be given for it.

In Table 11 example release coefficients for landfills for some elements are given. They are expressed as the ratio of the concentration in the leachate to the concentration in the waste.

TABLE 11. TYPICAL RELEASE COEFFICIENTS FOR LANDFILLS (AFTER [27])

Element	Release coefficient (kg m^{-3} leachate/kg m^{-3} waste)		
	Smith et al. (1988) [85]	Baccini et al. (1987) [86]	Ehrig (1989) [87]
Cd		1 E-4	3 E-3
Cl (unspecified)	5 E-2		
Cl^-		7 E-2	1.5
Organic Cl			2 E-3
Co	1 E-2		
Cu		3 E-4	7 E-4
Fe	1 E-2	1 E-4	
Hg		1 E-4	3 E-2
Ni	5 E-2		3 E-2
Pb	1 E-2	1 E-4	4 E-4
Se	1 E-2		
Sn	1 E-2		
Zn	1 E-2	3 E-4	2 E-3

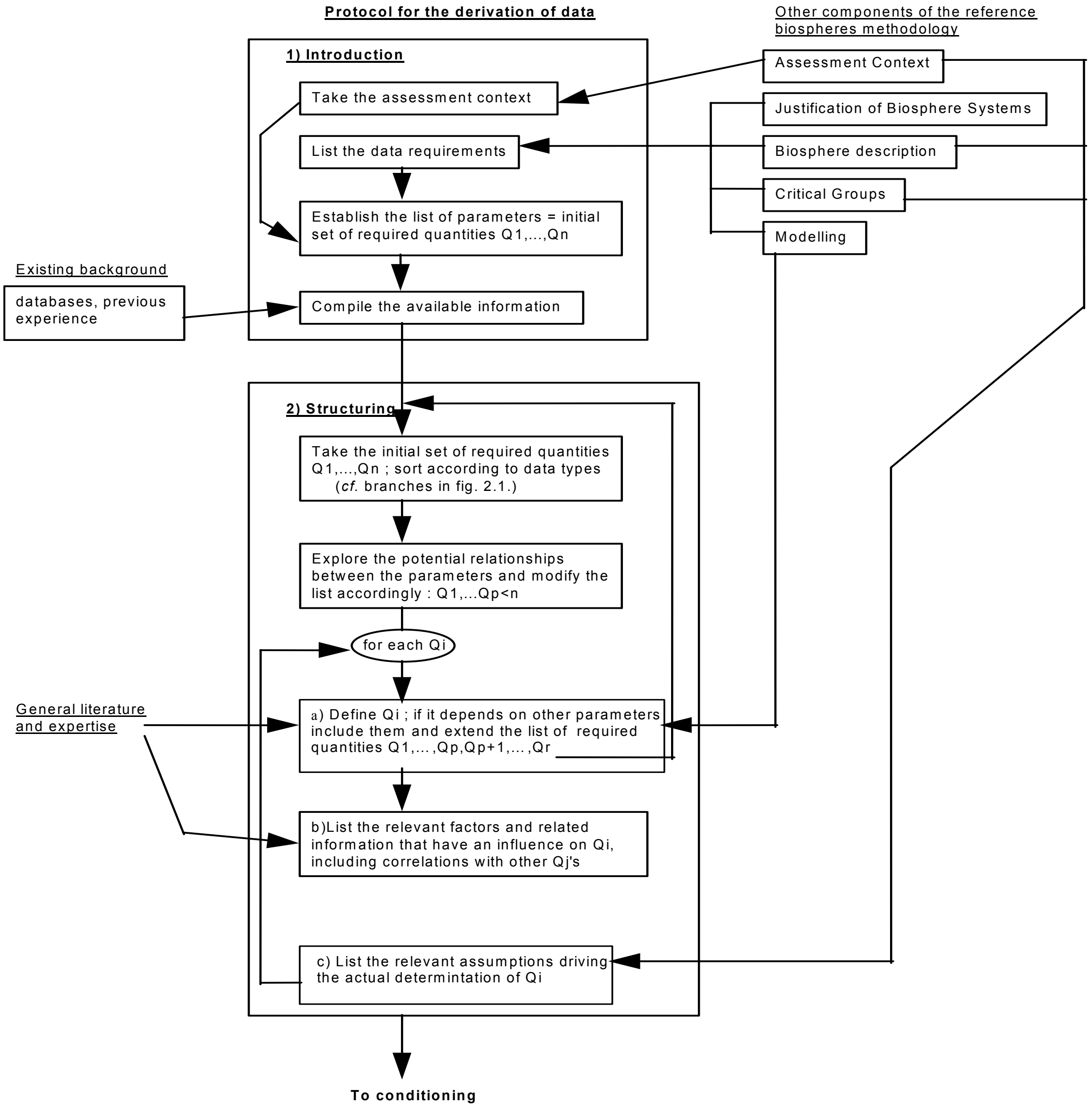


FIG. 29. The BIOMASS Theme 1 Data Protocol (after [82]).

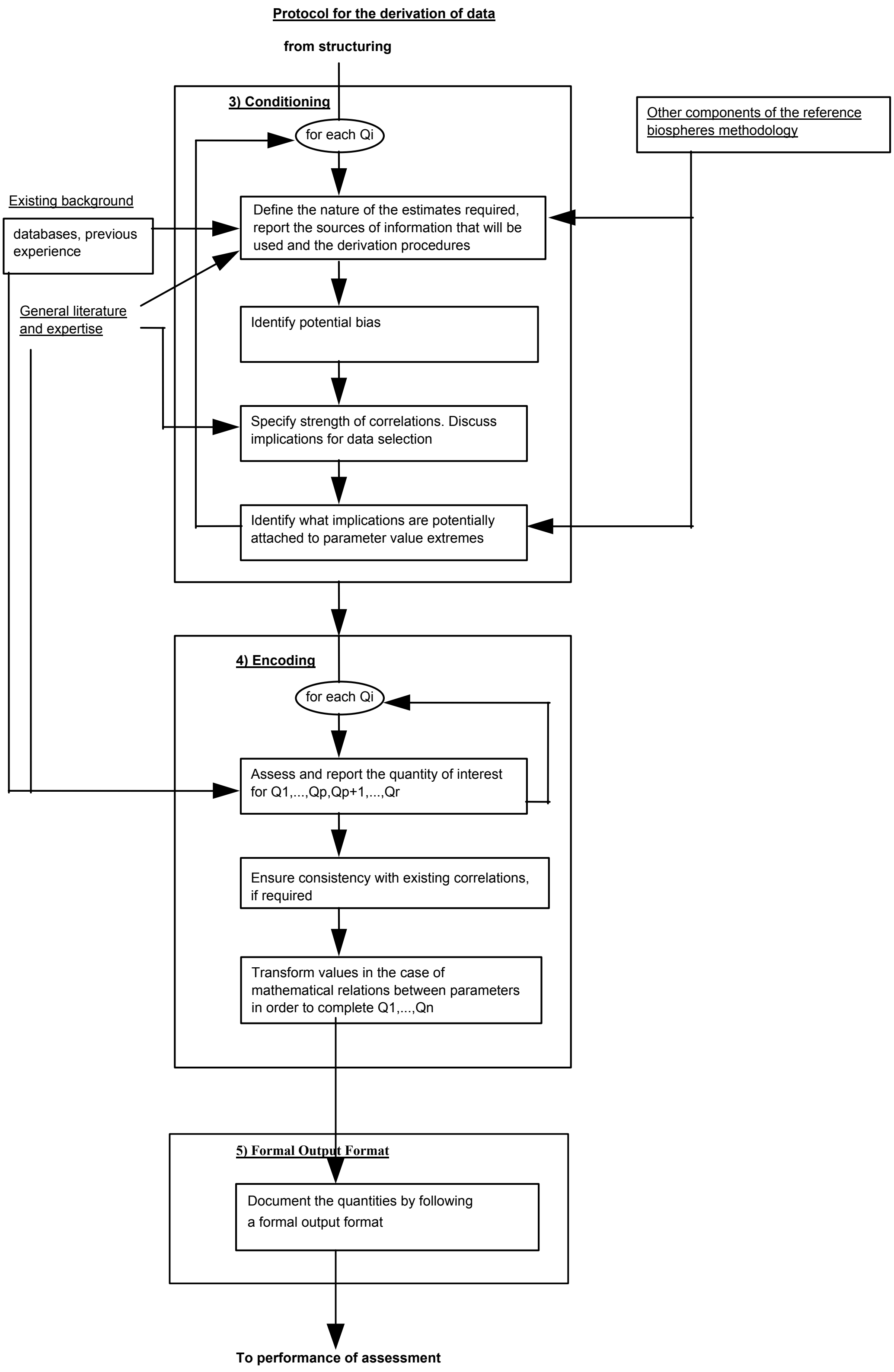


FIG. 29 (continued). The BIOMASS Theme 1 Data Protocol (after [82]).

Total porosity

The total porosity of a porous medium is the ratio of the pore volume to the total volume of a representative sample of the medium. Assuming that the porous medium is composed of three phases – solid, liquid (water), and gas (air) – where V_s is the volume of the solid phase, V_l is the of the liquid phase, V_g is the volume of the gaseous phase, $V_p = V_l + V_g$ is the volume of the pores, and $V_t = V_s + V_l + V_g$ is the total volume of the sample, then the total porosity of the soil sample is defined as: V_p / V_t.

Effective porosity

The effective porosity is the ratio of the volume of interconnected pore spaces available for transport to the total system volume. It is used to estimate the velocity at which ground water and radionuclides travel through a porous medium.

Density

Density, as applied to any kind single phase material of mass M and volume V, is expressed as the ratio of M and V. Under specified conditions, this definition leads to unique values that represent a well-defined property of the material. For heterogeneous and multi-phase materials, however, such as porous media, application of this definition can lead to different results, depending on the exact way the mass and volume of the system are defined.

A typical heterogeneous multi-phase porous system in its general form contains three natural phases: (1) the solid phase or the matrix; (2) the liquid phase; and (3) the gaseous phase, which contains air and other gases. In this three-phase porous system, the concept of average density can be used to define the following densities: (1) density of solids or soil particle density, ρ_g; (2) bulk or dry density, ρ_b; and (3) total or wet density, ρ_t.

The masses and volumes associated with the three phases must be defined before the definitions of the different densities that characterize the porous system can be formalized. Thus, considering a representative elementary volume (REV) of the porous medium the masses of the phases composing the medium can be defined as follows:

M_s = the mass of solids,

M_l = the mass of liquids,

M_g = the mass of gases negligible compared with the masses of the solid and liquid phases),

and

$M_t = M_s + M_l$ = the total mass.

Similarly, within the REV, the volumes associated with the porous medium phases can be defined as follows:

V_s = the volume of solids,

V_l = the volume of liquids,

V_g = the volume of gases,

$V_p = V_l + V_g$ = the volume of pore space, and

$V_t = V_s + V_l + V_g$ = the total volume.

These mass and volume definitions can be used to define the concepts of grain or particle density, bulk (dry) density, and total (wet) density. The dimensional unit of density is mass per unit of cubic length (kg/m^3).

— Grain (particle) density

The grain (particle) density, ρ_g, or the density of solids, represents the density of the mineral particles collectively and is expressed as the ratio of the solid phase mass to the volume of the solid phase of the porous medium, i.e.:

$$\rho_g = M_s / V_s \tag{62}$$

— Bulk (dry) density

The bulk or dry density, ρ_b, is the ratio of the mass of the solid phase of the soil (e.g. dried soil) to its total volume (solid and pore volumes together) and is defined as follows.

$$\rho_b = M_s / V_t \tag{63}$$

The bulk density is related to the grain density by the total porosity, ρ_t, according to the following equation:

$$\rho_\beta = \rho_\sigma (1 - \rho_\tau) \tag{64}$$

where

$1 - \rho_t$ is the ratio of the solid volume (V_s) to the total volume ($V_s + V_l + V_g$).

From the above definition, it is clear that the value of the dry density is always smaller than the value of the grain density. For example, if the volume of the pores ($V_l + V_g$) occupies half of the total volume, the value of dry density is half the value of the grain density.

Distribution coefficient

The distribution or sorption coefficient, K_d , is the ratio of the mass of solute species adsorbed or precipitated on the solids per unit of dry mass of the porous medium, S, to the solute concentration in the liquids, C. The distribution coefficient represents the partition of the solute in the matrix and pore water, assuming that equilibrium conditions exist between the solid and solution phases. A linear Freundlich isotherm, which assumes complete reversibility on ion adsorption, has been extensively used to correlate the relationship between S and C, that is:

$$S = K_d C \tag{65}$$

The transfer of radionuclides from the liquid to the solid phase or vice versa may be controlled by mechanisms such as adsorption, ion exchange and precipitation, depending on the radionuclides. The dimensions of the distribution coefficient are given in units of length cubed per mass ($L^3 M^{-1}$).

Cement based grouts or concrete is a commonly used waste matrix and engineered barrier material. An extensive study of sorption on cementitious materials has been performed [88], [89]. K_d values are given for an extensive list of elements, for three pH regions and for both oxidising and reducing conditions (see Table 12). The pH regions correspond with different phases in concrete ageing and are defined as follows [90] and [91].

TABLE 12. DISTRIBUTION COEFFICIENTS (IN M^3 KG^{-1}) FOR CEMENTITIOUS MATERIALS (AFTER [89])

Element	State of cement degradation Region 1		region 2		region 3	
	oxic	reducing	oxic	reducing	oxic	reducing
H(HTO)	0	0	0	0	0	0
C ($CO3^{2-}$)	*	*	*	*	*	*
CI	5E-03	5E-03	5E-03	5E-03	5E-04	5E-04
K	0	0	1E-04	1E-04	1E-04	1E-04
Co	1E-01	1E-01	1E-01	1E-01	1E-02	1E-02
Ni	1E-01	1E-01	1E-01	1E-01	1E-02	1E-02
Se	0	0	0	0	0	0
Sr	1E-03	1E-03	1E-03	1E-03	1E-03	1E-03
Zr	5E+00	5E+00	5E+00	5E+00	1E+00	1E+00
Nb	1E+00	1E+00	1E+00	1E+00	1E-01	1E-01
Mo	0	0	0	0	0	0
Tc	1E-03	1E+00	1E-03	1e+00	0	1E-01
Pb	1E-01	1E-01	1E-01	1E-01	1E-02	1E-02
Ag(NaHCO3)	1E-03	1E-03	1E-03	1E-03	1E-03	1E-03
Sn	1E+00	1E+00	1E+00	1E+00	1E-01	1E-01
I	1E-02	1E-02	1E-02	1E-02	1E-03	1E-03
Cs	2E-03	2E-03	2E-02	2E-02	2E-02	2E-02
Pb	5E-01	5E-01	5E-01	5E-01	5E-02	5E-02
Po	0	0	0	0	0	0
Ra	5E-02	5E-02	5E-02	5E-02	5E-02	5E-02
Ac	1E+00	1E+00	1E+00	1E+00	2E-01	2E-01
Th	5E+00	5E+00	5E+00	5E+00	1E+00	1E+00
Pa	5E+00	5E+00	5E+00	5E+00	1E-01	1E+00
U	2E+00	5E+00	2E+00	5E+00	1E-01	1E+00
Np	5E+00	5E+00	5E+00	5E+00	1E-01	1E+00
Pu	5E+00	5E+00	5E+00	5E+00	1E+00	1E+00
Am	1E+00	1E+00	1E+00	1E+00	2E-01	2E-01
Cm	1E+00	1E+00	1E+00	1E+00	2E-01	2E-01

* Generally, very high "sorption" of C-14 as $^{14}Co_3^{2-}$ (~10 m^3 kg^{-1}) in cement/concrete have been reported. It is suggested that in these experiments sorption, in its usual meaning, is not being measured [89]. According to them isotopic exchange of $^{14}Co_3^{2-}$ with the finely dispersed solid carbonate phase is the main mechanism. They propose to use an effective distribution coefficient that is defined as the ratio of the inactive carbon (mol kg^{-1}) present as finely distributed carbonate, and the concentration of CO_3^{2-} in solution in the pore water (mol l^{-1}) as determined by the solubility limit of $CaCO_3$.

(1) Region 1 (fresh concrete)

The pH lies between ~13.3 and 12.5. The pore water composition is dominated by (K, Na) OH. The solution is saturated with respect to portlandite ($Ca(OH)_2$ ~2.10^{-3} M). The major solid phases present in cement have already formed, though hydration may be continuing.

(2) Region 2 (hardened, non-degraded concrete)

Contact with “flowing” water has removed virtually all of the highly soluble (K, Na) OH. The pore water composition is now dominated by portlandite ($Ca(OH)_2$ ~2.10^{-2} M), and has a pH of ~12.5. The portlandite is also being slowly removed by water flow but the quantities contained in the cement are so large that this phase buffers the system over very long periods of time. There are no significant changes in the major solid phases present in the region 1 and 2.

(3) Region 3 (degraded concrete)

The removal of Ca $(OH)_2$ has become significant and the pH falls continuously. The CSH (calcium-silica-gel) gel is no longer stable and begins to dissolve incongruently. The Ca^{2+} concentration decreases continuously to ~1 to 5. 10^{-3} M at pH ~11.

Tables 13 and 14 present further example K_d values for a range of elements and media.

TABLE 13. BEST ESTIMATE VALUES FOR DISTRIBUTION COEFFICIENT FOR VARIOUS MEDIA (AFTER [90])

Element	K_d (m^3 kg^{-1})			
	Concrete container	Grout	Engineered Damage Zone	Granite
C	2^*	2^*	0.0001^*	0.0001^*
Ni	0.1^*	0.1^*	0.001^{**}	0.001^{**}
Sr	0.0023^{**}	0.0023^{**}	0.005^{**}	0.005^{**}
Nb	0.0016^*	0.0016^*	0.00001^*	0.00001^*
I	0.0048^*	0.0048^*	0^*	0^*
Cs	0.001^{**}	0.001^{**}	0.1^{**}	0.1^{**}
U	2^*	2^*	0.1^{**}	0.1^{**}
Pu	2^*	2^*	0.5^{**}	0.5^{**}
Am	2^*	2^*	0.05^{**}	0.04^{**}

* anion
** non-anion

TABLE 14. DISTRIBUTION COEFFICIENTS FOR BENTONITE

Element	Batch K_d Values ($m^3\ kg^{-1}$) Realistic	conservative	Batch to in situ K_d value conversion factors
C	0	0	1
Cl	0	0	1
Ni	1	0.1	1
Se	0.005	0.001	1
Sr	1	0.1	0.01
Zr	1	0.1	1
Nb	1	0.1	1
Tc	0.1	0.05	1
Pd	1	0.1	1
Sn	1	0.1	1
I	0.005	0	1
Cs	1	0.1	0.01
Pb	1	0.1	0.01
Ra	1	0.1	0.01
Ac	5	0.5	1
Th	5	0.5	1
Pa	1	0.1	1
U	5	0.5	1
Np	5	0.5	1
Pu	5	0.5	1
Am	5	0.5	1
Cm	5	0.5	1

Diffusion coefficient

Diffusion is the movement of atoms or molecules in gas, liquid or solid from a region of higher concentration of the species to regions of lower concentration. It is independent of the fluid motion and usually is represented by Fick's Law:

$$F = -D\,\partial C/\partial X \tag{66}$$

where

D is the molecular (or atom) diffusivity or the diffusion coefficient in units of $L^2\ T^{-1}$.

In a porous medium the particles (molecules or atoms) can only move in the pores. As these pores form complex and tortuous pathways, diffusion through them will be slower than diffusion in a free phase. While for the diffusion coefficient in a free phase there exists a generally accepted definition (given above), several expressions exist for the diffusion coefficient in a porous medium (see for example [92]). Tables 15 and 16 present some diffusion coefficients for elements in pore water and air, respectively.

TABLE 15. BEST ESTIMATE VALUES FOR PORE WATER DIFFUSION COEFFICIENT (D_P) AND EFFECTIVE DIFFUSION COEFFICIENT (D_E)

Element	D_p (m^2 s^{-1})			D_e (m^2 s^{-1})
	Concrete container	Grout	EDZ	Granite
C	1E-11	2E-11	2E-14	1E-15
Ni	1E-11	2E-11	2E-13	1E-14
Sr	1E-11	2E-11	2E-13	1E-14
Nb	1E-11	2E-11	2E-13	1E-15
I	1E-11	2E-11	2E-14	1E-15
Cs	1E-11	2E-11	2E-13	1E-14
U	1E-11	2E-11	2E-13	1E-14
Pu	1E-11	2E-11	2E-13	1E-14
Am	1E-11	2E-11	2E-13	1E-14

TABLE 16. DIFFUSION COEFFICIENTS IN AIR OF VOLATILE SPECIES PRODUCED BY RADIOACTIVE WASTE

Gaseous Species	Diffusion Coefficient in Air (m^2 s^{-1})	Source
H_2O	2.4E-5	[93]
CO_2	1.4E-5	[93]
Rn	1.1E-5	[94]

Solubility

The solubility can be defined as the maximum total concentration of an element is solution under the governing chemical conditions. It is generally expressed in M L^{-1}. The solubility of elements generally depends on pH, Eh and the presence of complexing agents.

In Table 17 solubility ranges and the expected controlling solid phase and dominant phase in solution are given for a concrete environment (Eh < - 200 mV, pH > 11).

TABLE 17. SOLUBILITY LIMITS FOR CONCRETE ENVIRONMENT [BASED ON 95]

Element	Most probable Stable solid phase	Most probable dominating species	Solubility limit (mole l^{-1})
Ag	Ag	-	Practically Insoluble
Al	$AL(OH)_3.nH_2O$	AlO_2	2.40E-03
B	H_3BO_3	$H_2BO_3^-,HBO_3^{2-}$	1.00E-02
Ba	$BaSO_4$	Ba^{2+}	1.00E-05
Be	$Be(OH)_2,BeO$	$Be_2O_3^{2-}$	9.89E-5 to9.89E-11
C	CaCO3	CO_3^{2-}	1E-4 to 3E-5
Ca	$Ca(OH)_2$	Ca^{2+}	1E-2 to 1E-3
Cd	$CdCO_3CdS$	CdO_2^{2-}	2.60E-06
C1	NaCl	Cl^-	Very Soluble
Co	$Co(OH)_2$	$HcoO_2$	1E-3 to 3E-9
Cr	$Cr(OH)_3,nH_2O$	$Cr^{3+}CrO_4^{2-}Cr_2O_7^{2-}$	5E-6 to 3E-9
Cu	Cu,CuS	$Cu^{2+},HcuO_2^-$	max.1E-7
F	CaF_2	F^-	4.00E-04
Fe	Fe_2O_3	Fe^{2+},Fe^{3+}	1.5E-4 to 4.8E-12
Ga	$Ga(OH)_3$	$HgaO_3^-,GaO_3^{3-}$	7.68E-11 to 2.13E-8
H	-	H_2O	Very Soluble
Hf	$HfO_2.H_2O$	HfO_2^+	Practically Insoluble
Hg	Hg	$HhgO_2^-$	2E-4 to 8.8E-13
I	AgI	I^-	Very Soluble
K	KOH	K^+	Very Soluble
Mg	$MgCo_3,MgO_2$	Mg^{2+}	3.67E-5 to 3.67E-11
Mn	$Mn(OH)_2$, $MnCO_3$	$Mn^{2+},Mn(OH)_3$	1.3E-3 to 3.23E-6
Mo	-	MoO_4^{2-}	Very Soluble (1E-2)
N	-	NH_4^+	Very Soluble
Na	NaOH	Na^+	Very Soluble
Nb	Nb_2O_5	$Nb(OH)_6^-$	1E-2 to 1E-7
Ni	$Ni(OH)_2$	$Ni(OH)_2,HniO_2^-$	2E-4 to 3E-8
O	-	-	N.A.
P	$Ca_3(PO4)_2$	HPO_4^{2-},PO_4^{3-}	1.30E-04
Pb	PbO	$HpbO_2^-$	4.5E-3 to 1.82E-8
Pt	Pt, PtS	Pt,PtS	Insoluble
S	$CaSO_4.2H_2O$	SO_4^{2-}	Low Solubility
Sb	Sb_2O_5,Sb_2O_3	$SB(OH)_6^-,SbO_2^-$	1.00E-04
Si	SiO_2	$SiO_3^{2-},HsiO_3^-$	1.3E-5 to 1.3E-7
Sn	SnO,SnO_2	$SnO_3^{2-},Sn(OH)_3$	5E-3 to 3E-5
Sr	SrCO3	$Sr^{2+},SrOh^+$	1.00E-04
Ti	TiO_2	-	Insoluble
U	UO_2	$UO_2(CO)_3^{4-}$	3E-2 to 3.6E-6
W	WO_3	WO_4^{2-}	Very Soluble
Zn	$Zn(OH)_2$	$HznO_2^-$	max 1E-3
Zr	$ZrO_2.2H_2O$	$Zr(OH)_5^-$	1E-7 to 2E-9

Hydraulic Parameters

Hydraulic conductivity is the ratio of the Darcy velocity to the head gradient for viscous flow of a fluid in a porous medium.

In Table 18, an overview is given of the range of hydraulic conductivity and porosities for different unconsolidated media. Table 19 summarized hydraulic conductivity and other parameters required for the van Genuchten equations that were used in NSARS Test Case 2C [96].

TABLE 18. HYDRAULIC CONDUCTIVITIES AND POROSITIES FOR DIFFERENT UNCONSOLIDATED MEDIA

K (m s^{-1})			10	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}
grain-size	Homogeneous	pure gravel			pure sand			fine sand			silt		clay		
	Heterogeneous	coarse and medium gravel			gravel and sand		sand, loam and clay								
porosity (%)		37-25			45-30			23			61-34		60-34		
effective porosity (%)		24			27			23			8		3		

TABLE 19. HYDRAULIC PARAMETERS FOR SOME MATERIALS CONSIDERED IN THE NSARS TEST CASE 2C

Material	Saturated Moisture Content	Residual Moisture Content	Saturated Hydraulic Conductivity (m s^{-1})	Parameter □	Parameter □
grouted waste (0 – 500 y)	0.5	0.4	1E-8	4.41	7.36E-8
grouted waste (>500 y)	0.38	0.04	5E-5	2.43	1.55E-3
trench waste	0.30	0.07	1E-5	1.08	6.03E-5
clayey sand and sandy clay	0.30	0.07	1E-7	1.08	6.0E-5
clay	0.39	0.11	1E-10	1.33	8.0E-6
concrete (0 – 200 y)	0.15	0.12	1E-10	1.57	7.0E-9
concrete (200 – 500 y)	0.15	0.12	1E-8	1.57	7.0E-9
concrete (>500 y)	0.38	0.07	5E-5	2.43	1.55E-4
sand	0.38	0.07	5E-5	2.43	1.55E-4

5.4.2. Geosphere data

Infiltration or net precipitation

Infiltration or net precipitation is the amount of precipitation, which infiltrates through the surface. It is the difference between the total precipitation and the sum of the evapotranspiration and the surface runoff.

Precipitation is a meteorological term that refers to the total amount of water (rain, snow, etc) that falls on a site.

Evaporation is the net transfer of water from the liquid phase to the vapour one. Transpiration is the process by means of which plants remove moisture from the soil and release it to the atmosphere as vapour. Evapotranspiration, a combination of the above two processes, is the term used to describe the total water removal from an area partly covered by transpiration, evaporation from soil (actually from the water present in the void space of unsaturated soil), from snow, and from open water surfaces lakes, streams, and reservoirs). The runoff is the amount of precipitation that runs of a site (to e. g. a river or a lake) without infiltration into the soil.

Hydraulic conductivity

Hydraulic conductivity has been defined and data provided for unconsolidated media in Section 5.2.

Dispersion

Dispersion coefficients are very difficult to measure in the field and have been shown generally to increase with scale of observation. Thus a dispersivity deduced from a bench-scale column experiment can be expected to be less than a dispersivity that will match data at a larger scale, either in the laboratory or in the field. These difficulties are generally addressed by using dispersivity values from the published literature and refining these estimates during the model calibration process.

As shown before, the hydrodynamic dispersion is composed of two processes: mechanical dispersion (D_m) and molecular diffusion (D_o):

$$D = D_m + D_o \tag{67}$$

The mechanical dispersion (D_m) is consequence of the variation of the fluid velocity in the medium due to the pore size, friction, etc. and can be represented by:

$$D_m = \alpha V \tag{68}$$

Where α is a parameter known as dispersivity or dispersion length given in meters (m). Bellow some empirical formulas for dispersivity calculation from Neuman [97] are given below.

Based on field data [98], [99], a general approximation that is frequently used is that the longitudinal (in the direction of groundwater flow) dispersivity (α_L) is set to one-tenth of the scale of the problem [100]. A more refined approach that takes into account the scale of the problem has also been suggested [97]:

$$L < 100\ m:\ \alpha_L = 0.0017\ L^{1.5} \tag{69}$$

$$L > 100\ m:\ \alpha_L = 0.32\ L^{0.83}$$

where

L is the travel distance (m);
α_L is the longitudinal dispersivity (m).

Dispersion in an aquifer is in fact a three dimensional phenomenon and has to be represented by a tensor with three principal components, i.e. the longitudinal (α_L), horizontal (α_T) and vertical dispersion (α_V). On the basis of a recent literature review it has been concluded that the best estimate of the ratio of $\alpha_{L:}$ $\alpha_{T:}$ α_V /a/a_v is 1:0.2:0.0087.

Dispersivities have been observed to increase with increasing scale of the problem to which they are applied. This behaviour is extremely important in terms of practical applications of performance assessment; it means that dispersivities, easily measured at the bench scale, do not apply at the scale of interest. The only way to ensure that a dispersivity is appropriate for a particular scale is to calibrate the dispersivity using an existing plume. This calibrated dispersivity can be expected to reproduce similar plumes on the same scale, but cannot be extrapolated with confidence to other conditions or scales. Since tracer tests are often impractical at waste disposal sites, and are always expensive, this means that values for dispersivity that are considered accurate will usually be unavailable to the analyst.

In the absence of a site- and scale-specific dispersivity, a general approximation is frequently used, in which the longitudinal dispersivity is set to one-tenth of the scale of the problem [100]. This approximation is usually cited to have justification in the compilation of existing field-scale dispersion data by Gelhar et al. [98, 99] and a related attempt by Neuman [97] to develop a "universal' scaling for dispersivities. We note that neither Gelhar et al. nor Neuman suggested that the one-tenth rule was appropriate.

Indeed, Gelhar et al. criticised the idea that any universal regression fit would be appropriate. It can be noted that even a cursory examination of the data cited by Gelhar et al. [98] illustrates orders of magnitude variation in dispersivities about a regression line.

This discussion holds important implications for practical application of performance assessments. Site specific data on dispersion is a rarity when one is conducting a performance assessment. This means that dispersivities must be assumed for the sake of the analysis, but that there is no general way to choose them. Consequently, dispersivity should be considered to be highly uncertain, and should be varied over wide ranges to determine the importance of this parameter to the analysis.

5.4.3. Biosphere data

Transfer factors

Transfer factors can in general be defined as the fraction of the radionuclide concentration in one biosphere compartment (e.g. soil, root zone), which is at equilibrium transferred to another biosphere compartment (e.g. plant). A useful compilation of transfer factors and other related parameters is provided in [101].

Distribution coefficient

An extensive review of K_d's for four different soil types is given in [101]. The median K_d values from [101] are given in Table 20. Because of its dependence on many soil properties, the value of the distribution coefficient for a specific radionuclide in soils can range over several orders of magnitude under different conditions.

TABLE 20. MEDIAN VALUES FOR DISTRIBUTION COEFFICIENTS FOR DIFFERENT SOIL TYPES IN ML G^{-1} (AFTER [101])

Element	Sand	Loam	Clay	Organic
Am	1900	9600	8400	112000
C	5	2	1	70
Cl	0.8	0.25	4.4	11.3
Cs	280	4600	1900	270
I	1	5	1	25
Nb	160	550	900	2000
Ni	400	300	650	1100
Np	5	25	55	1200
Pd	55	180	270	670
Pu	550	1200	5100	1900
Ra	500	36000	9100	2400
Se	150	500	740	1800
Sn	130	450	670	1600
Sr	15	20	110	150
Tc	0.1	0.1	1	1
Th	3200	3300	5800	89000
U	35	15	1600	410
Zr	60	2200	3300	7300

Consumption rates, local production fractions, exposure times

Consumption rates of food products, local production fractions and exposure times depend very strongly on the local habits in a region, therefore no values are given here. In many countries, present-day values for these parameters can be obtained from the national institutes for statistics which keep records of the national agricultural production, life habits and land use.

Dose conversion factors

Dose conversion factors are the proportionality factors between a unit exposure to a radionuclide by intake, inhalation or direct irradiation and the effective dose. Factors for ingestion and inhalation are given in [102] consistent with the ICRP Publication 60 dose definition [80]. External irradiation factors can be obtained from http://tis.eh.doe.gov/oepa/risk/ which sets out exposure data, and additionally reports values for dosimetric data based on the ICRP Publication 60 dose definition.

Human intrusion

Parameters values used by the USNRC for analysis of intruder-construction and intruder-agriculture scenarios are presented in Tables 21 and 22.

TABLE 21. PARAMETER VALUES USED FOR THE ANALYSIS OF AN INTRUDER-CONSTRUCTION SCENARIO

Parameter	**Intruder-Construction**
Exposure Duration	500 hours
Volume of Intruder Excavation	906 m^3 (3 m Deep Basement for a 200 m^2 House)
Volume of Cover Excavated	675 m^3 (2 Meter Soil Cover)
Volume of Waste Excavated	232 m^3 (3 Meter Deep Excavation)
Soil Mass Loading in Air	0.565 μg m^{-3}
Time of intrusion	100 y Unstabilized Waste 500 y Stabilized Waste with Intruder Barriers
Site design and operation factor	0.5 Randomly Dumped Containers 0.75 Regularly Stacked Containers 0.5 Uncontainerized Waste
Waste form and package factor f_w (Air Pathway)	Unstabilized Waste 1E-6 Activated Metal
Waste form and package factor fw (External Irradiation Pathway)	Unstabilized Waste 0.08 Activated Metal
Site selection factor (Air Pathway)	0.057 (500 h y^{-1})
Site selection factor (External Irradiation Pathway)	2.01E-11

TABLE 22. PARAMETER VALUES USED FOR THE ANALYSIS OF AN INTRUDER-AGRICULTURE SCENARIO

Parameter	**Intruder-Agriculture**
Exposure Duration	6180 h y^{-1}
Time Indoors at Home	4380 h y^{-1}
Time Outdoors at Home	1700 h y^{-1}
Time Gardening at Home	100 h y^{-1}
Time Away from Home	2580 h y^{-1}
Area of Contaminated Zone	1750 m^2
Outdoor Soil Mass Loading in Air	0.1 μg m^{-3}
Indoor Soil Mass Loading in Air	0.05 :μg m^{-3}
Gardening Soil Mass Loading in Air	0.565 μg m^{-3}
Time of intrusion	100 y Unstabilized Waste 500 y Stabilized Waste with Intruder Barriers
Site design and operation factor (All Pathways)	0.125 Randomly Dumped Containers 0.188 Regularly Stacked Containers 0.125 Uncontainerized Waste
Waste form and package factor (Air Pathway)	Unstabilized Waste 1E-6 Activated Metal
Waste form and package factor (External Irradiation Pathway)	Unstabilized Waste 0.08 Activated Metal
Waste form and package factor (Ingestion Pathway)	1.0 Unstabilized Waste
Site selection factor (Air Pathway)	3.81E-11
Site selection factor (Ingestion Pathway)	0.5 (Fraction of Food Contaminated)
Site selection factor (External Irradiation Pathway)	0.27
Annual Vegetable Consumption	190 kg y^{-1} (wet mass)
Annual Meat Consumption	95 kg y^{-1} (wet mass)
Annual Milk Consumption	0.1 m^{-3} y^{-1}
Cow Fodder Consumption	50 kg y^{-1} (wet mass)

Soil densities

In sandy soils, dry bulk density can be as high as 1600 kg m^{-3}, in clayey soils and aggregated loams, it can be as low as 1100 kg m^{-3}. In most mineral soils, the soil particle density has a short range of 2600 – 2700 kg m^{-3}. This density is close to that of quartz, which is usually the predominant constituent of sandy soils. A typical value of 2650 kg m^{-3} has been suggested to characterize the soil particle density of a general mineral soil. Aluminosilicate clay minerals have particle density variations in the same range. The presence of iron oxides and other heavy minerals increases the value of the soil particle density. The presence of solid organic materials in the soil decreases the value.

5.5. COMPUTER TOOLS

As noted above, solution of the mathematical models is usually achieved by implementing one or more computer tools using the analytic and/or numerical techniques considered in Section 5.5. These tools may be proprietary tools and/or tools specifically developed for implementation of the chosen mathematical models. In either case, it is necessary to consider the associated process of software design, based on a given mathematical specification involves giving consideration to relevant data and process structures and developing appropriate solution algorithms. Software design should properly be conducted within an appropriate software quality assurance system in order to provide an audit trail for the software tool that is ultimately developed.

If there is only a limited set of conceptual and mathematical models to be represented, it may be possible to use one computer tool. However, if models differ markedly in terms of the processes or level of detail represented, it is often not desirable or feasible to use a single tool. Instead specific tools for individual sub-models can be used. This approach allows flexibility and the concentration of effort on those parts of the system that need more sophisticated modelling in order to ensure that the results are technically acceptable. The benefits of this approach can be significant when sophisticated models are used to provide added assurance that the disposal system will perform in an acceptable manner.

However, care should be taken to ensure that the transfer of information between the tools representing the different sub-models is well managed and that consistent interfaces between sub-models are specified. For example, when modelling the geosphere it is important to consider both internal processes (e.g. advection, dispersion, retardation) and external processes associated with the near field and biosphere that can influence water flow and chemistry in the geosphere. Decoupling the one component from the other components of the disposal system should be undertaken with caution.

When selecting one or more computer codes for use in an assessment, there is a need to ensure that the tool used is fit for the purpose of the assessment and its intended use. Factors to consider include: the assessment context (scoping vs. detailed calculations); resource availability (time, money and data); and the relative importance of the processes to be modelled.

A large number of computer tools have been developed for safety assessment. For example, 320 codes are identified in [103] covering the following topics: radionuclide inventory, corrosion, leaching, geochemistry, geomechanics, heat transfer, groundwater flow, radionuclide migration, biosphere modelling, safety assessment and site evolution. Another useful compilation of codes is provided in [104]. Additional information was collected from the documentation of other computer codes, where possible, the most recently available publicly available information was reviewed. In the review, the computer codes were grouped into four categories [104]:

- near field (source term) codes;
- far field (geosphere) codes;
- biosphere codes; and
- system-level (integrated) codes.

A list of example computer codes relevant to the assessment of LLW disposal facilities is provided in Table 23.

TABLE 23. EXAMPLE CODES USED FOR THE SAFETY ASSESSMENT OF LLW

Near field	Geosphere	Biosphere	System level
BARRIER	DRAF	GENII	AMBER
DUST	FEMWATER	RESRAD	PRESTO-EPA-CPG
HELP	GRDFLX	TAME	GTM-1
SOURCE1 and SOURCE2	MIGRAD		GOLDSIM
UNSAT-H	MODFLOW-96		
	PORFLO		
	TOUGH2		
	VAM2D		

In following sub-sections are the codes briefly described and evaluated from the point of view of input data requirements. More detailed information is provided in Appendix F.

5.5.1. Near field (source term) codes

Near field computer codes require varying levels of detail for waste form data, depending on the processes being modelled.

Three types of waste form data are generally required for each code: physical description; chemical and radiological description. Physical description includes such data as physical form (e.g., rags, concrete, activated metals), type of containers, dimensions of waste form or container, and volume of waste. Chemical and radiological description includes such data as inventories, solubilities, half-lives, pH, redox parameters, and major and minor ion concentrations. Physical properties include such data as saturated hydraulic conductivity, density, moisture retention characteristics, and moisture content.

Some codes, such as HELP and UNSAT-H, do not calculate the radionuclide flow from the disposal facility, but instead evaluate the infiltrating water flow in its vicinity. Their output can be used as an input for more near field or system-level transport codes.

5.5.2. Geosphere (far field) codes

Geosphere codes simulate the groundwater flow and/or contaminant transport in the geosphere. They require hydraulic (e.g. heads, hydraulic conductivities and porosities) and chemical parameters (e.g. distribution coefficients). and use detailed geologic data from a site.

Detailed groundwater codes typically require contaminant-specific inventories, retardation factors (or distribution coefficients), solubilities and hydraulic properties of the waste form. Time-dependent release rates from the near field to the geosphere or initial concentrations in groundwater are required for transport calculations in order to describe the source term. This requires some form of source term modelling often using another code (i.e., source term release is not typically calculated in the geosphere code).

Geosphere codes can be categorized according different criteria such as:

— basic simulation method (analytical or numerical, finite differences or finite elements);
— groundwater flow model (unsaturated, saturated and fractured flow);
— number of solved phases (multi-phase, single-phase); and
— groundwater transport capability (present or not).

Several hydrogeological flow codes do not include contaminant transport modules. However, for all widely used flow codes are these modules available, either in the form of independent codes or are directly incorporated into these codes.

The categorization of the example codes presented in Table 23 is summarized in Table 24.

TABLE 24. GENERAL CHARACTERISTICS OF THE EXAMPLE GEOSPHERE CODES

Code name	Simulation method	Groundwater flow model	No. of Phases	Transport solver
DRAF	finite differences	saturated and unsaturated flow	single-phase	Yes
FEMWATER	finite element	saturated and unsaturated flow	single-phase	External (FEMWASTE)
GRDFLX	analytical	saturated flow	single-phase	Yes
MIGRAD	analytical	saturated and unsaturated flow	single-phase	Yes
MODFLOW-96	finite differences	saturated flow	single-phase	External (MODPATH, MT3D)
PORFLO	finite differences	saturated flow	single-phase	Yes
TOUGH2	finite differences	flow in porous and fractured media	two-phase	Yes
VAM2D	finite element	saturated and unsaturated flow	single-phase	Yes

TABLE 25. FURTHER EXAMPLE GEOSPHERE CODES

Code name	Origin	Simulation method	No. of phases	Dimension	Transport solver
AQUA3D	Vatnaskill (Iceland)	finite elements	1	1-3	Yes
DCM3D	GRAM,SNL, NRC (USA)	finite differences	1	1-3	Yes
FEFLOW	VTT (Finland)	finite elements	1	1-3	
FEHM	LANL (USA)	finite elements	2	2,3	
FEMTRAN	SNL (USA)		-	2	Yes
FEMWATER	ORNL (USA)	finite elements	1		(transport only)
GWHRT	SKB (Sweden)	finite elements	2	1-3	
HST3D	USGS (USA)	finite differences	1	1-3	Yes
HYDROGEOCHEM	ORNL (USA)	finite elements	1-n		Yes
HYDRUS		finite elements	1	1	Yes
LLUVIA-II	SNL (USA)	finite differences	1	2	No
MSTS	PNNL (USA)	finite differences	1,2	1-3	Yes
NAMMU	AEA (UK)	finite elements	1	1-3	Yes
NAPSAC	AEA (UK)	finite elements	1	3	Yes
NORIA	SNL (USA)	finite elements	2	2	No
NORIA-SP	SNL (USA)	finite elements	1	2	No
NUFT	LANL (USA)	finite differences	1-n	1-3	
PORFLOW	ACRi (USA)	finite differences	3	1-3	
PTC		finite elements	1	3	Yes
SAGUARO	SNL (USA)	finite elements	1	2	No
STOMP	PNNL (USA)	finite differences	3	1-3	Yes
SUTRA	USGS (USA)	finite elements	1	1,2	Yes
TOSPAC	SPECTRA, SNL (USA)	finite differences	1	1	Yes
TRACR3D	LANL (USA)	finite differences	1,2	1-3	Yes
UNSATH		finite differences	1	1	No
VS2DT	USGS (USA)	finite differences	1	1,2	Yes

Selected codes represent only a fraction of existing geosphere codes. There are hundreds of different commercially available computer codes simulating hydrogeologic flow and contaminant transport, which can be used for much wider range of problems than the safety and safety assessment of near surface disposal facilities. Therefore, Table 25 contains list of other codes, which can be used for the flow and contaminant transport simulation.

5.5.3. Biosphere codes

Biosphere codes evaluate the migration and resulting radiological impact of the release of radionuclides to the biosphere. Depending on regulatory requirements, the end-point of calculation can be the maximum annual individual dose to members of a population group inhabiting the biosphere region or the health risk resulting from the release of radionuclides to the biosphere. Biosphere codes use the outputs from far field codes (e.g. radionuclide discharge into the biosphere) as input for the calculation of potential radiological exposure.

Biosphere codes for the assessment of radioactive waste disposal have been used since the late 1970's and early 1980's (see for example [105], [106] and [107]). Some of the codes were originally relatively simple extensions of codes developed for other purposes, such as estimating the consequence of routine discharges from nuclear power plants. In addition, further codes have been developed and applied for routine and accidental discharges from nuclear facilities (see for example [108]), and relevant experience has been transferred across to the codes used for waste disposal assessment. Projects such as BIOMOVS [26, 109], BIOMASS [76] and the Level 1B exercise of the PSACOIN (Probabilistic Safety Assessment Code Intercomparison) [110], have contributed to a greater understanding of relevant long term processes and how to model them. Therefore an increasing number of codes have been developed specifically for the biosphere assessment of radioactive waste disposals.

5.5.4. System level codes

A system level code attempts to integrate all important features, processes and events controlling the behaviour of radionuclides in a disposal system. Hence, rather than simply concentrating on just one component of the system (e.g., the source term, groundwater flow or radionuclide transport), a system level code attempts to simulate all of these aspects (each at an appropriate level) in order to more accurately represent the interactions and correlations within the system. Many input parameters in system level codes are lumped representations of parameters required or generated by more detailed codes - especially near field and geosphere codes.

System level codes can be based on a "top down" approach. There are two key points in the application of the "top down" approach:

(1) Less detailed component models and associated high level parameters should incorporate an appropriate representation of the model and parameter uncertainty resulting from their associated approximations; and

(2) As opposed to representing all processes with great detail from the outset (whether or not it is justified), details are only added when it is warranted that they are identified as being important with respect to the assessment of the system and where additional detail will reduce the uncertainty due to model simplification.

In a top down approach, the total system model evolves by iteratively adding detail (and reducing uncertainty) for specific components as further information becomes available. Such an approach helps to keep a project focused on total system performance without getting lost in what may prove to be unnecessary details.

Although detailed process-level models may not be directly implemented when using a “top down” approach, this is not to say that detailed modelling is not required. Detailed process-models can form the foundation for a “top down” total system model and can be used to generate the appropriate input parameters for the top-level model. These input parameters may be in the form of analytical expressions or response surfaces developed by an expert based on detailed modelling results.

5.6. TYPES OF CALCULATION

Once the conceptual and mathematical models have been developed and implemented in software tools and the associated data collated, calculations can be undertaken to assess the impacts of disposal facility. Four types of calculations can be undertaken as part of a safety assessment.

Scoping calculations – Such calculations are based on simple analytical formulae that can be computed using a hand calculator or spreadsheet and are not as data intensive as more detailed calculations. Scoping calculations can have an important role to play in scenario development, where processes and interactions having an insignificant effect on the system performance need to be screened out. They can also be used to check the order-of-magnitude of more detailed calculations and can be used at an early stage in the development programme for a disposal facility to help identify important scenarios and associated FEPs.

Worst case (bounding) calculations - One approach to dealing with uncertainty is to choose scenarios, conceptual and mathematical models, and parameter values which overestimate the impacts. Such bounding calculations have the advantage that they are generally rather straightforward to explain and defend to a variety of stakeholders. However, there are a number of problems with this approach [22]. The first is how to establish that an assessment is pessimistic since it is difficult to argue that particular scenarios or models are intrinsically pessimistic. The second is that critics might go on to make even more pessimistic assumptions. Therefore bounding calculations have a useful role to play in presenting safety cases to wide audiences, but they need to be backed up by more detailed models and uncertainty analysis.

Deterministic calculations – This approach makes use of models with fixed parameter values. A major advantage of this approach is that the detailed models can be used. Typically, a best estimate set of parameter values is used for a base case calculation. This provides a point of reference against which results from other calculations can be measured. Often a set of calculation cases whose parameters span the range of interest is evaluated in order to build up an appreciation of possible impacts of varying parameter values, and to develop an understanding of the system. The approach can be useful when presenting results of assessments to a range of audiences. A limitation of the deterministic approach is that there is often no systematic or complete coverage of the uncertainty space in parameter values and it might be difficult to justify the choice of the “best estimate” value for a parameter (e.g. should it be a conservative value or the average value?).

Probabilistic calculations – With this approach uncertainties are quantified in terms of probability density functions for the model parameters, and these are propagated through the model to give a distribution of impacts. This propagation is usually carried out by statistical sampling of the input distributions using the Monte Carlo method with random sampling techniques (such as Simple Random Sampling and Latin Hypercube Sampling). The ensemble of results produced by probabilistic calculations can be analysed to provide information on: various means, moments, percentiles and other statistics; the distribution of impacts which gives a measure of uncertainty; the relative importance of input assumptions and parameters. The ranking of input parameters can provide useful feedback to experimental programmes and facility design studies. The strength of the probabilistic approach lies in its ability to be comprehensive in exploring the space of the phenomena considered, and their associated model parameters. Its weakness is the need to make use of simplified models and the possibility that the statistical sampling may choose parameter combinations outside their range of validity. Furthermore it can be difficult to demonstrate regulatory compliance if the regulations are written in terms of deterministic standards and since parameter distribution probability are primarily based on judgement, output is mainly a result of judgement and not data.

These calculational approaches should not been seen as mutually exclusive. An assessment should usually present results calculated using more than one of these approaches. For example, a combination of probabilistic and deterministic approaches can be used, with deterministic calculations being performed as a check in high impact regions of parameter space identified from probabilistic calculations. Again, it is important to ensure that the calculational approach is appropriate for the assessment context.

5.7. LESSON LEARNT AND CONCLUSIONS

The process of formulating and developing models should be formal, defensible, and transparent to independent review. It consists of three main stages:

- Generation of conceptual models of the disposal systems using information from the assessment context, system description and scenario generation steps of the safety assessment methodology. A conceptual model should comprise of a description of: the model's basic FEPs; the relationship between these FEPs; the scope of application in spatial and temporal terms. While developing conceptual models it can be of help to divide the assessed domain into the near field, the geosphere, and the biosphere;
- Representation of the conceptual models and their associated processes in mathematical models through their translation into the formalism of mathematics. It usually involves sets of coupled algebraic, differential and/or integral equations with appropriate initial and boundary conditions in a specified domain; and
- Implementation of the mathematical models in computer tools that are then used to solve the mathematical models. Four groups of codes can be identified, those for: the near field; geosphere; biosphere; and total system.

The level of detail to which the models are developed will be a function not only of the assessment context but also the stage in the disposal facility life cycle. For example, during early stages (such as site selection or initial investigations) it might be sufficient to generate relatively simplistic models for scoping purposes that can be implemented using simple computer tools such as spreadsheets with limited data requirements. Following review of the results it might be appropriate to enhance certain models and implement them using more sophisticated computer codes. Models for later stages, especially the regulatory submission for the licensing of disposals, may need to be even more comprehensive and have greater data requirements.

It is recommended that at any stage, the model should be as simple as possible but should include enough detail to represent the disposal system's behaviour adequately for the purpose of the assessment (e.g. ensuring compliance with relevant safety requirements). In particular, the chosen model should be consistent with the assessment objective, easy to use (considering the complexity of the system), and one for which data can be obtained. A simple modelling approach is likely to be more efficient, easily understandable and justified. Nevertheless, it is important to ensure that there is a sufficient understanding of the disposal system to allow the resulting analysis to yield a meaningful analysis of the repository performance. Furthermore assumptions should be formulated on the basis of available data and knowledge of the system or similar systems.

Throughout the model formulation and implementation process, data are used to help develop the conceptual and mathematical models and provide input into the computer tools. The performance of safety assessment usually requires a significant amount of information and data related to the disposal system. The data are used throughout the safety assessment process, particularly in scenario development and justification, model formulation and implementation, and results interpretation. However, it is important to ensure that there is a sufficient understanding of the disposal system to allow the resulting analysis to yield a meaningful analysis of the repository performance. A number of issues arise which should be considered:

- The sources of uncertainty in parameter values and methods for dealing with them in the safety assessment;
- The use of generic data in the absence of site specific data and the trade-off between the use of generic data and the requirement for the collection of further site data; and
- The choice of methods to select appropriate ranges for input parameters for computer tools.

It should be remembered that uncertainties are associated with all stages of model formulation and implementation. These uncertainties need to be identified, reduced and, as far as possible, quantified as part of the safety assessment; and

It is particularly important that, in common with the rest of the safety assessment methodology, model development and implementation should be seen as an iterative process. Any lessons learned in applying the model and interpreting its results should be used to revisit assumptions and decisions made during the course of model development. It is likely that such information can be used to refine the model, perhaps by identifying particularly important FEPs or sensitive parameters.

6. BUILDING OF CONFIDENCE

6.1. INTRODUCTION

The purpose of confidence building in the context of a safety assessment is to provide readily understandable qualitative and quantitative evidence that all aspects of the safety assessment are based on sound scientific and technical principles and have been carried out in an systematic manner which is amenable to independent review.

In practice confidence building is achieved by a range of activities throughout the safety assessment process including the following:

- Comparison of assessment results with both national regulatory criteria and international guidelines; and

- Comparison with a variety of indicators may be used to interpret results from detailed modelling, these indicators may include:

- natural background radiation;
- natural background concentrations of contaminants;
- risks arising from other activities; and
- concentrations of contaminants for which there has been no observed health effect.

- Performance of very simplified or scoping calculations of the entire system or some components of the system and their comparison with the detailed modelling results. As noted in Section 5, the simplified calculations are often more transparent, and therefore more easily accepted and understood, particularly by the public.

- Use of sensitivity analysis as a method for providing confidence in safety assessment results. Through this type of analysis, the overall robustness of the disposal system can be demonstrated. Sensitivity analysis may also allow attention to be focused on those components of the system where the greatest improvements in performance can be obtained, and thereby assist in be used for the presentation of results. Many alternative representations are possible for displaying uncertainties and sensitivity analysis results for both deterministic and stochastic modelling outputs. For example, dose versus time curves showing the contribution to dose from significant radionuclides have been widely used.

- In addition to the specific areas explicitly mentioned above, other measures can be implemented to provide confidence. These include: the use of a systematic approach; striving for transparency in all aspects of the assessment; providing multiple and complementary lines of reasoning in support of the assessment; demonstrating good science and good engineering practice; applying quality assurance programme; ensuring consistency with best international practice; and using peer review.

The confidence building process can be considered as internal to the assessment process as well as external to it. The internal confidence building process involves the people performing safety assessment of disposal facilities building their own confidence in the assessment and results, proving that the analysis and the results are accurate and the uncertainties are clearly identified and minimized where possible. The external confidence building process involves building confidence in the regulatory body, competent authorities (for example as part of the licensing process) and in the public (for example as part of a public review), essentially providing an acceptable level of proof that the safety assessment is suitable for the purpose of making or supporting a decision.

The concept of confidence building and ‘confidence’ in assessment results can be captured in a few questions.

- How does the assessor gain a level of confidence in their own assessment results?
- How is a regulator provided with a level of confidence that allows a decision to made on proceeding with a disposal facility?
- How is the public provided with a level of confidence that the impacts from a facility will be within acceptable limits?

From the range of possible confidence building topics, ISAM focused on the following topics:

- What confidence building is and how it is included in safety assessment (see Section 6.2).
- Summarising uncertainty and sensitivity analysis approaches and how they can be used to enhance confidence in the safety assessment (see Section 6.3. and Appendix H).
- Developing some quality assurance procedures which can be readily and practically included in the safety assessment process (see Section 6.4.).
- Summarising the primary methods used to communicate safety assessment information (see Section 6.5.).
- Providing a summary of regulatory requirements and criteria relevant for safety assessment, stated in national legal acts and regulations (see Annex II).
- Determining how participants have documented safety analysis: what is included in a safety assessment report and why (see Appendix I).

The key lessons learnt and conclusions are presented in Section 6.6.

6.2. CONFIDENCE BUILDING IN THE SAFETY ASSESSMENT PROCESS

Safety assessments should be structured in a way that attempts to provide maximum confidence in the decisions that are made relating to the disposal facility. Therefore confidence building is a process that needs to be followed through all stages of the safety assessment of near surface disposal facilities. Each of these steps is examined in more detail in the following sub-sections, and the role of confidence building at each step of the ISAM project methodology is discussed.

6.2.1. Assessment context

Confidence building at the stage of developing the assessment context is based on demonstrating a sound and complete understanding of the key components of the assessment context.

In particular, confidence can be built by demonstrating an understanding of the existing regulatory requirements set by the regulatory body be they prescriptive or performance based. Such requirements can relate to the: facility design; waste types to be disposed; safety indicators to be calculated and associated limits/targets to be met; duration of institutional control periods; and any guidance or requirements relating to the scenarios to be assessed; and hypothetical group(s) (critical group(s)) to be protected, possibly including the description of the pathways and human behaviour parameters.

The legal framework defined by acts and regulations is generally understood to define the broad waste management policy; who is responsible for implementation of the policy, defines dose limits, specific requirements and the scope of radioactive waste management. It may be worthwhile noting that regulations typically fall into one of two categories either prescriptive or performance based.

The classification and the requirements on the type of the radioactive waste sets the upper limits for the repository according to which the disposal is defined. Waste classification establishes the boundaries of the waste inventory in terms of radionuclide content, activities, physical and chemical form, half-life, heat generation, dose (direct exposure), waste origin and ownership (e.g. defence). The waste acceptance criteria in addition defines the limits on the waste form (implicitly related to the performance of the facility), e.g. requiring container type (stainless steel, etc.), matrix type (cement), source term performance (leachability, compressive strength, solubility, etc.). Requirements on facility design (Annex II) are also meant to increase confidence in the overall performance of a repository. Requirements listed by ISAM participants (Annex II) can be classified as requirements designed to address risk/dose management and risk/dose assessment. For example, risk management requirements include such things as retrievability, transportation considerations, acceptance of the facility by local communities, etc. There may also be requirements directly affecting risk assessment, for example a requirement to consider certain scenarios such as earthquakes, high tides, groundwater use.

Targets including items such as dose and risk limits define the acceptable level of safety of near surface disposal facility. These targets set part of the goal of the safety assessment. Some countries (Annex II) define a specific hypothetical group (critical group) to be protected, possibly including the description of the pathways and human behaviour parameters.

The period of institutional control for a disposal facility can be classified as active and passive control periods. The characteristics of the ¨active¨ and ¨passive¨ control periods need to be clearly defined because institutional control has a direct influence on the definition of scenarios. For example, human intrusion scenarios are usually assumed not to occur during the institutional control period, because it is expected that necessary measures will be in place to prevent intrusion during this period. The institutional control over the facility contributes to the confidence that the facility will be maintained at an acceptable level of safety.

The period to be evaluated in the safety assessment is limited in some countries (for example up to 10 000 years or 100 000 years). Other countries (Annex II) do not prescribe such limits, they instead require a calculation of either peak dose or maximum risk, regardless of the time of occurrence. In any case the time period needs to be established on a credible scientific basis.

Long term monitoring of a disposal facility aims to build confidence that repository performance is in line with facility design and safety assessment. This type of monitoring is to be distinguished from the process of collecting data site specific data to improve the safety assessment and build confidence it and in the stakeholders different form regulators,. Almost all countries perform monitoring related to the performance of the disposal facility, including possible releases to the environment. In addition, identification of stakeholders and planning for public communication should be considered. Public communication is intended to build confidence by openly and clearly presenting the results of the safety assessment. Public communication also serves to allow input (feedback) from the public on the issues of concern to be addressed in the safety assessment. If specific items of public concern are included in the safety assessment this in itself can help generate confidence in the assessment.

International documents are often used to define good practices, recommendations, and guidelines for siting, design, construction, operation, safety assessment, and long term care and monitoring of disposal facilities. With specific regard to the safety assessment process, international documents have also been used to standardize some of the key aspects of the safety analysis. For example, most countries (Annex II) utilize internationally accepted dose conversion factors instead of directly addressing the uncertainty of the dose response model in the safety assessment process.

6.2.2. Description of the system

Building confidence in the description of the system covers both the engineering and the natural aspects of the disposal system. The engineering aspects include confidence about the knowledge of the facility design, waste form, inventory, etc. The natural aspects include confidence about the knowledge of the geology, hydrogeology, surface environmental processes, etc. Confidence could be built through the collection and use of relevant site specific data.

In establishing the system description some attention should be directed to possible uncertainties. This could include data knowledge (parameters), uncertainty in the performance of the facility as a function of time, as well as uncertainty in the natural processes and variability of the system. Confidence in the final safety assessment results can be enhanced by demonstrating that these uncertainties have been adequately considered and the best available knowledge on the disposal system has been used.

6.2.3. Development and justification of scenarios

Development of scenarios and their justification is an essential step in the whole safety assessment process. To build confidence, this has to cover development of a comprehensive set of scenarios in a systematic fashion that represent the possible (credible) future evolution(s) of the disposal system. The systematic approach for including or excluding scenarios should be well described. In common with all aspects of the safety assessment The process of development and justification of scenarios should be well documented, transparent, and traceable. The screening process used to reduce the number of scenarios to be assessed should be defensible.

6.2.4. Formulation and implementation of the models

The first step in confidence building at this stage of the safety assessment process is to define the conceptual models that are consistent with the description of the system and represent the different scenarios to be investigated. The mathematical model is a representation of the conceptual model, that is usually solved by utilization of a computer code.

Building confidence in the conceptual model begins with recognising that multiple conceptual models may be consistent with the description of the system. Sometimes the ¨worst case¨ model could be selected and assessed or alternatively the different conceptual models could be run in parallel and analysed with the aim of assessing the importance of conceptual model uncertainty. Once mathematical models have been developed and encoded in software tools, confidence needs to be built in their ability to solve the mathematical models correctly and accurately through the use of verification. Further confidence can be built in the model if field and/or experimental results can be reproduced with sufficient accuracy (the process of validation). This can be achieved through the quality assurance process including for example peer review.

6.2.5. Analysis of results

Confidence in the interpretation of the results is enhanced by demonstrating a thorough understanding of the underlying science and engineering, which are governing the safety assessment results. For example identification of key radionuclides, pathways, environmental processes, etc. and understanding the impact of the engineered features. Comparisons with natural analogues may be an important aspect to consider at this stage. Key to understanding the system and facility performance is the appropriate treatment of uncertainty. For example, following a deterministic approach, a sensitivity analysis can help to identify the most important features of the disposal system. Certainly, confidence in the final safety assessment results can be enhanced by demonstrating that uncertainties have been adequately considered within the assessment.

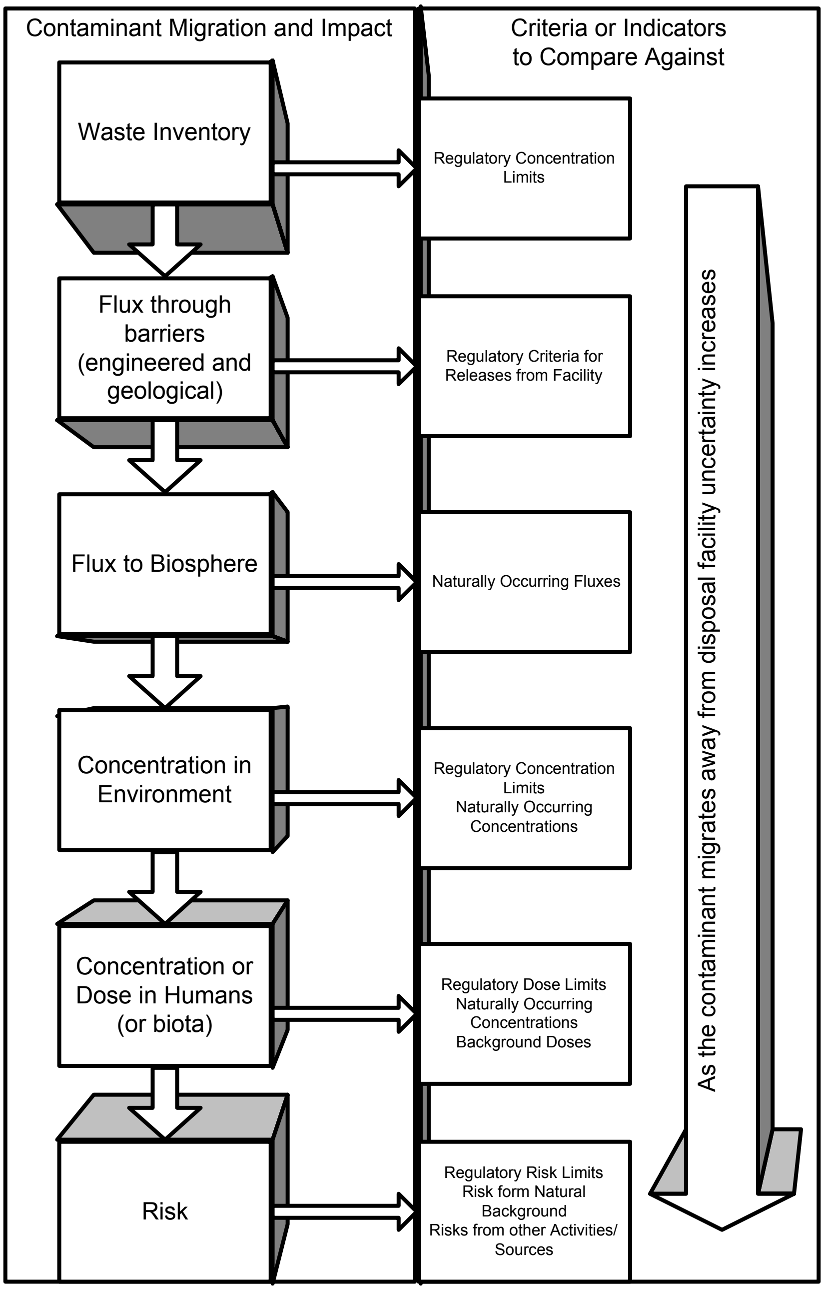


FIG. 30. Typical assessment outputs and regulatory criteria and safety indicators (based on [111]).

Confidence in the results of the safety assessment can be further enhanced by demonstrating compliance with the regulatory requirements and recommendations set out in the assessment context. Figure 30 outlines the general consensus of the ISAM as to how and where various criteria may be applied or compared to safety assessment results and data. This figure illustrates several of the typical or commonly available output stages of an assessment along the left hand column. Assessments from different organizations will proceed down the left hand column to a level appropriate for meeting their regulatory criteria. It is possible that in some cases, based on inventory information alone, a safety case could be made that was acceptable to allow implementation (in many cases this is how clearance levels function). On the other hand, it could be required to proceed down along the left hand column to assess risks to humans and possibly non-human biota. The most commonly used regulatory criteria, based on ISAM survey results (Annex II), are based on dose to humans. One of the points of view that surfaced during the discussions at ISAM meetings was that the purpose of safety assessment was to compare results against regulations, and any other comparisons were of little benefit. Nonetheless, it was also a widely held opinion that comparison with additional indicators other than regulatory criteria would be beneficial, particularly with the public.

Possible additional indicators include:

- Toxicity of water leaving the near field;
- Radionuclide fluxes from the near field;
- Toxicity of water entering the biosphere;
- Radionuclide fluxes into the biosphere;
- Radionuclide concentrations in environmental materials;
- Doses to non-human biota;
- Individual dose to a potential exposure group member;
- Collective dose (and risk); and
- Individual risk.

Table 26 provides some of the important advantages and disadvantages of each of these possible measures of impact.

TABLE 26. ADVANTAGES AND DISADVANTAGES OF VARIOUS IMPACT MEASURES

Measure	Advantages	Disadvantages
Toxicity of water leaving near field	Readily understandable concept	Not directly related to biosphere impacts
Radionuclide fluxes from near field	Readily understandable concept	Not directly related to biosphere impacts
Toxicity of water entering biosphere	Directly related to drinking water pathway	Only relates to one potential pathway
Radionuclide fluxes into biosphere	Does not depend upon human behaviour assumptions	Comparisons with natural fluxes can be difficult
Radionuclide concentrations in environmental materials	Does not depend upon human behaviour assumptions	Comparisons with natural concentrations can be difficult
Doses to non-human biota	Demonstrates protection of the environment	Unnecessary if man is protected?
Individual dose to member of potential exposure group	Direct comparison with natural background	Likely to be exceeded by ‘unlikely’ events
Collective dose (and risk)	Optimization?	Difficult estimate. Of limited use for v. low individual doses
Individual risk to member of potential exposure group	Direct comparison with ‘tolerable’ levels	Multiple definitions of risk. Risk dilution problems Presentational difficulties

The first two indicators (items 1 and 2) relate to the performance of the near field barriers and can be regarded as “intermediate” measures as they do not relate directly to the impacts of actual concern which occur in the biosphere. If a regulator requires such measures to be met, this requirement will have to be based on assessments that consider the relationship between these criteria and impacts in the biosphere. If such relationships can be established, these “intermediate” measures provide a valuable guide to the design of near field barriers.

The idea of using calculated fluxes of radionuclides from the geosphere into the biosphere (item 4) as the basis for regulatory criteria has received more attention in recent years. For example, the nuclear safety authorities in Denmark, Finland, Iceland, Norway and Sweden have published the "Nordic Flagbook" which includes consideration of this idea. Care has to be taken to define appropriate areas and volumes over which the fluxes are to be defined in order to make comparisons between repository-derived and natural radionuclide fluxes valid, and to the choice of the radionuclides to be included in the fluxes to be compared, particularly as some repository-derived radionuclides are not found in natural systems.

Doses to non-human biota (item 6) is the first measure in the list which is a direct measure of impacts on the biosphere. Historically, consideration of measures based on impacts to non-human-biota was not considered to be necessary, as it was assumed that if man is adequately protected then non-human biota will also be, at least at the level of individual species. Whilst this assertion is not necessarily incorrect, increased interest in such measures has been shown internationally in recent years.

Individual doses to a suitably chosen exposure group of humans (item 7) forms the generally accepted basis for radiological criteria for present day releases of radioactivity into the environment, and continues to be used for the "normal" development of the repository system in many countries, i.e., for the groundwater transport pathway in the absence of any disruptive events. The fundamental problem with the use of a dose-based criterion for all pathways is that it is always possible to postulate low-probability high consequence scenarios in which any reasonable criterion is exceeded. Some concept of acceptable probability has to be introduced for such high consequence scenarios. The question of how human intrusion should be dealt with poses particular conceptual difficulties, and a subject of frequent debate on the basis of the new ICRP recommendations.

Collective radiation doses (item 8) have often been considered in optimization studies for present day operations, but have not usually been considered in any detail for repository assessments. This is even more the case for collective risks. In the radiological protection community there is a general tendency to reduce the importance associated with collective dose calculations, particularly for situations where the collective dose derives from a very large number of very low individual doses. Note, however, that criteria in the USA for limiting the release into the accessible environment were derived in part on the basis of limiting the collective health impacts of such releases.

Risk to individuals in the potential exposure group (item 9) was introduced as a performance measure in order to overcome some of the difficulties associated with low probability high consequence events. Superficially this is an attractive measure as calculated risks can be compared directly with risk levels that are considered "tolerable" for other types of present day activities and operations. In practice difficulties arise in evaluating risk as there is no unique definition of the quantity to be evaluated, and meaningful calculations become increasingly difficult to make at long timescales after repository closure.

6.2.6. Review and modification

Following an iterative safety assessment process, it is necessary to review each of the assessment components. The review of the proposed modifications should be based on a transparent prioritization process. Modification of any of the assessment components should be conducted in structured manner where any changes are tracked and should include adequate justification for the proposed changes. Demonstrating improvements in the safety assessment process e.g. by reducing uncertainties or a more realistic representation of the system will build confidence. For example it could be the case that it is considered important to put more effort on obtaining additional data (e.g. site characterization). Alternatively, modification of one or more aspects of the facility design, scenarios and models, could be considered.

6.3. UNCERTAINTY AND SENSETIVITY ANALYSIS

Safety assessment for near surface waste disposal facilities requires the interaction of a large number of disciplines in order to model environmental phenomena necessary to evaluate the long term safety of disposal. The physical systems involved can often be very complex. Typically, the safety analyst has to simplify the physical system into a conceptual model that can be represented mathematically. An important step in this process involves defining an exposure scenario and this is often a significant source of uncertainty (**scenario uncertainty**). Simplification of the physical system to a mathematical model is another source of uncertainty, commonly called ***model uncertainty***. Uncertainty analysis is recognized as a key factor in the decision process for safety assessment.

Uncertainty in the data (i.e. directly measurable quantities) and parameters (i.e. quantities derived from direct measurements) used as inputs in the modelling are also important. These can arise from a number of sources: lack of sufficient data; instrument errors (mainly caused by the imprecision and malfunctioning of the available measuring devices); human errors (for example, incorrect or misapplied measuring techniques and systematic errors such as measurements taken on disturbed samples, because in situ measurements are impossible); and the data used to derive a parameter may not be representative of the parameter due to scale and geometric effects. Uncertainty and variability in data can be viewed as two separate phenomena [112]. Both lead to uncertainty in decision-making. Variability is the representation of the heterogeneity in sample population and uncertainty is the representation of the lack of perfect knowledge. Variability arises from the stochastic nature of the processes and features considered, e.g. the temporal distribution of drum corrosion times and the spatial heterogeneity of a host geological formation. Uncertainty arises due to incomplete or imprecise knowledge of the processes and conditions expected in the future, e.g. uncertainty in the estimation of solubilities and sorption coefficients for important radionuclides. In assessments the analyst may need to rely on expert judgement due to lack of data, lack of knowledge concerning future conditions and parameter values (and distributions), or any aspects of the system under study that are not well understood by current science. This generates another kind of uncertainty, "***subjective uncertainty***".

Difficulties in decision making arise due to these uncertainties that are inherently related to the modelling of environmental phenomena. The ability to identify, quantify and reduce the uncertainties, as well as to identify the most important parameters is of key importance for good decision making. It is impossible to guarantee with absolute certainty that one has made the correct decision, but the possibility of making the right decision is increased by identifying and quantifying the uncertainties in the safety assessment.

The identification of sources of uncertainties as well as the types of uncertainties are necessary in order for the analyst to find the best way to quantify and consequently improve the degree of confidence he or she can have in the safety analysis.

Understanding uncertainty will also be a major factor in the acceptance of the safety assessment case by technical audiences including the regulatory authorities. Three examples of how sensitivity and uncertainty analysis have been approached is described in Annex II. The safety assessment process is iterative, and as refinements in data, scenario descriptions or other factors are obtained the assessment can be improved with a corresponding decrease in uncertainty. Initially, an estimate of the sensitivity of specific parameters can be used to focus attention where the greatest benefit can be derived — this can be considered to be internal to the assessment. Eventually, the assessment focus will be turned outward, as the goal becomes to demonstrate the safety of the system under consideration to the regulators and the public.

Substantial efforts have been expended to define the role and use of uncertainty and sensitivity analysis in the context of safety assessment (see for example [113] to [121]). It is not the intent to review these in detail as this has been done elsewhere as indicated, however this section will present a cursory review of what has been done in this field. Three examples of how uncertainty and sensitivity analysis have been approached in safety assessments are described in Appendix H.

6.3.1. Sources of uncertainty

Scenario uncertainty

Source of uncertainty is related to the long term future behaviour of the disposal facility. It includes human use of the land, geophysical processes, intrusion, and other long term processes.

As discussed in Section 4, is not possible to make an exact description of the future, however, one can represent what is the most probable evolution of the system based on past experiences and data. Expert judgement is very important in this approach. Another widely used approach to approximating future conditions is to select scenarios based on current conditions (e.g., set climate conditions based on current conditions). In this case, these reference conditions may serve as a baseline for comparison between different scenarios and parameter sets (see Fig. 31). An important part of this approach is to choose conditions which permit a defensible, scientifically robust decision to be made.

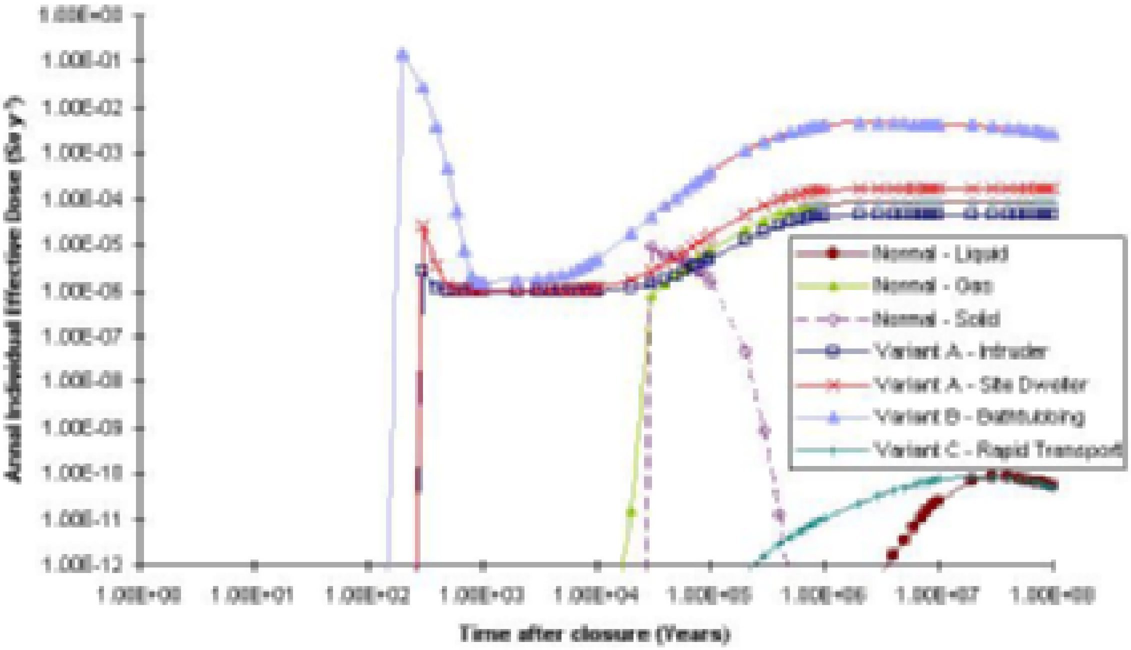


FIG. 31. Example of Doses for Different Scenarios for a Hypothetical Near Surface Disposal Facility.

Model uncertainty

The most appropriate method to representing the physical and chemical processes in the mathematical models is not always clear. Model intercomparison studies provide some insight into the effect of choosing different conceptual models and/or different mathematical representations of a conceptual model. An example of an intercomparison of this nature was published by the IAEA [3], and it demonstrates the different results obtained when different models (and modellers) were applied on a relatively simple test case (see for example Fig. 32). Also for reasons of control and economy, the experiments on which models are calibrated are often carried out on a small scale in laboratories, rather than over larger field scales. These uncertainties arise because it is not clear if a model describes transport on a small scales, it will be appropriate for transport predictions over larger length-scales.

Other causes of model uncertainties are ignorance of the actual relationships between processes that occur, and the uncertainty resulting from the simplification of very complex processes.

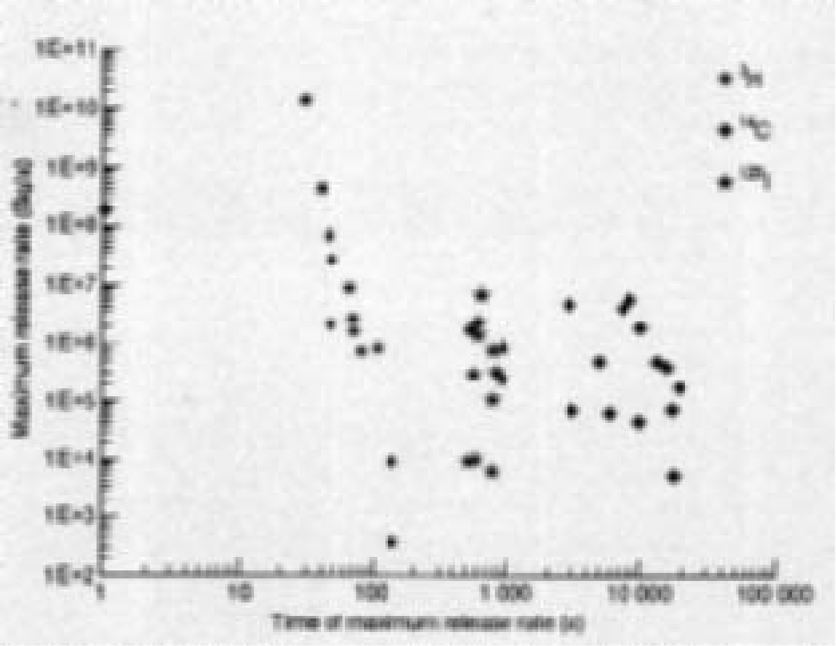


FIG. 32. Maximum Release Rates from Vault and Associated Timings for the NSARS Vault Test Case [3].

Data/parameter uncertainty

Parameters are variables used to represent physical processes in the safety assessment models and. As noted above, they are often derived from directly measured data. A complete safety assessment requires the collection of a large amount of data [20]. A partial list of data which are used to define the parameters follows:

(a) *Waste characteristics* - radionuclides composition as a function of time; total inventory; physical and chemical form; etc.;
(b) *Containers characteristics* — mechanical and chemical performance; waste form composition in each container;
(c) *Repository characteristics* — dimensions; backfill material; concrete characteristics;
(d) *Site characteristics* — hydrogeology; geochemical properties; and
(e) *Biosphere characteristics* — weather conditions; land use; population distributions.

Frequently there are large temporal and spatial variations in some of these parameters. For example the parameter known as dispersivity, which is a measure of how much spreading occurs in the contaminant plume during transport from the disposal site to the receptor, is variable. In this case, the impossibility of having a complete understanding of parameter variability is a result of lack of knowledge. Professional judgement is then necessary to find the best values for parameters in the case of deterministic calculation and the probability distribution function (pdf's) in case of probabilistic approach.

Two examples showing the sensitivity of a specific parameter value on a dose estimate are given in Figs 33 and 34. Figure 32 shows the effect on total dose from a set of 500 simulations where the distribution coefficient (K_d) was randomly selected from a predetermined "realistic" range. From Fig. 32, it can be seen that the estimated dose from one of the radionuclides (^{239}Pu) exhibited greater sensitivity based on a 500 trial simulation within the realistic range.

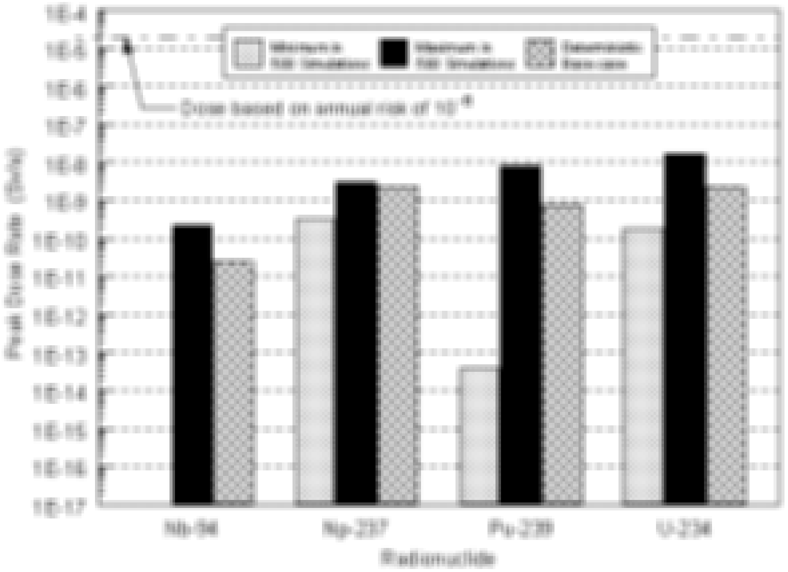


FIG. 33. Effect on a total dose from a set of 500 K_d's randomly selected [122].

Figure 34 shows the effect of varying the K_d in the aquifer and within the disposal facility backfill for a specific radionuclide. In this case the data are plotted as pairs (one pair for each K_d value of backfill and aquifer). This representation clearly indicates it is the K_d in the backfill which has the more significant impact.

Analysis of this type can be used to help guide the assessment team in focusing effort on data and parameters which have the greatest impact on the results. However, it should be kept in mind that different models may have sensitivity to different parameters.

Subjective uncertainty

Subjective uncertainty arises from the need to rely on expert judgment judgement due to lack of data, lack of knowledge concerning future conditions and parameter values (and distributions), or any aspects of the system under study that are not well understood by current science. The effect of subjective uncertainty is illustrated by the user interpretation exercise in BIOMOVS II [123]. The exercise involved giving participants the same three scenarios and the same software tools to analyse the scenarios. For any set of calculations, it was found that the variation in best estimates was greater than an order of magnitude and most calculations showed order of magnitude differences when best estimates were compared with the actual measured values (Fig. 35). In the BIOMOVS II user interpretation exercise, it was found that the choice of parameter values contributed most to user-induced variability, followed by scenario interpretation, and to a lesser extent user error. The contribution due to code implementation was low [123].

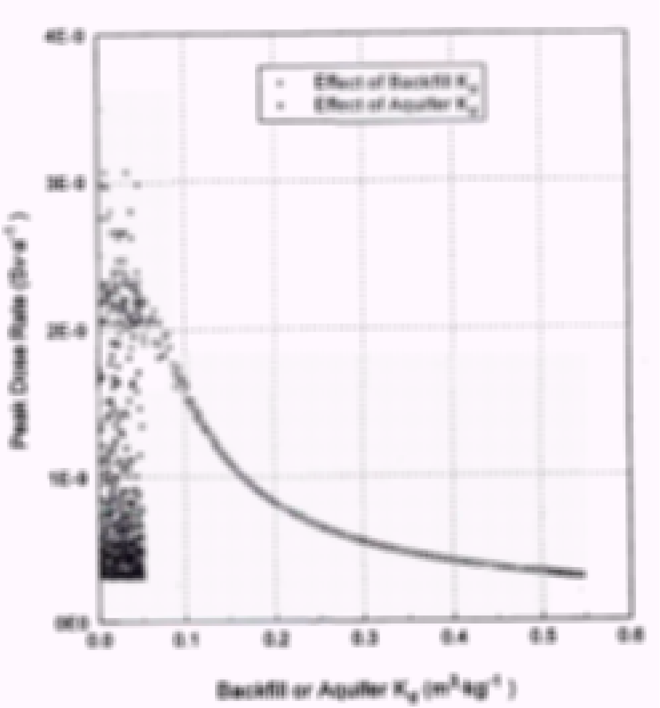


FIG. 34. Effect of different K_d values on peak dose [122].

6.3.2. Types of uncertainty

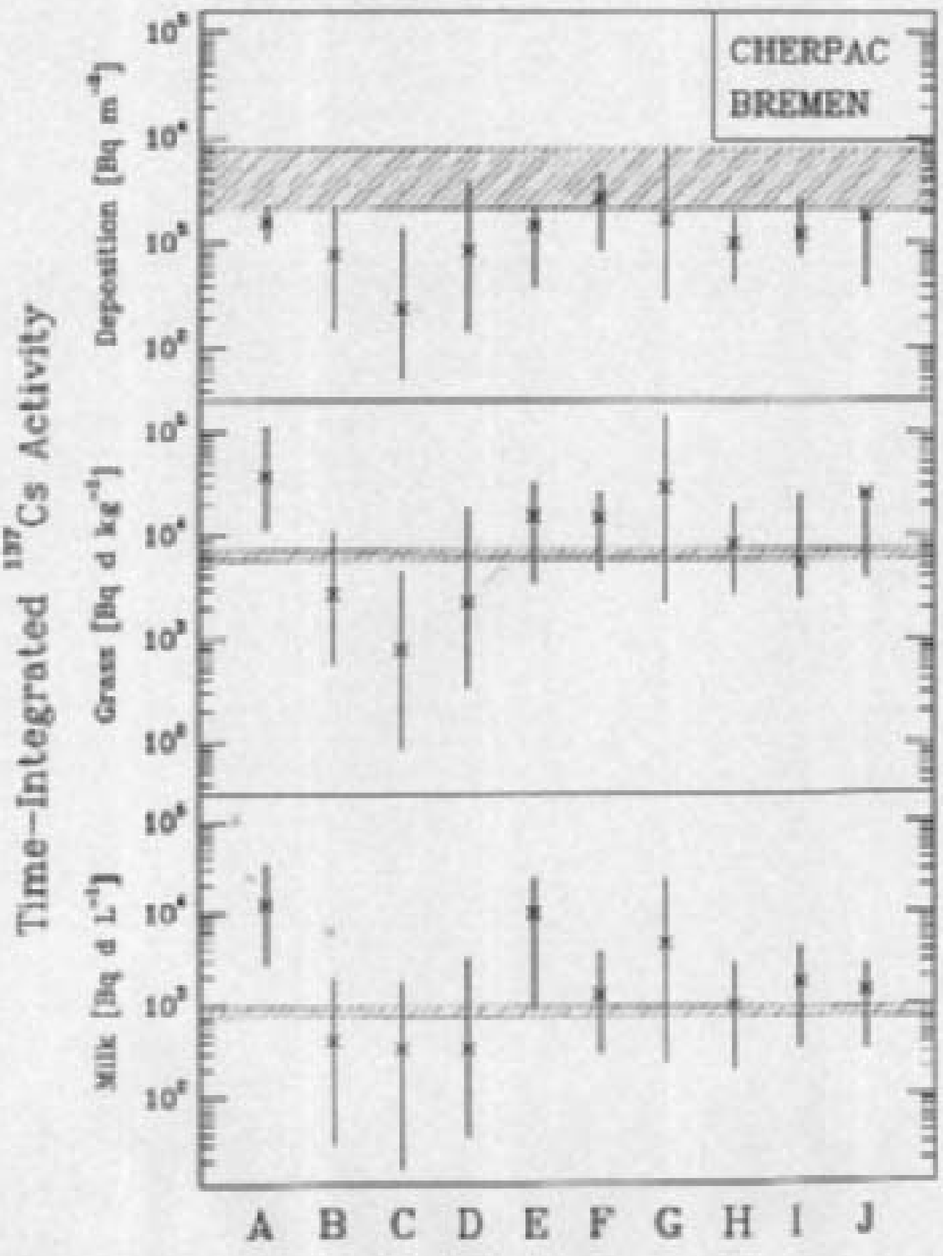
Two types of uncertainties, type A and type B, can be identified [116].

Type A uncertainty is due to random variability. For example, if the distribution coefficient, K_d is measured by laboratory experiments for the same type of soil with the same properties, one can find several different values. If the number of measurements tends to infinity, the mean value for K_d will be a constant number.

Type B uncertainty is due to lack of knowledge and includes conceptual model uncertainty and parameter uncertainty due to non-stochastic effects. An example for this type of uncertainty could be the actual K_d values under field conditions. Heterogeneity in soil compositions can result in K_ds and other soil hydraulic parameters varying by an order of magnitude or more from one location to another within a small distance. Therefore this variability could not be treated as chance or measurement variability.

These two types of uncertainties require different approaches to deal with them in order to improve the quality of the safety assessment.

Both types of uncertainties A and B can be found in safety assessment. During the entire safety assessment process the analyst constantly has to make decisions as to the best set of parameter values or probability distribution of values to represent a system, and the best conceptual models of the system. Those decisions are based on the analyst's expertise and not on sample evidence, i.e., the decisions are subjective. So, type B uncertainty has a major role in safety assessment.



Total deposition and time-integrated concentrations of Cs-137 on pasture grass (May 3 - June 27) and in milk (May 14 - June 27) for Bremen; capitals denote the participants; best estimates and 95% confidence intervals on the predictions calculated with CHERPAC are given; hatched areas denote the 95% confidence intervals of the measurements.

FIG. 35. Example Results from the BIOMOVS II User Interpretation Exercise [123].

An example of combined Type A and B uncertainty in safety assessment is the determination of maximum annual committed dose equivalent per individual of the most exposed population group due to a release of radioactivity to groundwater [116]. In this case, the dose per individual is treated as a random variable, type A, since it is impractical to model each individual. However, additional type B uncertainty is introduced due to the lack of knowledge about the appropriate mathematical models and parameters values to use for hydrologic dispersion in groundwater as well as many other parameters to represent all processes involved in reaching the final result [116].

6.3.3. Approaches for uncertainty analysis

Deterministic approach

In this approach the model and the representative sets of input parameters are selected and the analysis is performed providing a single outcome. To address uncertainties a single parameter sensitivity analysis is performed by altering a single parameter and measuring the effect on the projected outcome. The procedure is repeated for all parameters that are expected to have a major impact on the outcome.

This approach does not permit a rigorous mathematical estimate of uncertainties. To overcome this difficulty, parameters are often chosen which will over predict the dose. Thus, the confidence needed to make the decision on the safety assessment of the disposal depends on the confidence with which the selected parameters lead to conservative outcomes.

Probabilistic approach

This approach is based on the assumptions that the data are random and independent. Monte Carlo is one very commonly used method of uncertainty propagation analysis. Monte Carlo can be performed using one of two random sampling processes: Simple Random Sampling (SRS) or Latin Hypercube Sampling (LHS) [117].

In both approaches uncertain variables are assumed to be described by statistical parameters which define the probability of the variable having a given value.

In SRS, a random value is taken from the probability distribution specified for each uncertain model parameter, and a single estimate of the desired endpoint is calculated. This process is repeated for a specific number of samples or interactions. The result is an empirical approximation to the probability distribution of the model output or assessment endpoint.

In Latin Hypercube sampling, the range of each variable is divided into n intervals of equal probability. A single variable value is randomly selected from each interval. The n values for x_1 are randomly paired without replacement with the n values for x_2 to produce n pairs of variable values. These pairs are randomly combined without replacement with the n values for x_3 to produce n triples of variable values. This process is then continued until all n variables have been incorporated into the sample.

In probabilistic analyses, parameter variability is addressed through a rigorous mathematical procedure. Combinations of parameters leading to the highest projected outcome are calculated through the sampling procedure.

Limitations of the probabilistic approach include: requiring more computational effort and more man-time to set up, interpret and present the calculations than a deterministic approach; being less transparent for non-technical audiences than a deterministic approach; needing to recognize correlations between parameters otherwise physically unrealistic combinations of parameter values might occur; and needing to be able to justify the chosen probability distributions for each sampled parameter. More fundamentally, the use of probability theory may be inappropriate for the types of uncertainty that are to be addressed. Often it is the experts rather than the parameter values that are uncertain. Thus, the uncertainties are largely subjective. Such problems are compounded by the fact that regulatory targets are usually expressed as deterministic rather than probabilistic numbers.

To address subjective uncertainties, some authors recommend the use of subjective probability. This approach uses the probability approach discussed above, however experts judgement is used to generate the probability distribution functions (PDF) representing the resulting state of knowledge for the assessment endpoint [113]. The most common probability framework for informational uncertainties is Bayesian probability theory in which the assessments are seen to be quantification of degrees of belief.

Possibilistic approach

An alternative approach for treating subjective uncertainties is the possibilistic approach which use of fuzzy sets theory. This approach provides a conceptual framework for the solution of imprecisely formulated problems. This is one of the reasons why it has been applied in a wide variety of fields of science, from medicine to industrial process control and credibility analysis [118].

The theory of fuzzy sets was developed to treat uncertainties that are non-stochastic in nature, i.e., subjective variations. This kind of uncertainty appears due to the extreme complexity of a problem. Also in problems where subjective opinions are part of the decision-making criteria, this subjective component can be represented as a fuzzy number.

In the possibilistic approach a degree of membership is assigned for each input parameter which is a member of a fuzzy set. This allows the data to have ambiguous characteristics belonging to two or more different sets in different degrees. For example: if there are two sets (A-plums and B- peaches), what will be the classification of the nectarine, which is a hybrid of peaches and plums, within these groups? In a traditional approach, crisp sets classification, one should assign degree one or zero for the nectarine in one or another group, i. e., it is either a plum or a peach. In the fuzzy sets approach however, one can assign degree of membership 0.3 to the peach set and 0.6 to the plum set. This means that fuzzy sets theory is much more flexible allowing quantifying ambiguity in information.

Fuzzy sets could be used in safety assessment in many different ways. For example, due to the variability in soil properties Kd is expected to vary over the transport path. Expert judgment could be used to classify the values as members of the fuzzy sets High, Medium and Low Kd's. By this procedure the Kd values are transformed into fuzzy numbers. The fuzzy set Low could correspond to 10 <= Kd <= 30; Medium for 25 <= Kd <= 80 and High for 70 <= Kd <= 100. This could be very helpful for site characterization when making experiments for determination of Kd would be expensive, but at the same time a certain level of accuracy is wanted. In this example, the fuzzy sets for Kd correspond to ranges of values and the assigned degree of membership represent the degree of belief that a particular value belongs to a certain range. For certain portion of the soil Kd could have degree of membership 0.8 to the fuzzy set High, for example. Using a similar approach structure as for Monte Carlo analysis, all of the possibilistic variables are sampled and the result is a range of possible outcomes quantified by the degree of membership. This permits the analyst to judge the most likely outcome as well as the likelihood of other outcomes.

As an example, fuzzy set theory has been applied to waste characterization . In this approach, the whole repository is divided into groups of wastes according to certain characteristics like release process, waste form, inventory, package material, origin and others that could be of importance for that particular facility. As it is difficult to say exactly what is inside of each package, or even if it were known, it would be difficult to find a set of parameters that fit the hundreds of packages at the same time, the analyst would than use the appropriate techniques to assign degrees of membership for each packages into a certain group or class of set of parameters. Further these degree of membership are combined using specific techniques to find the more likely waste release from that facility.

Kato et al [124] presents a unified methodology to handle variability and uncertainty by using probabilistic and possibilistic techniques respectively for the safety assessment of radioactive waste disposal (Fig. 36). Uncertainties associated with scenarios, models and parameters were defined in terms of fuzzy membership functions derived through a series of interviews with the experts, while variability was formulated through the use of PDFs based on available data sets. The exercise demonstrated the applicability of the approach and, in particular, its advantage in quantifying uncertainties based on expert opinion and in providing information on the dependence of assessment results on the level of conservatism.

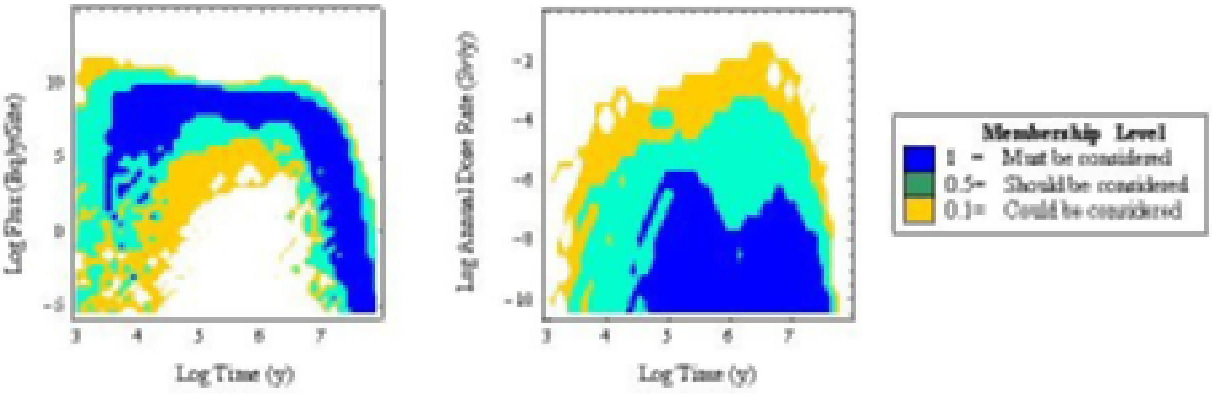


FIG. 36. Radionuclide Release Rate from the Near field (left) and Dose (right) Calculated for each Level of Plausibility [124].

It is very important not to confuse probability distribution function and membership function. Probability deals with objective variability that is a result of chance or randomness. For example, problems like picking coloured balls out of an urn . Fuzzy sets deals with ambiguousness in information due to lack of knowledge, complexity and vagueness.

6.3.4. Sensitivity analysis

Sensitivity analysis allows the effect of perturbations in the values of input parameters to be investigated. Such perturbations could arise from data/parameter uncertainties but also future and model uncertainties and therefore. therefore overall robustness of the disposal system to changes in parameter values (and changes in scenarios and models) needs to be assessed. This in turn allows attention to be focused on improving those aspects of the assessment that have the greatest impact on the model output. However, it should be recognized that different models might have sensitivity to different parameters, depending upon the structure of the model.

IAEA emphasizes the important role of sensitivity analysis. It suggests that single parameter variation or variation of combinations of a few parameters should be considered as a starting point. Different methods for varying parameter values can be used for this task, but the analysis should be structured with care to ensure that the combinations that are chosen by the computer code are not physically unrealistic. In addition, the output from the safety assessment should be structured to preserve the information needed to determine the sensitive combinations and to identify sensitive parameters.

6.4. QUALITY ASSURANCE

6.4.1. Introduction

Quality assurance (QA) is incorporates factor in building confidence in the safety assessment for a near surface disposal facility. QA is the means by which accepted systematic processes are incorporated as appropriate and applicable, into the safety assessment process. Application of QA standards is a means of helping to ensure that activities are properly planned, data and methods are properly documented, and an auditable trail is developed as the safety assessment proceeds. QA procedures provide a tool to ensure that sources of input data are traceable and that analyses are carried out in a reproducible manner. The use of QA does not necessarily ensure that the analysis is right, but the use of quality procedures does ensure that the decision process is documented, the staff carrying out tasks and reviews are identified, the method of arriving at conclusions is reviewed by identified people and there are clear signoff responsibilities.

It is now generally accepted that formalized QA procedures are required in safety assessments for waste disposal. Indeed many organizations already have a quality policy and quality manual which can be used for safety assessment.

The application of QA procedures and standards uses resources. The organization undertaking a safety assessment for a near surface disposal facility should decide on the level of certification required for different tasks and at various stages of the safety assessment. For most countries, the preparation of a safety assessment is an infrequent event and it would be more efficient if others can gain from the experience of those who have already applied QA to safety assessment for near surface repository. Inevitably there will be local differences in style and requirements, but much can be gained by reviewing how QA has been applied to previous assessments. With this in mind, the ISAM CRP undertook to seek information on the QA standards that are being or have been applied in the safety assessment projects in various countries. Information was sought on the procedures and the forms used to control processes, whether these standards are related to international recommendations and what QA procedures applied to the data and models used in the safety assessments.

Section 6.4.2 summaries QA standards of potential relevance to safety assessment, whilst in Section 6.4.3. the results of the survey on the experience of several countries in the application of QA to safety assessments for near surface disposal facilities. As part of the effort to provide specific examples of QA measures that can be applied within the safety assessment process, two audit trail forms and corresponding procedures (a parameter input control form and a document review form) were developed within ISAM. These are discussed in Section 6.

6.4.2. Quality assurance standards

The standard discussed below are not specific to the safety assessment of near surface radioactive waste disposal facilities. Therefore the use of these standards requires some care when they are implemented in a safety assessment to ensure that procedures and controls are focused on important issues and do not unnecessarily restrict progress. Furthermore, it should be recognized that the following brief review of QA standards does not cover all standards nor what those standards require.

This brief review of QA standards does not cover all standards nor what those standards require and it has not attempted to compare the applicability of the various standards to the specific case of preparation of a safety assessment for a near surface repository. Although the various standards use different formats and words, they basically cover the requirements to achieve quality assurance.

International standards organization

The main international QA standards issued by the International Standards Organization is the ISO 9000 family of standards. The standards in the ISO 9000 family are based on the understanding that all work is accomplished by a process that has inputs and outputs. A product is the result of activities or processes. The ISO 9000 family of standards provide a generic core of quality system standards applicable to a broad range of industry and economic sectors.

The original ISO 9000 standard was issued in 1987 and this has been followed by updates in 1994 and 2000. ISO 9001:1994 *Quality Systems- Model for Quality Assurance in Design, Development Production, Installation and Servicing*, provided the basis for a quality system for design and development activities such a preparation of a safety assessment. This standard placed requirements on management responsibility, establishment of a quality system, contract review, design control, document and data control, purchasing, product identification and traceability, process control, inspection and testing, control of test equipment, inspection and test status, control of non-conforming product, corrective and preventative action, handling and storage, control of quality records, internal quality audits, training, servicing, statistical techniques.

The new ISO 9000:2000 is a new approach to quality management systems. It is based on a business-oriented process approach, and features easier-to-understand requirements, increased emphasis on customer satisfaction and continuous improvements, compatibility with environmental management and other management systems, and wider applicability for activities other than traditional manufacturing activities. The 20 standards in the ISO 9000:1994 series are reduced to 3 quality management systems standards: ISO 9000:2000 (Fundamentals and vocabulary), ISO 9001:2000 (Requirements) and ISO 9004:2000 (Guidance for performance improvement). The definition of requirements in ISO 9000:2000 provides a more flexible approach which is better suited to preparation of a safety assessment than the earlier ISO 9001:1994.

The new ISO 9001:2000 is based on eight quality management principles:

(a) Customer focused organization,
(b) Leadership,
(c) Involvement of people,
(d) Process approach,
(e) System approach to management,
(f) Continual improvement,
(g) Factual approach to decision making,
(h) Mutually beneficial supplier relationship.

International Atomic Energy Agency

The IAEA issued a Code on *Quality Assurance for Safety in Nuclear Power Plants and Other Nuclear Installations* (IAEA Safety Series No. 50-C/SG-Q, 1996). This Code provides the basic requirements for establishing and implementing quality assurance programmes for the stages of siting, design, construction, commissioning, operation and decommissioning nuclear power plants. The IAEA issued Safety Guides to describe acceptable methods of implementing the Code. Safety Guide Q8 (IAEA 1996, page 169) is on *Quality Assurance in Research and Development* and Safety Guide Q9 (IAEA 1996, page 187) is on *Quality Assurance in Siting*. Much of the guidance in Safety Guide Q9 would be applicable to a safety assessment for a near surface disposal facility. For example Annex II of Safety Guide Q9 on *The Design, Testing, Application and Change Control for Computer Modelling*.

United States of America

The USA has issued several standards on QA that are relevant to near surface radioactive waste disposal facilities [125]. These standards include:

(a) 10 CFR 50, Appendix B.
(b) NUREG 1293. Quality Assurance Guidance for a Low Level Radioactive Waste Disposal Facility.
(c) NUREG 1383. Quality Assurance for Characterising LLRW Disposal Sites.
(d) ASME NQA-1-1989. Quality Assurance Program Facilities for Nuclear Facilities.

6.4.3. Findings from the ISAM QA questionnaire

The availability of information on the how quality assurance is applied in the safety assessment of near surface disposal facilities depends on how recently the assessment was undertaken. The development of formalized QA standards and systems suitable for safety assessment projects is a relatively recent development and so information relating to QA tends to be more prominent in recent assessments. Information on the QA system applied is also less readily available if the disposal facility siting process is still at an early stage.

The results from the survey undertaken within the ISAM project confirm the importance of QA standards and procedures in the siting and licensing of near surface disposal facilities. In general, the QA standards used were traceable to ISO 9001 and/or the IAEA Code on Quality Assurance.

Information on QA programmes in some countries has been published. For example QA for disposal of low and medium level radioactive waste in France is described in [125 and 126]. The application of QA to the safety assessment for low level radioactive waste disposal facilities in the USA is described in [127].

For most countries, there is no clear distinction between the QA for the safety assessment and the QA for design, construction and operation of facilities. Usually, safety assessment is one task in the overall project to establish a near surface facility, which means that the project to prepare a safety assessment adopts the QA procedures for the whole project. However, work on the safety assessment can begin well before the design and construction tasks, which means that the safety assessment can be under way before the overall QA system and procedures are developed. Clearly, it is important to ensure that the safety assessment is prepared under a QA system that will satisfy the QA criteria required for licensing the disposal facility.

For safety assessment, QA procedures need to be established for the collection of data, selection of scenarios and calculation of consequences to ensure that the results are valid, documented and defensible. As mentioned above, many organization undertaking a safety assessment will already have established QA procedures and a QA manual.

Peer reviews are an important component of QA. Peer reviews can take place at several stages within the safety assessment process and are not limited only highly technical areas. Records of peer reviews should be retained and a mechanism for tracking the review comments and resolutions should be implemented. To assist the QA development of harmonized approach the safety assessment for the post-closure assessment ISAM has developed a Document Review procedure and form for this purpose, which is discussed in Section 6.4.4.

Safety assessments are by their nature iterative, starting with a preliminary study to identify issues and processes, followed by increasing study of process is found to be important. There is a continual improvement in confidence in safety assessment results. Therefore there is a need at early stage to provide confidence in the conclusions of any initial study, which is used as the basis for decisions of what processes to further study. All inputs to decisions should be documented to ensure that the final safety assessment is acceptable when licensing begins. Indeed, any safety assessment, no matter how preliminary, should have sufficient QA to ensure that:

- All input data are properly checked and documented (approached selected and decisions made);
- Scenario selection and development is documented;
- Proper selection of computer tools (approach, criteria and decisions) the process of selecting pathways;
- The reasons for selecting particular computer codes;
- The sources and all input data are properly documented;
- The tests used to verify computer codes are analysed; and
- All results of the safety assessment correspond and are traceable to the input data.

6.4.4. Development of example QA forms and procedures

One of the common need identified by the participants in the ISAM CRP – development of simple quality assurance related procedures to be used in their own national safety programmes. Although various participants had previously obtained documents on general; quality assurance, the translation of this information into specific procedures for use in their programmes has proved difficult.

Therefore to address this concern and to provide participants with some experience in the use of QA tools it was decided to develop two forms and associated procedures; one for document review process, and input parameters for used in the safety assessment calculations.

Document review form and procedure

As the safety assessment progresses various documents are generated many of which require review before they can be accepted and become part of the project record. The documents generated can be primarily for internal use or can be targeted to an external audience (regulators etc). The document review form and procedure (Appendix J) provide a means of formalising the review process and can be used as an auditable paper trail. In this procedure the process to be followed for document review is described, the responsibilities of all individual parties in the process are defined and the description of the use of the record is provided. Additionally some guidance on time required for review and comment resolution is provided indicating the responsibility of the author (assessor) and reviewer. There view form and procedure have two significant benefits. Firstly, they provide a written record of reviewer comments in a traceable manner and obligate the reviewer to provide some indication of a suitable resolution to the comments. Secondly, the form provides a mechanism for documenting the resolution adopted and requires that both the author and reviewer agree to the resolution.

Parameter input form and procedure

The parameter input form recognizes the importance of having defined procedures for data collection and traceability. The completion of the forms for each of the parameters in the safety assessment provides a mechanism to qualify data when regulatory (or peer) review is required. The parameter input form (Appendix K) can be used by the individuals involved in the technical aspects of developing a safety assessment. It is intended to serve as the record of parameter values used in the different calculations performed as the safety assessment is developed. The form and procedure also allow documentation o the source of the parameter input value (literature, measured etc.) and also requires that the value(s) selected for use are justified, with the supporting information forming a component of the form.

6.4.5. Adequacy of the safety case

In most cases, safety assessment for near surface disposal facilities are performed with the view together with the supporting documentation and arguments to develop a safety case to be presented to the regulatory body primarily as A part of the licensing procedure. This step is represented by a decision box in the ISAM safety assessment process which implies a simple yes or no decision. However, in the case of a ‘no’ decision it may be possible to modify the system (facility design, site etc.) or some of the assessment components. Equally, the case when the results meet the assessment criteria has to be carefully analysed, and it is likely that the one or more additional iterations of safety assessment may be undertaken. Sensitivity analysis used to define the important model parameters can offer guidance on where further attention should be focused.

6.5. COMUNICATION OF THE SAFETY ASSESSMENT

An important step in safety assessment for near surface disposal facilities is the communication of the results of safety assessment to different audiences – regulators, public, etc. The ISAM project undertook a survey and obtained information from participants on the topic of communications by means of a questionnaire. The main focus of this ISAM activity was to focus on approaches and mechanisms used in different countries in dialogue with a range of stakeholders. The survey results are presented in Tables 27 and 28 in terms of the percentage of respondents. It should be noted that these survey results may reflect a bias as a result of receiving completed questionnaires mainly from those organizations which have a well developed communications programme.

Table 27 summarized the main audiences identified, the percentage of respondents communicating with each audience and the perceived importance of each audience from the point of view of the respondents. In addition to the audiences listed in Table 27, some more specific audiences were also identified such as school students, visitors groups, anti-nuclear groups or youth groups. However, the relative frequency of communications with these groups can be considered as very low compared to the other audiences discussed in Table 27.

In communicating with the different audiences, diverse methods and tools have been used by radioactive waste management organizations. The perceived relative importance of these methods and tools is presented in Table 29. Other methods and tools mentioned include workshops, topical days, seminars, official statements, personal contacts, lectures, conferences and training courses. The efficiency of the various communication methods and tools was ranked on a scale from 1 to 5 (with 5 being the most effective), although it should be noted this is a very subjective process. Most organizations have received feedback on the communication methods and tools that they have used. From regulatory and government bodies, the feedback was generally technical. Feedback from the media was generally perceived as positive. Schools and student groups tend to show a high level of interest, raising specific questions. There were a number of comments which suggested a high degree of belief that with non-governmental organizations, use of efficient communication methods and tools can contribute to improved relationships.

About 30% of the respondents had conducted surveys or opinion polls. The types of surveys conducted ranged from polls of public perception about radioactive waste to specific questions related to radioactive waste management issues. It was also mentioned that in many countries, groups other than radioactive waste management organizations also make use of public polling to determine attitudes on radioactive waste and other topics involving nuclear power.

Regarding the decision making process related to siting and construction of radioactive waste management facilities, the following audiences and stakeholders have in general been identified and consulted: local inhabitants, political authorities, non-governmental organizations, academic audiences and experts, and regulatory bodies. In some cases there are national laws or policies, which make this a requirement as part of the process of obtaining permission to develop a disposal facility.

Regarding the use of referenda in issues related to waste management; only one country/organization reported conducting one, and the result of this referendum was negative.

TABLE 27. AUDIENCES FOR SAFETY ASSESSMENTS AND PERCEIVED IMPORTANCE

Audience	Proportion of respondents (%)	Perceived importance
Regulatory Bodies	88	High
Academic and Scientific organizations	100	Medium
The Public	94	Medium
The Media	94	Medium
Government Bodies	100	Low
Non-Governmental Organizations	88	Low

TABLE 28. COMMUNICATION METHODS AND TOOLS AND THEIR RELATIVE IMPORTANCE BY AUDIENCE

Communication methods and tools	Regulatory Bodies	Academic and Scientific Organizations	The Public	The Media	Government Bodies	Non-Governmental Organizations
Pamphlets, brochures, leaflets	44	56	88	69	56	81
Video tapes	25	31	63	44	25	38
Visitor centers, facility tours,	19	56	69	69	50	50
Presentations at schools	0	25	56	0	0	0
CD-ROMs	6	13	31	13	13	0
Web pages	50	63	63	63	50	63
Technical papers	94	94	19	19	69	44
Progress reports for governments	50	38	6	6	81	19
Paid advertisements	6	6	19	25	6	13
Press conferences	6	0	19	75	6	13
Others	19	31	13	19	25	25

TABLE 29. COMMUNICATION METHODS AND TOOLS AND THEIR RELATIVE EFFICIENCY (RANKED ON A SCALE FROM 1 TO 5, 5 BEING THE MOST EFFECTIVE)

Communication methods and tools	Regulatory Bodies	Academic and Scientific Organizations	The Public	The Media	Government Bodies	Non-Governmental Organizations
Pamphlets, brochures, leaflets	2	2	4	3	2	3
Video tapes	2	3	3	3	2	3
Visitor centers, Facility tours,	2	3	4	4	3	4
Presentations at schools	1	3	3	1	1	1
CD-ROMs	3	3	3	2	2	2
Web pages	2	2	3	3	2	2
Technical papers	4	4	1	2	3	3
Progress reports for governments	4	3	1	3	4	2
Paid advertisements	2	2	3	3	1	3
Press conferences	2	2	3	4	2	2

The ISAM survey also revealed that when communicating with the different audiences there are several frequently asked questions which consistently recur:

- How dangerous is radioactive waste?
- Where does the waste come from?
- What are the plans for future management of radioactive waste in the country?
- Is the repository safe?
- What is the future of the repository?
- What sites have been studied?
- What will happen in the longer term?
- How can you put the public in jeopardy by transporting the waste on public roads or through communities and towns?
- What else are you hiding from us?

General questions may also be raised by stakeholders regarding the strategy and status of radioactive waste management activities, about the environmental impact of radioactive waste (along with impacts on plants and animals), public protection, licensing conditions and plans for deep geological disposal of radioactive waste.

6.6. LESSONS LEARNT AND CONCLUSIONS

Safety assessments should be structured in a way that provides maximum confidence in the decisions that are made on development of a radioactive waste disposal facility. Therefore confidence building is a process that needs to be followed through all stages of the safety assessment process.

In defining and considering the assessment context, it is important to choose safety criteria (in addition to those imposed by regulation) that comply with the following requirements:

- To be reliable, based on well established principles and applicable over a wide range of situations;
- To be relevant to the safety and the features of the repository and environment;
- To be simple and facilitate communication;
- To be direct and closely linked to some of the system’s features; and
- To be practical tools.

A majority of disposal regulations are based on estimated effective doses to individuals, with estimated risk to individuals also used in some jurisdictions. It is apparent that safety assessments use criteria in addition to the regulatory criteria, for comparing the modelling results. A common safety indicator used for the comparison with estimates of dose is natural background exposure levels.

The most appropriate method to represent the physical and chemical processes in mathematical models has not always been clear and model inter-comparison studies provide some insight into the effect of choosing different conceptual models or different mathematical representations of a conceptual model.

Formalized QA procedures are essential in safety assessments for near surface disposal facilities. The use of such QA systems builds confidence that proponents Whilst, neither the ISO nor the IAEA QA standards are specific to safety assessment for near surface radioactive waste disposal facilities, they do offer platforms upon which a safety assessment can be built.

Thus the use of these QA standards requires some care when they are implemented in a safety assessment to ensure that QA procedures and controls are focused on the important issues. The ISAM CRP has contributed in this respect by developing a Parameter Input Form and Document Review Form for use in the safety assessment process.

It is clear that a variety of communication methods are actively being used by various organizations in Member States involved in radioactive waste disposal. It is difficult to identify a single most effective way to provide information and gather feedback from various audiences. Therefore, most organizations have used a range of methods that they have observed in use by others.

The post-closure safety case is the main method of communicating results to the regulatory authorities, which are often the audience of prime concern. It is clear that there is a good level of similarity between the many already existing examples of safety documentation. This includes the specification of the significant components of the safety assessments report.

7. GENERAL LESSONS LEARNT AND CONCLUSIONS

The general conclusions that could be made from the work performed under the ISAM project could be summarized as follows:

- The ISAM project methodology provides a useful tool for evaluation of long term safety of near surface disposal facilities in a traceable, well documented and transparent manner. It is also recognized that there are different ways to perform safety assessment and there is no single way to do it.
- A systematic scenario generation framework (i) provides a formal basis for scrutiny of the logic of the underlying assumptions leading to the safety assessment, (ii) assures that the assessment has effectively addressed all potentially relevant FEPs and FEPs interactions to produce qualitatively different outcomes or scenarios and (iii) provides the setting for demonstrating how uncertainties are addressed and considered into the safety case.
- Finding definitions for scenario, feature, event or process (FEP) can be difficult. The definition used for scenario should be consistent with the purpose and scope of the assessment, as well as the approach followed to generate the scenarios. In ISAM, the term “FEP” is still preferred mainly because of its common use in assessment literature.
- Scenario generation, which is commonly followed today in post-closure safety assessments to address uncertainties in the future evolution of a disposal system, is central to the safety assessment process. More than one method can be used to generate and justify scenarios; there is no prescriptive approach, while commonalties and differences exist among the different approaches. The approach selected should ensure that it is directed to the overall objective of the assessment as described in the context document.
- The NEA FEPs list [19], which focuses on geological disposal systems for solid radioactive waste, was adopted and revised to be suitable for near surface disposal facilities. This forms the ISAM FEPs list, the current version of which has been developed with the intent to be comprehensive. It is also intended to be well structured,

to allow easier use and should serve as a very good starting point to identify site specific features, events and processes. Some of the FEP definitions and comments associated with the FEPs have been altered to be more representative of near surface disposal conditions. The ISAM FEPs list consists of high level FEPs that could influence the behaviour of the disposal system. The example FEPs enclosed in the list as lower level FEPs, are very useful to facilitate model development.

- The ISAM FEPs list plays a pivotal role in most scenario generation approaches, although its application may vary depending on the assessment context. The list can be reduced (or enlarged) to satisfy site specific needs using expert judgement or specific screening criteria. Documenting the screening processes (selection of FEPs) is necessary for traceability, transparency and confidence building. in safety assessment.

- There is a need to develop the models in a formal, defensible manner transparent for independent review, taking in mind that the level of detail to which the models are developed will be a function not only of the assessment context, but also of the stage of the disposal lifecycle.

- Safety case documentation appears to be the main method of communicating results to the regulatory authorities, which is often the audience of prime concern. One of the main findings regarding existing safety assessments is how the documentation or output from these efforts have a good level of similarity between them in terms of their significant components.

- The availability of the ISO 9000 and IAEA standards is a positive development for the safety assessment process. Many organizations do not have no specific quality assurance standards that originate from their own countries, and have been adapting QA standards. The Document Review Form and Parameter Input Form developed for use within the ISAM project. A majority of disposal regulations are based on predicted doses to individuals, with predicted risk to individuals also used in some jurisdictions. During discussions in ISAM and in the survey results it is apparent that safety assessment use criteria in addition their regulatory criteria, for comparison with their modelling results. On the most common safety indicators was comparison of predicted doses with natural background exposure levels.

- Uncertainty analysis is recognized as a key factor in the decision process for safety assessment. The uncertainties associated with the models used, as well as the other steps of the safety assessment process need to be identified, reduced and as far as possible quantified as part of the safety assessment.

- Understanding uncertainty will also be a major factor in the acceptance of the safety assessment case by technical audiences including the regulatory authorities.

- From the work in the area of communications it is clear that a variety of communication methods are actively being used by various organizations involved in radioactive waste disposal. It was found most organizations expend little effort to determine the most effective ways to provide information and gather feedback from various audiences. Most organizations use methods that they have observed in use by others. Safety cases are prepared with the regulator in mind.

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APPENDIX A: GENERATION OF SCENARIOS FOR GEOLOGICAL DISPOSAL SYSTEMS

A-1. INTRODUCTION

Geological disposal system as used here refers to a nuclear facility for waste disposal located underground, usually more than several hundred metres below surface, in a stable geological environment to provide long term isolation of radionuclides from the accessible environment. These disposal systems are usually used for the disposal of long-lived and/or high radioactive level waste.

A-2. DEVELOPMENT OF FEPS LISTS

As mentioned in Section 4, a common element in scenario generation methodologies is the initial construction of a comprehensive list of FEPs that can directly or indirectly influence the disposal system and the migration and fate of radionuclides within it.

The first FEP lists date back to the early 1980s, when the IAEA reproduced a list of about 60 phenomena potentially relevant to release scenarios for waste repositories [A1, A2]. This was presented as a "suggested checklist of phenomena" and has been cited as the starting point for scenario development activities in a number of repository safety studies. The IAEA reports do not state the origin of the list, but the list is similar to that reproduced in Annex B which were developed in the USA.

Also during the 1980s, Sandia National Laboratory (SNL) in the USA was developing a scenario development methodology on behalf of the US Nuclear Regulatory Commission [A3, A4]. Cranwell *et al.* [A5] and related reports present a list of 30 "potentially disruptive events and processes" that have been the basis for preliminary scenario development studies for the assessment of the disposal of transuranic wastes in bedded salt at the WIPP[4] site [A6]. In Europe, a list of 25 "primary events" was used as a starting point for a probabilistic assessment of radioactive waste disposal in clay based on a fault-tree methodology [A7], and lists of processes and events relevant to the disposal of high level waste in crystalline basement and short-lived intermediate-level wastes in marl were presented in the Swiss Project Gewähr reports [A8, A9]. In the Project Gewähr reports, tables were included to indicate, for each process or event, the time period of importance and the treatment or effect in the assessment model chain.

All of the above lists comprised events and processes that were mainly scenario initiating (e.g. potentially disruptive) phenomena, or phenomena that would lead to changes in the disposal system or the pathways for radionuclide release and migration. In the late 1980s, however, the Swedish Nuclear Fuel and Waste Management Company (SKB) and Nuclear Power Inspectorate (SKI) carried out a Joint Scenario Development exercise, which was distinct in several respects [A10].

— Lists of features, events and processes were derived by four groups of experts working semi-independently. The groups included experts from the Swedish national waste management programme, from other countries, and from broader scientific disciplines; previous lists had been derived mainly through in-house expertise.

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[4] USDOE Waste Isolation Pilot Plant, near Carlsbad, New Mexico.

— Efforts were made to record ***all*** potentially relevant FEPs, not just scenario initiating or potentially disruptive phenomena.

— For each FEP a “memo comment” was written which recorded information on the process, its effects, references to the process and whether the FEP could be omitted (screened-out) from quantitative analysis. The information was compiled in an electronic database created by dBASE III Plus.

The list focused on the performance of the engineered barriers and geosphere for a repository for spent fuel in Swedish bedrock; a separate, smaller group undertook elicitation of FEPs related to the biosphere.

In the late 1980s and early 1990s, Atomic Energy of Canada Limited (AECL) prepared a catalogue of factors for use in scenario development for post-closure assessment of the Canadian nuclear fuel waste disposal concept [A11] and, in the United Kingdom, both UK Nirex Ltd. [A12] and the UK Department of Environment [A13] developed FEP lists for assessing of low- and intermediate-level waste disposal. The AECL catalogue of factors comprised a large number of FEPs (over 250) and supplied descriptions for each, including classification codes, e.g. indicating the recommended treatment [A14]. In the UK DoE study [A13], the elicitation of the FEP list was carried out by a group of 12 experts with a broad range of relevant scientific expertise. The process of eliciting and refining the list, done over several meetings and by correspondence, was recorded in detail. Work on scenario methodology for UK Nirex Ltd. formed the basis of an example of FEPs that appeared in a NEA Scenario Working Group report [A15].

In Switzerland, comprehensive FEP catalogues have been developed for the assessment of vitrified high level waste in crystalline basement rock [A16]. A feature of this work is that the FEP database and scenario analysis is expected to provide a method of active management and development of a safety case [A17]. This is done through the mapping of FEPs to models and the identification of “reserve FEPs” and “open questions”, i.e. FEPs that are not treated in the current assessment models but may be mobilized or require consideration in future phases of assessment.

A method of identifying scenarios in terms of “independent initiating events” has been developed and applied during the CEC EVEREST project [A18]. In this method initiating events are identified from a FEP list and the scenarios that result as a consequence are described [A19].

The US Department of Energy has developed a comprehensive list of FEPs for the WIPP facility [A20]. FEPs were eliminated from quantitative treatment by detailed screening arguments. Scenarios were formed based on the set of remaining FEPs. Detailed descriptions provided of how these FEPs are incorporated in the performance assessment system model.

In the UK, a computer program has been developed to facilitate scenario analysis and conceptual model formulation [A21]. The program implements a systematic methodology based on the use of “Directed Diagrams” that are similar to fault-tree structures. It is used to record technical information, expert views and decisions from meetings and, thus, build up an audit trail for an assessment.

The NEA's Radioactive Waste Management Committee (RWMC) and its Performance Assessment Advisory Group (PAAG) set up a Working Group on the identification and selection of scenarios for performance assessment of radioactive waste repositories in 1987.

The final report of that Group provided a summary of the status of scenario methods and their application up to about 1990 [A15]. Further discussions at PAAG and RWMC meetings confirmed that scenario development continued to be an area of high priority that was particularly suitable for international co-operation. It was suggested that the development of an international database of FEPs would be a valuable follow-up activity and, in 1993, PAAG set up a Working Group to oversee the development of such a database. The final document describing the outcome of the Group's work to develop an "International Database of Features, Events and Processes" relevant to the post-closure safety of repositories for solid radioactive waste, was published in 2000 [A22].

Table A-1 summarized information on published FEP lists, catalogues and databases from OECD countries and international organizations, compiled from [A23]. This list encompasses a range of radioactive waste types, repository designs and geological environments, though it is not intended to be complete.

TABLE A.1. PUBLISHED FEP LISTS, CATALOGUES AND DATABASES FROM OECD COUNTRIES AND INTERNATIONAL ORGANIZATIONS [A22]

Country /organization	Project/disposal concept	Contents and format of FEP list/database	Reference
Belgium SCK-CEN	Assessment of geological radioactive waste disposal in the Boom clay at the Mol Site.	~130 FEPs classified according to cause based on the list appearing in NEA [1992]. Descriptions are added plus comments on the relevance to, or treatment in respect of, assessment of waste disposal at the Mol site.	A23
Canada AECL	Assessment of a reference geological disposal system consisting of spent CANDU fuel in durable containers in deposition holes in the floor of caverns in a granite pluton based on characteristics of the AECL Underground Research Laboratory at the Whiteshell site.	~280 factors classified as - vault; - geosphere; - biosphere. Coding to indicate, for example, component affected, mechanism, recommended treatment. Each factor has a description, and most have further information on the judged importance of the factor for the specific assessment study.	A24
Canada AECL	Analysis of safety issues for the preliminary safety analysis report on the Intrusion Resistant Underground Structure (IRUS) for near surface disposal of wastes.	~150 issues each with a description of the issue, response (evaluation), related issues and priority for safety assessment. These are selected from a preliminary list of ~350 issues.	A11
CEC ANDRA/IPSN/ CEN-SCK/GRS /ECN	Scenario selection in the framework of the CEC EVEREST Project. (Geological disposal)	10 "Independent Initiating Events" (IIE) are considered leading to the identification of scenarios for repositories in alternative geological environments: 7 in clay, 5 in granite, 7 in salt.	A19
France ANDRA	Assessment of deep geological disposal options.	At the time of the Working Group, a FEP database was under development at ANDRA	Unpublished

Country /organization	Project/disposal concept	Contents and format of FEP list/database	Reference
IAEA	Generic check list of phenomena potentially relevant to release scenarios for waste repositories.	~60 phenomena classified as: - natural processes and events, - human activities, - waste and repository effects. Phenomenon names only.	A1, A2
IAEA BIOMOVS II	International BIOsphere Model Validation Study – Phase II	A structured classification scheme for FEPs related to the biosphere. ~140 FEPs with descriptions, comments and codes indicating their treatment in biosphere models.	A24
NEA Scenario WG	Example compilation of features, events and processes for a geological repository (in hard rock).	~130 phenomena classified according to cause: - natural phenomena; - human activities; - waste and repository effects. with further subdivision into 13 subcategories. FEP names only.	A15
NEA Future Human Actions WG	List of "scenario-building elements for development of future human action scenarios".	~60 elements classified as: - subsurface activities; - surface activities. No descriptions, but references to discussion or analysis of FEPs in assessment studies are included.	A25
Netherlands ECN/RIVM/ RGD	Assessment of radioactive waste disposal in the salt formations in the Netherlands. (Geological disposal)	~130 FEPs classified according to cause based on the list appearing in NEA [1992]. Descriptions are added based on work in Belgium, plus comments on the relevance to, or treatment in respect of, assessment of waste disposal in salt formations.	A26
Spain	Assessment of nuclear fuel waste in a deep repository in crystalline rock. (Geological disposal)	~120 factors related to near field and geosphere, classified according to cause and the element affected. Descriptions, references and qualitative estimates of time frame, importance and probability are included (in Spanish).	A27
Sweden SKB/SKI	Joint SKB/SKI scenario development for assessment of spent fuel in copper canisters in Swedish bedrock. (Geological disposal)	~160 FEPs related to near field and geosphere, classified according to the element of the disposal system affected. Descriptions of process and effects included, plus references, and codes indicating potential treatment in assessments.	A10
Sweden SKB	Identification of important issues affecting the long term function of the geological barrier of an underground repository for spent nuclear fuel. (Geological disposal)	~150 interactions between the main features of the geological barrier, and between the geological barrier and adjacent system parts (buffer, biosphere) including judgments on their importance.	A28
Sweden SKI	SITE-94 assessment of spent fuel in copper canisters in Swedish bedrock based on the Äspö site. (Geological	~165 FEPs in the "Reference Case and Central Scenario" (names only) plus note of very much larger number of influences between FEPs with short descriptions.	A29

Country /organization	Project/disposal concept	Contents and format of FEP list/database	Reference
	disposal)		
Switzerland Nagra	Kristallin-I assessment of vitrified high level waste disposal in the crystalline basement of Northern Switzerland. (Geological disposal)	~240 FEPs classified according to main safety-relevant features of the disposal system plus external influences. Descriptions plus comments on the treatment in the safety assessment are included in a supporting report.	A16 A17
Switzerland Nagra	Assessment of disposal of low and short-lived intermediate wastes in concrete lined caverns in marl at Wellenberg.	~50 summary FEPs classified according to model domain or external influences (in German).	A30
United Kingdom DoE/HMIP	Dry Run 3 assessment of hypothetical disposal of low- and intermediate-level waste in clay strata at Harwell.	~300 FEPs classified as near field, geosphere, biosphere or short-circuit pathway. No FEP descriptions, but method of derivation/development of the FEP list is documented.	A13
United Kingdom HMIP	Assessment of UK Nirex Ltd. proposed disposal of intermediate-level waste in volcanic rock at Sellafield.	~80 FEPs classified as near field, geosphere, climatology, biosphere or short-circuit pathway. FEP descriptions and discussions of the relevance of each process.	A31
United Kingdom UK Nirex Ltd.	Assessment of proposed disposal of intermediate-level waste in volcanic rock at Sellafield.	At the time of the Working Group, a FEP database was under development at Nirex.	Unpublished
United States SNL for USNRC	Development of methodology for risk assessment of geological disposal of radioactive wastes.	~30 “potentially disruptive events and processes” classed as: - natural; - human-induced; - waste and repository-induced. Phenomenon names only.	A5
United States USDOE	WIPP Project – assessment of disposal of transuranic waste in bedded salt in south-eastern New Mexico (Geological disposal)	~240 FEPs classified as - natural; - waste- and repository-induced; - human-initiated. Detailed FEP descriptions and comments on screening out of FEPs.	A20 (Appendix SCR)

A-3. NAGRA SCENARIO GENERATION APPROACH

The National Co-operative for the Disposal of Radioactive Waste (NAGRA) approach to developing scenarios can be considered as an iterative process comprising of the following steps:

— Identification of all possible categories of FEPs relevant to geological disposal, and a classification attempting to ensure completeness (e.g. natural, human induced, waste, facility and barriers induced). International FEP lists can be used for this purpose;

— Preliminary screening of this list according to safety assessment aims and the disposal concept under consideration. This will produce a list of FEPs *relevant* and irrelevant to the current safety assessment;

— Further screening of the list of FEPs by scoping calculations of impact, estimates of likelihood and compatibility with currently available assessment models. This will produce a list of FEPs to be included in the safety assessment calculations, and lists of:

- *Unimportant* FEPs having no significant impact on safety;
- *Reserve* FEPs that will be beneficial to safety but not included in current assessment due to a lack of suitable models;
- *Open questions*, identifying issues that may adversely effect safety, but that are not adequately understood at present and thus are treated in a conservative manner.

— Identifying the influences between the FEPs and combining them into a set of scenarios to be used in consequence analysis.

A-4. SANDIA SCENARIO GENERATION APPROACH

Probabilistic approaches for scenario development stem from the work of [A5], and which has become known as the Sandia Scenario Approach. The main objective of the Sandia Approach was to combine FEPs into scenarios and to produce, by means of an objective and consistent procedure, a set of scenarios that is important in a potential disposal site analysis. Fault trees are then developed to represent key aspects of the scenario, and the branches of the fault tree are assigned probability values that may be propagated to produce an overall probability of occurrence of the scenario. This approach was further developed and modified for use in the Waste Isolation Pilot Plant (WIPP) and Yucca Mountain repository programmes [A6, A23]. In these revised approaches, FEPs were screened based on expert judgement about either likelihood or consequence; whilst remaining FEPs were assigned probabilities (largely based on expert judgement). The full scenario can then be screened based on either propagated probabilities or on expert judgement about consequences. The Sandia Scenario Approach can be described by the following general steps:

— An initial comprehensive identification of those FEPs that are considered to be important to the long term isolation of radioactive waste in a repository;
— Classification of FEPs into a scheme is then needed to make the list as complete as possible;
— The FEPs are then screened based on well-defined criteria;
— Scenarios are formed by taking specific combinations of those FEPs remaining after the screening process;
— The scenarios are then screened; and
— A final set of scenarios is then selected for use in the evaluation of the potential disposal site being considered.

Ref. [A24] describes the drawbacks of the Sandia Scenario Approach. These difficulties are primarily a poor ability to address time dependency, and the potential generation of a large number of scenarios that should be evaluated. It is, however, worth noting that both of these issues are not relevant for the U.S. high level waste disposal context for which the approach was developed. The disposal context for U.S. high level waste included analysis of the discharge at the accessible environment integrated over time, so time dependencies were largely irrelevant. The disposal context also included a requirement to include the effects of human intrusion in the base case analysis, and this dictated the need to consider larger numbers of scenarios than would a different assessment context. In short, the Sandia Scenario Approach was intentionally tailored to the unique U.S. high level waste assessment context, and should be applied with care outside of that context. In addition to the drawbacks noted in [A4], it should also be noted that probabilities assigned using the Sandia Scenario Approach are invariably derived primarily from expert judgement. As a result, use of the approach requires significant resources for elicitation of judgements, and the resulting outcomes are strongly influenced by these judgements. There is a risk when using such probabilistic approaches that the results will be misinterpreted as having more mathematical significance than they actual have.

A-5. EVEREST GENERATION APPROACH

A-5.1. General

The European Commission EVEREST approach implies a systematic procedure leading to a limited set of well-individualized scenarios covering all aspects of the possible future events or combination of events concerning the repository system. For this purpose, three logical schemes were chosen for consideration.

- The Independent Initiating Event methodology (ANDRA, IPSN) based on the production of a limited list of about 20 independent initiating events with associated induced events and processes;
- The PROSA methodology (SCK-CEN, ECN) based on a comprehensive list of about 150 FEPs; and
- The Transport Mechanism Methodology (TMM) (GRS), based on radionuclide transport mechanisms combined with the entities that have an influence on these transport mechanisms.

Each scheme ends up with a final list of scenarios. Depending on the expected severity of their consequences, these scenarios can be treated in the framework of EVEREST in a qualitative or semi-quantitative way or can be analysed in detail with associated sensitivity analysis studies. The time scale of concern, which may be quite different for each scenario, can be specified, as shown in Table A.2.

A-5.2. Independent initiating events methodology

The Independent Initiating Event (IIE) methodology was established in France by the Institute of Nuclear Safety Protection (IPSN) and the National Agency for radioactive waste management (ANDRA). This resulted in a list of scenarios included in the Basic Safety Rule for the Deep Geological Disposal of Long Lived Nuclear Waste issued in June 1991 by the Direction of the Safety of Nuclear Facilities of the Industry and Foreign Trade Ministry, and followed the recommendations of the Goguel report.

TABLE A.2. THE TIMESCALES USED IN THE EVEREST APPROACH AS WELL AS THE CONDITIONS THAT NEED TO BE CONSIDERED FOR EACH TIMESCALE

Timescale (Years)	Conditions That Need to be Considered
0 to 500	Records on the existence of the repository may be assumed to exist
500 to 10 000	A certain tectonic stability can be predicted, but human intrusion cannot be excluded
10 000 to 60 000	Ending with a Würm type glaciation
> 60 000	Strong Riss type glaciations are to be expected

Within the IIE methodology, the scenario selection proceeds in four phases:

- The first phase consists of a complete set of initiating and independent events, which may affect the repository. They may be induced by the repository itself or due to natural phenomena from outside the repository or due to human action.
- The second phase consists of a set of induced events derived from the initiating events, and by their probability. Events are eliminated which are of too low probability, have too small consequences or are irrelevant for the rock formation or the geographical location studied, or those being outside the scope of the performance assessment.
- In the third phase, scenarios are constructed starting with one initiating event or a combination of initiating events if the resulting probability is high enough.
- The final phase consists of scenario selection and definition of scenario families. Envelope scenarios are then identified which correspond to the scenario of the family with the greatest consequences.

This approach allows a coherent definition of scenarios where all relevant phenomena connected with the independent considered events are taken into account.

A-6. PROSA SCENARIO GENERATION APPROACH

The PROSA (**PRO**babilistic **S**afety **A**ssessment) methodology developed for the Boom clay at the Mol site in Belgium [A25] is based on the principle that the repository is a multi-barrier system, whose evolution can be characterized by the state of the barriers. For each barrier, a number of FEPs or combination of so called primary FEPs, can be identified which define the state of the barrier. The FEPs that directly affect the barrier state are used to define the scenarios. This approach to scenario formation is called the "top-down" approach. For each barrier state a further set of FEPs, the so called secondary FEPs, which can influence the transport and the state of the radionuclides, or which can modify some boundary conditions, can be identified. In the method, a systematic procedure is used to find the FEPs defining the scenario and identify the processes needed in the consequence analysis. This implies that for each FEP one has to assess whether it is of importance or not and if so, define its role and the part of the repository, which is affected. The approach implies an exhaustive and well-documented justification of the assumptions made.

The method used to select the scenarios and find the processes needed for consequence analysis, contains the following steps:

- Production of a list of FEPs;
- Screening of the list of FEPs;
- Classification into primary and secondary FEPs;
- Definition of possible barrier states;
- Determination of the primary and secondary FEPs for each of the barrier states;
- Screening of the primary and secondary FEPs for each of the barrier states; and
- Selection of the scenarios to be analysed further and the selection of the processes to be taken into account in the consequence analysis.

The starting list of FEPs, which might influence the state of the barriers, the release and transport of radionuclides (i.e., the long term performance of the repository), is based on available literature [A10]. The list contains 63 natural phenomena, 48 human induced phenomena and 36 waste and repository induced phenomena. Each FEP has been given an identification number. The first two digits correspond to the category given in Table A.3. The list is neither site nor host rock specific. The structure of the list is the same as the one given in the paper of the NEA working group. Accordingly, a categorization has been made related to the origin of the FEP (see Table A.3). The classification has been performed to help in completing an exhaustive list.

TABLE A.3. CATEGORIES OF FEPS CONSIDERED IN THE PROSA APPROACH

Natural Phenomena	Human-Induced Phenomena	Waste & Repository Induced Phenomena
1.1 Extra terrestrial	2.1 Design and construction	3.1 Thermal
1.2 Geological	2.2 Operation and closure	3.2 Chemical
1.3 Climatological	2.3 Post-closure sub-surface activities	3.3 Mechanical
1.4 Geomorfphological	2.4 Post-closure surface activities	3.4 Radiological
1.5 Hydrological		
1.6 Transport		
1.7 Geochemical		
1.8 Ecological		

Although it cannot be proven that the list is complete, it can be shown relatively easy that the list contains all FEPs reported in the NEA document [A15], the SKB/SKI study [A10], the Mol study, the WIPP study, [A6], PSE study, and the VEOS study. So it can be stated that the list of FEPs as used for EVEREST, contains all FEPs, which are considered to be potentially important according to the present day knowledge. This is not restricted to FEPs induced by nature or the waste but also includes human induced FEPs.

The next step in the PROSA approach is to screen the FEPs list with respect to the site (i.e. type of rock formation) and their probability of occurrence. Based on this relatively simple criterion, some natural, human induced and waste or repository induced FEPs are screened out. The screening can be done using experts, specialists in biology, applied mechanics, engineering mechanics, geology, hydrology, mathematics, physics, and theology.

The screening of the FEP list is followed by the classification of FEPs into primary and secondary FEPs. A primary FEP attacks or bypasses one or more barriers of the multi-barrier system. This implies that the primary FEPs are defining the state or evolution of the repository. The secondary FEPs influence the transport of the radionuclides or boundary conditions. This implies that the secondary FEPs determine the transport of the radionuclides for a given state or evolution of the repository and should be included in the transport model or code.

For the definition of the states or barrier evolution in the multi-barrier system, a simple division into present or bypassed FEPs is proposed. Also, a relatively small number of essential barriers are proposed to limit the number of possible barrier states. For a repository in a salt formation, for example, the multi-barrier system consists of three main barriers.

- The engineered barrier: waste form, waste container, borehole backfill, borehole plugs and seals, backfilled gallery, dams, and backfilled shafts;
- The isolation shield between the repository and the boundary of the salt formation; and
- The overburden between the salt formation and the biosphere;

For a repository in a clay formation the barriers consist of the engineered barrier, the host clay layer, and the aquifers.

The primary FEPs belonging to each barrier state are determined in the following way.

- For each primary FEP, each barrier is recorded. Some primary FEPs may influence more than one barrier;
- For each barrier, all primary FEPs influencing that barrier are listed; and
- The primary FEPs related to one barrier are split up in two subgroups. The first gives the primary FEPs influencing that barrier and the second gives the primary FEPs bypassing that barrier.

For each barrier state the radionuclide transport and exposure is determined by the secondary FEPs. The determination of the secondary FEPs for each barrier states is a straightforward procedure:

- For each secondary FEP, the barrier involved is recorded;
- For each barrier and for the biosphere all secondary FEPs related to that barrier are listed; and
- For each barrier state, the secondary FEPs related to the barriers in that barrier state are listed.

Prior to the consequence analysis the primary and secondary FEP lists have to be screened. Some FEPs can be ignored without a detailed analysis, as they will not significantly influence the consequences.

In the first round of screening, the FEPs occurring more than once in a particular barrier state will be skipped. This "non-uniqueness" is a consequence of the fact that some FEPs are related to more than one barrier.

The next round of screening is based on the time scale whilst the FEPs are active. This for instance implies that for the multi-barrier states where the isolation shield is still present, all short term engineered barriers related FEPs could be ignored. From the remaining primary FEPs, making correct combinations of the dominant ones can identify the scenarios.

The consequence analysis of each scenario has to take into account all remaining secondary FEPs belonging to the barriers present.

A-7. TRANSPORT MECHANISM METHODOLOGY

The Transport Mechanism Methodology is based on the principle that humans can only be affected negatively by a repository, if the original condition of the repository changes and the biosphere is exposed to the radionuclides from the repository. A radionuclide release, on the other hand, may occur only via transport mechanisms. A transport mechanism is a process that results in a displacement of the stored radionuclide. The definition of a scenario implemented in this procedure reflects this methodology:

"... a scenario represents a combination of a transport mechanism and the involved entities (FEPs) that have the potential for radiological effects on the biosphere".

The methodology is focussed on the essential mechanism in the repository system which may convey radioactivity to humans. For the selection of scenarios used for the consequence analysis the following multi-step approach can be followed.

- A comprehensive list of all relevant FEPs, that might influence the safe disposal of radionuclides in a repository, is generated;
- A FEP list is extracted containing all possible transport mechanisms potentially relevant for the repository system;
- The transport mechanisms which have a negligible influence on radionuclide release or which have a low probability, can be ignored;
- The FEPs are chosen for the relevant transport mechanisms, which can influence the radionuclide transport process from the containers into the biosphere. The number of possible transport mechanisms combined with the FEPs that have a bearing on this transport process corresponds to the number of scenarios; and
- The representative scenarios are then constructed. Transport processes which are active simultaneously and which contribute significantly to the radionuclide release into the biosphere are combined to a representative scenario.

A-8. PROCESS SYSTEM APPROACH

The Swedish Nuclear Power Inspectorate (SKI) and Nuclear Fuel and Waste Management Co. (SKB) carried out a scenario development exercise, for a hypothetical repository for spent fuel and high level waste, using the Sandia methodology as a starting point [A10]. After this first phase SKI and SKB continued the scenario development separately. This did not include the biosphere except the impact of climate variations in geosphere, as well as some human actions that could affect the repository. The technique for scenario identification consisted of the following steps:

- Identification of Features, Events and Processes (FEPs);
- Classification of FEPs in order to attempt to assure completeness;
- Screening of these FEPs based on well-defined criteria;
- Scenario formation by combining the remaining FEPs;
- Initial screening of the formed scenarios; and
- Selection of a final set of scenarios.

An important extension of the original Sandia method introduced in the Project-90 [A26] was the Process System (PS). This concept was introduced as:

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

According to this definition, FEPs are classified based on differentiating FEPs acting within a “Process System” and those that act externally. The Process System is comprised of “internal FEPs” that are considered in physical models of the behaviour of the system. External FEPs are those that influence the system, but which are chosen to act on the system rather than to be an intrinsic part of it. One can envision the model to be a control volume, in which some FEPs are considered internal to the control volume, while others are considered to act on it from the outside. The choice of a FEP as being internal or external is largely dependent on the preference of the analyst, and on the practicality of explicitly including FEPs in a mathematical model. Some of the external FEPs may be considered to be “scenario-generating FEPs.” These scenario-generating FEPs are chosen to be the external FEPs that lead to strongly different potential future evolution patterns for the site. Consequently, several similar external FEPs can be considered to be represented by a single scenario. The choice of the FEPs to be treated as scenario-generating ones is entirely qualitative. The intent is to capture the key issues that external FEPs can impose on the Process System, without explicitly modelling all possibilities.

The SKI SITE-94 exercise improved the system identification formalization, identifying explicitly the system boundaries and relationships, through the use of FEPs to define the PS and introducing the Process Influence Diagram (PID) to identify scenarios [A24].

Broadly speaking, this approach produces a similar structure to the Sandia approach, but the level of detail included in the Process System FEPs increases significantly. In addition, there was no attempt to develop probabilities associated with the FEPs and scenarios, which avoids the difficulties in the fault tree analysis. Instead, the approach of SKI relies more heavily on FEP justification using expert judgement, which is not assigned a numerical value. In the Sandia approach, an equivalent level of detail in process FEPs has been considered to be part of a "Conceptual Model Manager," which is considered to be separate from the FEP process [A27]. The Conceptual Model Manager for the Sandia approach is only available in limited form at this time, whereas the Process System FEP approach is more advanced in development.

Differences between published scenario development approaches represent differences between methods used for one or more of these steps, or different ordering of the steps. For instance, the original scenario development procedure developed in [A28] only calls for screening the full scenarios, whereas more recent scenario development approaches emphasize screening at the FEP level [A29] or screening both FEPs and full scenarios [A28]. Despite the differences in approaches and ordering of the steps, the concepts behind these four steps are the same for all scenario development procedures.

FEPs were categorized in the SKI SITE-94 exercise [A30] in eight categories: waste, container, buffer/backfill, repository, far field, biosphere, human actions and geological/climatic evolution. More than one category can be applied to one FEP. Screening criteria were then added to identify and subsequently remove those FEPs, which are irrelevant to the disposal concept, the disposal site and/or the assessment basis. Techniques for screening FEPs or scenarios from further consideration can be categorized as (1) based on probability, (2) based on consequence, or (3) based on expert judgement. In practice, expert judgement permeates all aspects of any screening procedure. In the case of SKI SITE-94 assessment, the criteria that were used were based on those applied by NAGRA [A17 and are presented in full in [A31] and summarized in [A24].

The next step in the process is to link the screened FEPs into a coherent structure capable of being analysed. Increasing levels of regulatory and public scrutiny of safety assessments have led to increasing requirements for scenario and model justification and traceability. Approaches that have been described in the literature for this step include (1) lists and tables, (2) influence diagrams, and (3) the Rock Engineering System, RES matrix approach.

The FEPs lists produced were used to perform an audit of the preliminary list of FEPs, which are considered to be part of the Process Influence Diagram (PID) or to be FEPs external to it. Duplicates in the audit list were eliminated at this stage, and EFEPs were identified and tabulated separately. For each FEP, which was identified for inclusion in the PID, a note was made of the addition, together with its cause and effect.

To facilitate the construction of the PID [A30], the Process system is divided into five main regions representing the different barriers in the KBS-3 disposal concept, namely fuel and canister, bentonite buffer, tunnel backfill, near field rock, and far field rock. Interaction between FEPs are identified and represented on the PID by arrows linking pairs of FEPs and showing the direction of the influence. In order to maintain a comprehensive record, and to avoid confusion or misinterpretation, a set of FEP documents is prepared. Each FEP has unique entry containing its description, its cause and effects, and references to the literature. These FEP records are electronically linked to the PID entries within the modelling software, to form a FEP database. Similarly, each influence is recorded on the database in terms of its code number, the nature of the interaction and the FEPs coupled.

Importance levels have to be associated with the influences between the FEPs. These revisions are made by expert judgement. However, since the importance of an influence may be scenario dependent, the scenario premises should be defined before judging the importance of the links. Importance levels are obtained by asking the question whether the influence should be included in the assessment or its influence is negligible. An importance level (IL) value (taken as an integer in the range 0 to 10) is assigned to each influence, as shown in Table A.4. An influence with an importance level of 10 is one where it would be completely unreasonable to ignore in an assessment.

After identifying a set of EFEPs to form scenarios, these EFEPs need to be applied to the PID in order to check for potential changes in influence levels, etc.

The main difference between different systematic scenario development methods concerns the means of structuring the Process system. In the RES system [Eng *et al.*, 1994], which was developed for approaching rock engineering problems, the structuring of the PS is achieved by the use of an interaction matrix. The main variables or parameters of the studied system are identified and listed along the leading diagonal of a square matrix. The interactions between the diagonal elements occur in the off-diagonal terms. The initial conditions and states of the repository components covered by the PS as well as of the boundary conditions have to be defined. The identification of interactions and the setting of priorities may reveal requirements on modifications of the definitions of the diagonal elements in the matrix. Building the interaction matrix is therefore an iterative process. The SKB are developing and applying the RES methodology [A32], [A29]. Other applications of the RES methodology include the BIOMOVS II project [A33], the application for the biosphere component of the safety assessment for the proposed Yucca Mountain [A34] repository in the United States, as well as under R&D projects applications for the biosphere consideration in PA [A35].

Ref. [A36] presented an evaluation of the practical applicability of PID and RES. The most apparent difference concerned the general visualization; the resolution, RES generally contains less detail than a PID. Once constructed a RES appears to be more systematic than a PID, but the PID is more intuitive. A PID is basically generated bottom-up starting with general thermo-hydro-mechanical-chemical relations, whereas a RES is generated top-down starting with identifying the most important variables. However, in reality construction of a RES or a PID involves both top-down and bottom-up. A RES matrix maybe less adaptable to different external conditions, as this may require change of the leading diagonal elements. In a PID the effect is generally alterations of importance levels. On the other hand both approaches try to produce a rationale for the development of scenario calculation cases and an understanding of the uncertainties via representation of interdependencies within the coupled Process System. They both use expert judgement, are practical, documentable, and quality assumable with associated protocols; they can be adapted to various resolutions, nesting or subsystems.

TABLE A.4. IMPORTANCE LEVEL (IL) VALUE (TAKEN AS AN INTEGER IN THE RANGE 0-10) OF INFLUENCES OF THE PID

IL value	Importance of an influence on a full- system PA
10	Total loss of confidence in PA if influence is excluded
8	Considerable loss of confidence it is not considered
6	It should be included but effect on confidence marginal
Influences scoring below this line will normally be omitted from any assessment	
4	PA would be just acceptable without the influence
2	It may be interesting to include the influence
0	No loss in confidence in the PA if it is excluded

The complexity of time sequences, i.e. that the order of occurrence of EFEPs, as well as the time in relation to the evolutionary processes in the repository, can potentially be very important to the scenario consequences. Thus, for the SKI SITE-94 exercise, the following scenarios have been established:

- Design Scenario, which include a set of EFEPs which concern deviations from the proposed repository design and operation;
- Reference Case, which considers the repository constructed according to the Design Basis that will start to evolve even without external influences;
- Central Climate Evolution Scenario, which includes a large group of FEPs related to climate change and its effects on the large surface environment and thence on the disposal system; and
- Selection of interesting combinations of remaining EFEPs, to be applied singly or in groups to the Central Scenario.

In the last SKB exercise, SR 97 [A56], the choice of scenarios was based on the system description and experience from previous work. The method for structuring processes and interactions in the safety assessment was new. For the system description, the repository was divided into the four subsystems: fuel, canister, buffer/backfill and geosphere. All known thermal, hydraulic, mechanical and chemical processes that were of importance for the evolution of the repository were identified for each subsystem. Influences between subsystems were also charted. The state in a subsystem is characterized at any given moment by a set of variables. All variables were time-dependent and influenced by one or more processes, and all processes were influenced by one or more variables. All the processes and variables for each subsystem and their interdependencies were gathered into a diagram, which also includes interactions with adjacent subsystems. The diagram is called a THMC diagram, after the classification of the processes and interactions into thermal (T), hydraulic (H), mechanical (M) and chemical (C) categories. The diagram also contains radiation-related processes, which have to do with radioactive decay and radiation attenuation in the repository system and processes related to the transport of radionuclides.

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APPENDIX B: GENERATION OF SCENARIOS FOR NEAR SURFACE DISPOSAL SYSTEMS

B-1. GENERIC SCENARIOS

For those who do not want to go through a complete scenario generation process, a set of generic scenarios can serve as a guide to the scenarios to be considered for a specific setting and facility type. For this purpose, a list of scenarios developed in previous safety assessments can be used or a more formal procedure can be used to develop a set of generic scenarios.

B-1.1. Use of scenarios from previous assessments

Many countries have developed or partly developed safety assessments for either proposed or operating facilities. Scenarios have been defined for these assessments, although often formal scenario generation procedures have not been developed and applied. If all this experience can be distilled, then some generic descriptions of scenarios can be formulate that varied according to specific settings, facility types and waste types and conditioning. Criteria that can be used to group the scenarios used in the assessment, include:

— Status	concept or operating
— Location	coastal or inland, flat area or highland
— Climate	temperate, arid/dry, tropical
— Timeframe	short term (e.g. less than 1000 years); long term (e.g. more than 1000 years)
— Design	trench, vault, borehole, shallow tunnel
— Waste	LLW, ILW, short-lived, long-lived, loose, packaged
— Backfill/cover	soil cover, grout, concrete containers, steel containers

Based on a simple hypothetical near surface disposal proposed or operating facility a range of generic scenarios might be pertinent, as summarized in Table B.1.

TABLE B.1. RANGE OF GENERIC SCENARIOS THAT MIGHT BE PERTINENT IN SAFETY ASSESSMENT OF NEAR SURFACE RADIOACTIVE WASTE DISPOSAL FACILITIES.

Scenario Class	**Scenarios**		
Normal/Design/Reference (Where the process of disposal facility degradation over time takes place as per design)	Groundwater and Gas Pathways	by	- disposal facility barrier performance evolves and locality evolves (e.g. cliff erosion) - Water infiltration, leaching, advection, diffusion, migration - Discharges take place to surface, shore, river, cliffs, with potential for return in water/sea spray - Water ingestion, food ingestion
Altered Evolution/Intrusion (Where unintended disruptive events caused by humans, animals, plants accelerate disposal facility degradation and accelerate migration of radionuclides)	Disposal facility Disruption	by	- Site occupation (e.g. by residence, farm, agriculture), development/construction (e.g. by building, road or through well drilling), in or local to migrating radionuclide plume
Discounted (Where *some* scenarios can be discounted due to their location and operating envelope, for example)	Fire, plane crash, tsunami, heavy flood, seismic event, climate change, food chain change, extreme wind, glaciation etc		

B-1.2. Formal development of generic scenarios

B-1.2.1. General approach

An example of a formal approach to developing a set of generic post-closure scenarios was used in [B1] for the derivation of quantitative acceptance criteria for disposal of radioactive waste in near surface facilities. This approach, which has been included in this document for illustrative purposes, consists of:

- Defining the main elements to be considered in the assessment, for example the disposal facility components and the human access to the site;
- Defining the states of the components of the disposal system (barriers and human behaviour);
- Constructing the state combinations; and
- Checking the scenarios generated and grouping them into main categories.

The first component of the disposal system is composed of the wastes. They can be mixed or not mixed with a matrix (e.g. grouted), put or not put in containers. Their states are chosen as:

- Put in containment structure and *unaltered*: only a given minimal amount of water can leak through and leach the waste;
- *Partly degraded*: due to weathering, ageing or defects, an increasing substantial amount of water can leak through and leach the waste; and
- *Totally degraded or no containment structure*: the waste form is not a limiting factor for water flow and for the leaching of radioactivity.

The second component of the disposal system, the states of which are discretised, is constituted by the engineered features of the facility (the cover in particular). Their states affect the water flow rate and the potential for intrusion:

- The *unaltered* state ensures a low flow rate;
- The *partly-degraded* state tends to increase the flow rate, usually with time; and
- The *non-existing/disappeared* state means the absence of such barriers.

The geosphere (saturated and unsaturated zones) and biosphere are considered as broadly pre-determined and time invariant. Consequently, no state is attributed here even if some discussions are allowed later when discussing the scenarios generated (esp. the unsaturated zone thickness).

The human behaviour component is related to the human control of the site (social barrier). Its three main states are:

- The existence of an *institutional control period* preventing any intrusion on the site and ensuring the disposal maintenance;
- A limited possibility of *access on but without intrusion in the system*; it can be explained by the performance of a partial control (e.g. limited surveillance and environmental monitoring) preventing residence and heavy constructions but not casual intrusions; and
- The *access without restriction* if the site is released into the public domain after the institutional control period.

Having defined the main assessment components with their different states, it is possible to combine them, so that to obtain the 3 × 3 × 3 = 27 combinations (Fig. B.1.) allowed by the levels of freedom previously introduced.

B-1.2.2. List of generic scenarios

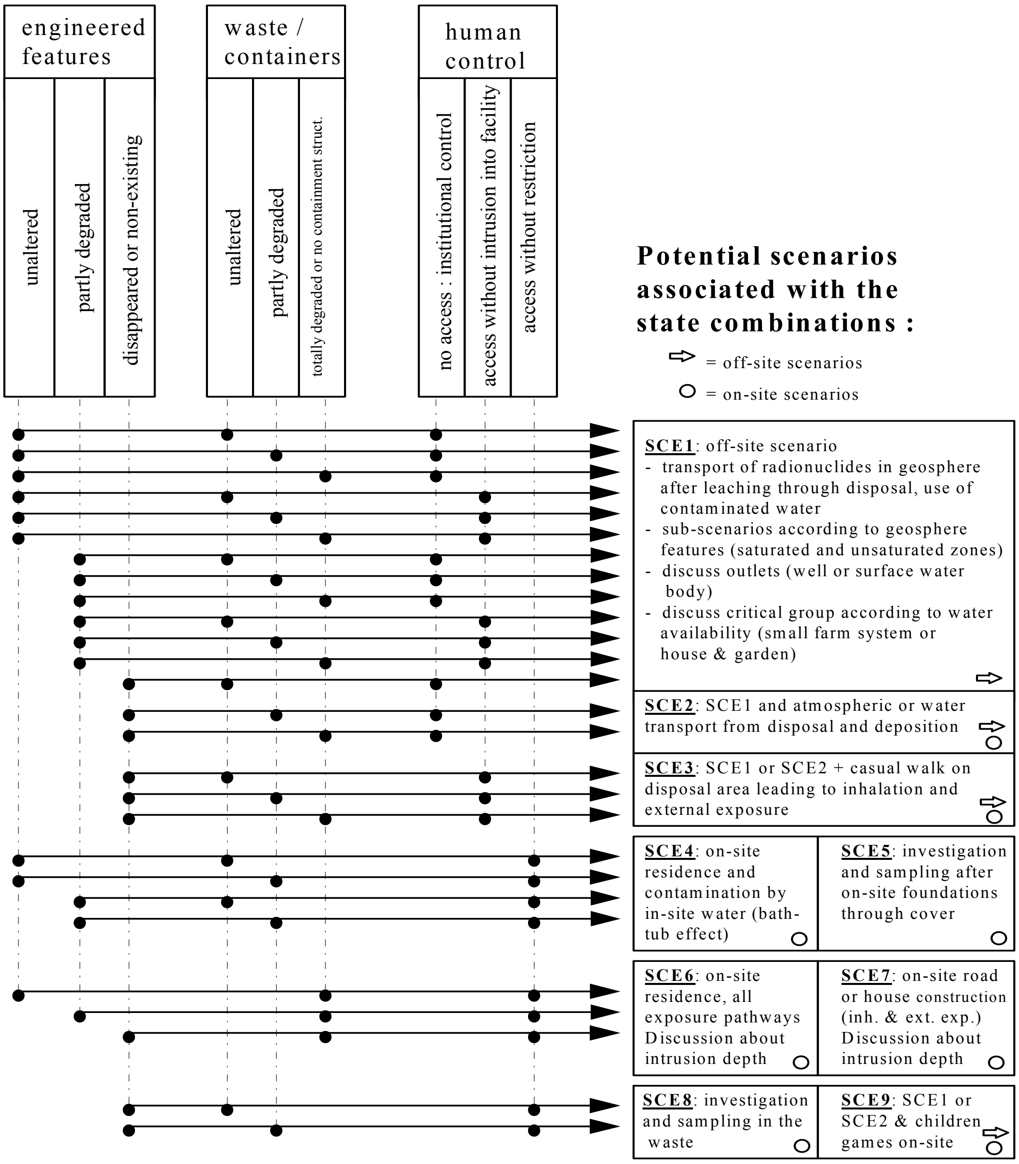
Scenarios SCE1 to SCE3 and SCE9 refer to off-site situations in the sense that the critical group is mainly located outside the disposal facility. Scenarios SCE4 to SCE8, on the other hand, describe on-site situations by which the critical group interacts directly with the disposal system.

In order to properly understand and analyse the combinations produced in Fig. B-1 is necessary at this stage to introduce that knowledge of the system, which was mentioned when discussing about the phenomena relevant to scenario analysis.

Scenario SCE1 corresponds to the use of contaminated water in the biosphere compartment at the interface with the geosphere, after migration of the radionuclides through the geosphere.

The radionuclide concentration in water at the interface does not only depend on the waste and cover performances but also on the geosphere characteristics. For example, the existence or not of an unsaturated zone below the disposal and the hydrogeological properties of the geosphere are important features to be taken into account during the modelling phase. The interface between the geosphere and the biosphere can be either a well intercepting the radioactive plume in the geosphere downstream of the disposal facility, or a surface water body. Whereas the surface water body is generally considered on a site specific basis, the well is usually arbitrarily located in an off-site location where the concentration is the highest (e.g. at the downstream site boundary). Nonetheless, it should not be forgotten that there is a need to ensure consistency between the water availability and the nature of the biosphere assumed.

Accordingly, the biosphere can be composed of a small farm system when water is not limiting, or of a kitchen garden, when water is limiting. Scenario SCE2 differs from SCE1 because of the fact that the cover has disappeared – or was not at all present – and that the waste structures are at least partly degraded, enabling the wind erosion of the disposal and the subsequent atmospheric transfer and deposition of radioactive particles in the critical group location. Depending on the site features (terrain morphology), water erosion and the transport of radionuclides by the water flow can also be processes leading to the contamination of an off-site biosphere system.



SCE1: off-site scenario
- transport of radionuclides in geosphere after leaching through disposal, use of contaminated water
- sub-scenarios according to geosphere features (saturated and unsaturated zones)
- discuss outlets (well or surface water body)
- discuss critical group according to water availability (small farm system or house & garden) ⇨

SCE2: SCE1 and atmospheric or water transport from disposal and deposition ⇨ ○

SCE3: SCE1 or SCE2 + casual walk on disposal area leading to inhalation and external exposure ⇨ ○

SCE4: on-site residence and contamination by in-site water (bath-tub effect) ○

SCE5: investigation and sampling after on-site foundations through cover ○

SCE6: on-site residence, all exposure pathways Discussion about intrusion depth ○

SCE7: on-site road or house construction (inh. & ext. exp.) Discussion about intrusion depth ○

SCE8: investigation and sampling in the waste ○

SCE9: SCE1 or SCE2 & children games on-site ⇨ ○

FIG. B-1. Generation of a Set of Scenarios (SCE) According to Various States of the Disposal and Human Behaviour Components.

In scenario SCE3, it is considered at the same time that there is no cover (any more) and casual access onto the site is possible. Under such conditions, casual internal exposure or external exposure can occur during these short-time intrusions on the disposal facility.

In the on-site scenarios SCE4 and SCE5, the existence of a cover and the unaltered/partly degraded nature of the waste structures limit the site exploitation and thus reduce the transfer pathways. It is only considered that boreholes can be drilled into the disposal facility. In the particular case of SCE4, it is envisaged that the water resulting from a leakage accumulation (bath-tub effect) could contaminate a residence system by over-flow. However, once again, it is necessary to emphasize the need for a proper justification of such a scenario (e.g. water availability and time necessary for filling the structure with water before the overflow).

In the on-site scenarios SCE6 and SCE7, the wastes are considered totally degraded and so are in a physical state that could result in multiple exposure pathways if they were to be unearthed. Nevertheless, consideration should be given to the status and thickness of the cover, which provides some protection against intrusion, due to its thickness. Moreover, in the case of fully engineered facilities (e.g. waste packages grouted in vaults), it is necessary to consider assumptions like the fact that most of the structures should have collapsed and that people will not use their technology for analysing the system; thus, the suggestion is to assume that such scenarios could not occur before a period of time in the order of several centuries, for example 500 years, consistent with the timescale for concrete degradation.

Finally, for scenarios SCE8 and SCE9, even if the cover is absent, the fact that the waste structures remain unaltered, or only partly degraded, limit the potential exposure to the radioactive materials because the number of relevant pathway is reduced for such a case.

Having defined a relevant set of scenarios, it is then necessary to sort them according to their probability of occurrence. Some events are almost certain to occur and should therefore be used to define a so-called normal evolution scenario (sometimes also called the reference case). The assumptions used in developing this normal evolution scenario are based on extrapolation of existing conditions into the future and incorporation of changes expected to occur with the passage of time, and do not usually consider major perturbations of the system. Typically, an off-site scenario like SCE1 in Fig. B-1, where a small farm system is located downstream the disposal facility is a relevant type of normal evolution scenario. This use of a farm system is a means to ensure that a comprehensive range of exposure pathways is assessed.

Events, which are less likely to occur may introduce significant perturbations to the system and require the development of so-called alternative scenarios. Even if not certain, some of them are usually considered on a deterministic basis as relevant for the safety assessment in general, and the derivation of generic waste acceptance reference levels in particular [B2]. Typically, such scenarios include on-site situations like SCE6, related to the residence on the disposal facility, and SCE7 related to a road construction across the disposal facility. Moreover, some situations are considered as very unlikely to occur, but leading potentially to important radiological impacts. For example, contact with and sampling of a relatively high concentration “hot-spot” (SCE5 and SCE8) can produce a non-negligible impact but with a low probability. In such cases, the probability of occurrence could be assessed at the same time as the associated dose.

Generally, off-site scenarios like SCE1 and on-site scenarios like SCE6 or SCE7, even if considered in the same safety assessment procedure, are assumed independent from each other. One difficulty which arises is the apparent discrepancy between the assumptions underlying off-site situations, for which the initial waste leaching is maximized, and the assumptions linked to on-site scenarios, where the loss of radioactivity from the source term is minimized by assuming loss by radioactive decay only. In fact, the on-site scenarios are often envisaged at the very end of the institutional control period during which the disposal system is supposed to be maintained. If a cover has been properly designed, then the infiltration rate can be assumed reduced and constant during the control period, leading also to limited waste leaching. Moreover, the selection of off-site scenarios is justified on the basis that the radioactive elements have to migrate through the geosphere. Such migration usually takes longer than the control period duration, except perhaps for a very mobile radionuclide such as ^{3}H.

However, one should be aware of the existence of such discrepancies, all the more since some scenarios can account for mixed situations, partly off-site and partly on-site (e.g. see SCE3 and SCE9).

In light of the above discussion, it is possible to propose a limited and justified set of scenarios to be taken as a basis for deriving the example values. For this study, the scenarios to be considered are:

- The small farm system using water extracted from a well or a surface water body as off-site scenarios (the leaching scenario – SCE1);
- The road construction scenario as an on-site scenario (the road construction scenario – SCE7);
- The on-site residence scenario on totally degraded waste (the on-site residence scenario – SCE6); and
- Due to its relevance to existing situations, it is also suggested to take into account a residence scenario incurring the contamination by leachate accumulated in the disposal facility (the on-site bathtubbing scenario – SCE4).

B-2. HUMAN INTRUSION SCENARIOS

An important issue in the safety assessment of near surface disposal facilities is the approach used to consider the future human actions, as they have significant potential to result in exposures. There is general consensus that only inadvertent human intrusion needs to be considered in the safety assessment of a disposal facility. Intentional future human actions (including actions such as sabotage or any unplanned remediation or retrieval) are considered to be out of the scope of the assessment. The argument is that current society cannot protect future societies from their own actions if they understand the potential consequences [B3].

ICRP in its publication No 81 [B4] place exposure scenarios into two broad categories: the ones initiated by natural processes and a second group by human activities. For the definition of the latter, there is need of analysing the assessment context premises, in terms of the international recommendations on the radiological protection constraints, the definition of the critical groups, as well as the time frames.

Scenarios that consider the future human activities can be defined, as for the other scenarios, from the initial screening of the FEPs List. From the structure of the FEPs list, three aspects need to be considered:

- The motivation for inadvertent disturbance of the disposal facility (drilling activities, mining and other underground activities, surface excavations, water management, etc), which are included as EFEPs;
- Factors from the system domain (wastes and engineered features, the geological and surface environment, human behaviour); and
- Radionuclides/contaminant factors (contaminant characteristics, release and migration as well as exposure factors).

B-2.1. Identification of human activities

Current human activities can have an influence in the system performance at a global scale, for example climatic changes due to the release of greenhouse to the atmosphere. They can also affect the surrounding area of the facility, at a local scale, for example the groundwater abstraction or mining activities. The scenarios that explore possible future human activities illustrate the potential behaviour of the system, whereas the scenarios, which consider current human activities (global or local), can be considered as less speculative. An analysis of the current population activities and demography can, in principle, give an estimation of the future human activities, avoiding speculations about the level of technological and scientific development.

B-2.2. Scenario description

Following the ICRP's recommendations [B4], the consequences from one or more plausible *stylized scenarios* should be considered in order to evaluate the resilience of the disposal facility to human intrusion. During the licensing process, the proponent will undertake various assessments: for the site selection, the disposal facility design, optimization, renew the licence, etc. Depending on the different purposes, the intrusion scenarios may show some differences. For example, if the assessment is performed for the site selection, more emphasis should maybe given to the human activities oriented to the exploitation of natural resources. At the design phase, more emphasis may be given to the behaviour of barriers and the resistance to human drilling (for example). It is up to the proponent to justify the relevance of the scenarios included at any stage of the disposal development process.

A relevant issue in the consideration of the future human activities in the safety assessment is the institutional controls, which play a significant role of avoiding the possibility of human intrusions into the site during the institutional control period.

B-2.3. Grouping into families of scenarios

As with other scenarios, it is possible to group human intrusion scenarios into families, according to the transport pathways and potential radiological consequences to hypothetical exposure groups. Different scenarios may have different probabilities of occurrence, varying with time, and the peak of radiological risk does not always correspond to the peak of dose. It can then be important to show, for each exposure group, the scenarios with the associated probability. However, ICRP 81 states that there is little or no scientific basis for predicting the nature of future human activities and hence it is not appropriate to consider probabilities of such events. ICRP considers that:

"… in circumstances where human intrusion could lead to doses to those living around the site sufficiently high that intervention on current criteria would almost always be justified, reasonable effort should be made to reduce the probability of human intrusion or to limit its consequences. In this respect, an existing annual dose of around 10 mSv may be used as a generic reference level below which intervention is not likely to be justifiable".

B-3. ANDRA SCENARIO GENERATION APPROACH

This scenario generation approach predates the ISAM project.

B-3.1. Strategy

The different safety assessments conducted in designing and operating the Centre de l'Aube low level radioactive waste disposal facility rely on a number of tools allowing qualitative and quantitative analysis. Confidence in the safety of a concept is secured by demonstrating that the safety level required is achieved, in others words that:

- The concept meets the protection objectives throughout the different life phases of the disposal facility; and
- The concept is robust to the different processes and events that could occur, and to the uncertainties associated with the site and the design.
- The safety assessment includes a qualitative aspect and a quantitative aspect. The qualitative analysis has three main objectives to:
- Correctly define the normal operation of the disposal facility;
- Identify the favourable arrangements or factors serving to obtain a robust concept by limiting the likelihood of disturbing events of internal and external origin occurring (preventive arrangements), or by limiting their consequences (protective arrangements); and
- Identify and describe altered scenarios based on a failure analysis, identify their likelihood and identify what kind of process, features and events are relevant.
- The quantitative analysis or performance assessment, including parameter sensitivity analysis, is aimed at the need to:
- Quantitatively check the concept proposed at each phase achieves the safety functions assigned to the different components and that the protection objective is achieved; and
- Demonstrate that in case of the failure of certain preventive arrangements, the exposures still remain acceptable.

After the selection and the description of each scenario, the quantitative assessment consists of a mathematical model, as shows in Fig. B-2.

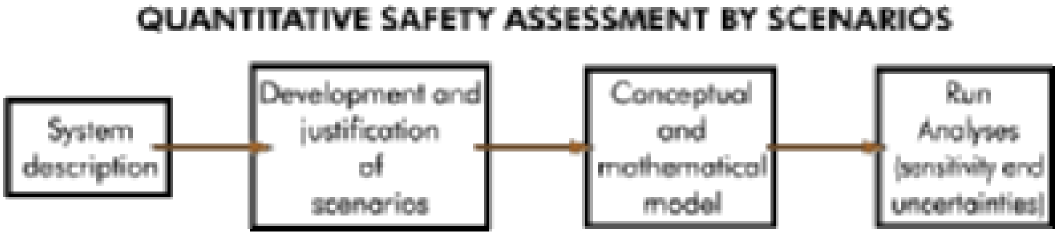


FIG. B-2. ANDRA's Quantitative Safety Assessment Process Using Scenarios.

The stages in the qualitative analysis are described in more detail below.

B-3.2. Functional analysis

Every disposal facility in France must comply with the safety objectives set by the regulatory body, the Nuclear Installation Safety Directorate (DSIN). In a design phase, functional analysis enables ANDRA to present how a disposal facility can receive waste, while meeting the safety objectives assigned to it.

These needs are first expressed overall by facility safety functions for each situation. This corresponds to the External Functional Analysis. For each disposal facility phase, an identification of external elements of the system is performed and culminates in the determination of the main function, which formulizes the interactions of the system with the external elements, as shown in Fig. B-3. For example, the external functions resulting from this method in the Centre de l'Aube are:

- Isolation of radioactivity during the operational phase; and
- Limitation and delay of transfer of the radioactivity to the biosphere and limitation of personal exposure in the post-closure phase.

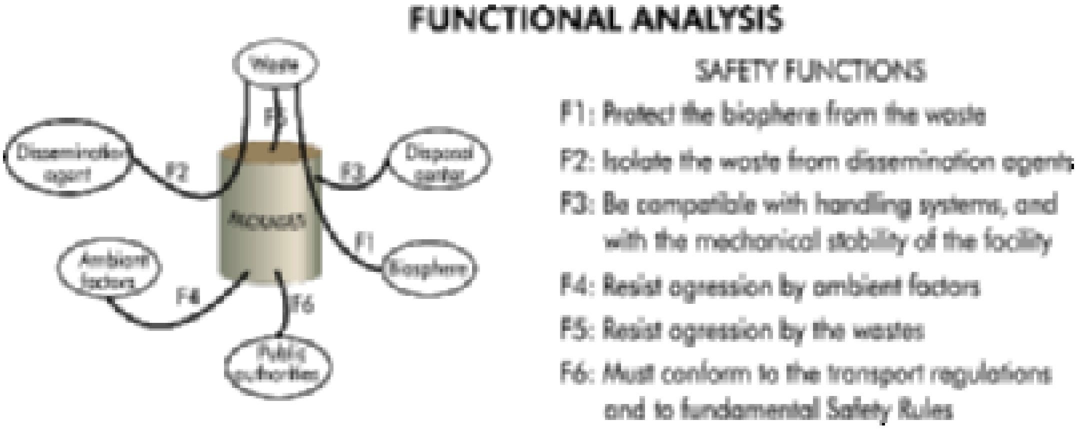


FIG. B-3. ANDRA's External Functional Analysis.

It is necessary secondly to carry out an internal functional analysis of each external function by distinguishing the different components of the facility, in order to find technical solutions.

Centre de l'Aube is based on a multi barrier system: the waste package; the disposal structure; and the host site. Each barrier could be composed of one or a combination of components, characterized by:

- Functions - for example protection of workers against irradiation during the operating phase for the Centre de l'Aube.
- Performance - the parameter and its value during the period the function is required ; for example limitation of the activity present in the packages.
- Availability - its ability to perform at the desired time; for example durability to protect the waste against external events can be guaranteed by a concrete envelope.
- Its reliability - the ability to maintain performance in different situations, for example the capability of a cap to maintain its performance during the monitoring period.

B-3.3. Qualitative Analysis

B-3.3.1. Risk analysis

On completion of the functional analysis the next step is to perform a qualitative risk analysis, a flow diagram of which is presented in Fig. B-4. This approach guarantees both the robustness of the facility faced with external events and internal failures and the traceability of the different decisions during this process.

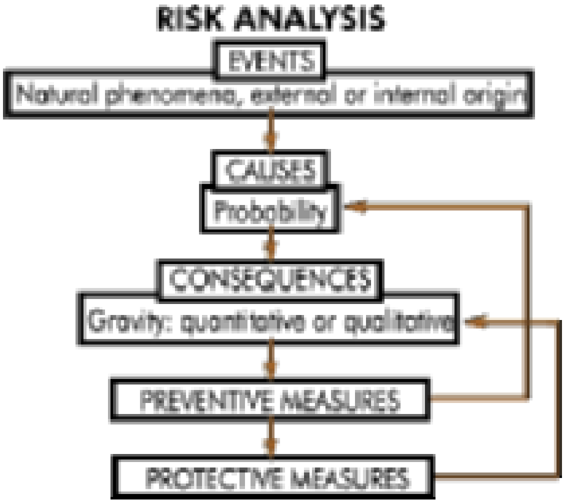


FIG. B-4. Flow Diagram of the Qualitative Risk Analysis Process Used by ANDRA.

The aim is twofold.

- To demonstrate that the different potential events involving the multi-barrier system will not give rise to unacceptable consequences, due to preventive or protective measures sometimes associated with monitoring of relevant parameters.
- To derive relevant scenarios for potential changes in the system, which could be evaluated in the quantitative analysis.

In the risk analysis, the following information is required to create arguments acceptable to the different stakeholders for the different features, events and process that have been examined.

- ***Probability***: based on knowledge of usual practices or a conventional choice. For example, in the Centre de l'Aube, intrusion events are given in the Safety Fundamental Rule RFS.I.2 after previous discussions between ANDRA and the regulator. The qualitative analysis describes the different processes involved with building a road and constructing a permanent residence. This step provides information on the probability of these events.
- ***Causes***: external events or internal process in the disposal facility. For example, in the Centre de l'Aube, the identification of causes for the dropping of waste packages during the operational phase.
- ***Preventive arrangements***: material or function serving to reduce the occurrence of disruptive events and taking into account the uncertainties in the knowledge of the causes and consequences. For example, no explosive materials in the waste package to prevent explosions.
- ***Protective arrangements***: designed to limit the effects of the occurrence of an event or a process that could not be avoided. For example, in the Centre de l'Aube, limitations on the radioactivity in the waste packages comes from deriving the effect of human intrusion in the post-closure phase and to protect the public and workers in operating events such as package dropping during handling and package fires.

This process helped to determine the important safety elements that have to be monitored in the institutional control period and to be specified in the post-closure phase.

The risk analysis in the operational phases focuses on the installation and its operating conditions, for example handling of waste packages or the detection of fire. The risk analysis in the post-closure phase focuses on the containment barriers with their evolution in time taking into account the different processes that can perturb their normal evolution including human intrusion.

B-3.3.2. Description of scenarios

At Centre de l'Aube, the wastes are immobilized in a matrix in a concrete or steel container. The packages are placed in structures comprised of (from the bottom up): a raft; shells; and (after filling) a concrete closure slab. Steel containers are themselves immobilized by a grout filling the different disposal units, while concrete containers are surrounded by gravel. The disposal structures are built on a low permeability sand layer which itself overlies a water tight clay layer. When the operating phase is finished, a cap will cover the facility.

The normal scenario, also called the design scenario, is the linking of events and processes describing the possible transfer pathways of radioactivity to the public or workers. There are two types of transfer pathways: water pathways and air pathways. The development of the normal scenario involves the following items: lists of processes and features; descriptions of the pathways; endpoints and indicators to be quantified; and a sensitivity analysis if necessary.

Using the risk analysis, the alternative scenarios for the Centre de l'Aube involving water pathways and air pathways can be identified. The alternative scenarios involving the water pathways are: the collapse of the structure cap; loss of containment performance of the structure during the institutional control period; the use of a well sunk directly above the facility in the post-closure period; and the use of a well sunk at the boundary of the facility in the institutional control and in the post-closure periods. Those involving the air pathways relate to operational and human intrusion scenarios. Operating accidents considered include package dropping during the handling operations and package fires. Intrusion scenarios for the post closure control phase include road building and the construction of a permanent residence on the facility. These scenarios involve air pathways.

B-4. AECL SCENARIO GENERATION APPROACH

This scenario generation approach predates the ISAM project.

B-4.1. Introduction

A key element of the strategy adopted by Atomic Energy of Canada Limited (AECL) for managing radioactive wastes is the construction of a near surface disposal facility called the Intrusion Resistant Underground Structure (IRUS) at AECL's Chalk River Laboratories (CRL). IRUS is a reinforced concrete vault that will be constructed above the water table in a large sand ridge and will receive about 1900 m^3 of baled and bituminized low-level radioactive waste from CRL operations [B5]. It is designed to protect human health and the environment from the waste contained in it, without a reliance on institutional control beyond 100 years following closure of the vault.

AECL has prepared a safety case for IRUS to seek a construction licence from the Atomic Energy Control Board (AECB). The safety case is contained in the IRUS Preliminary Safety Analysis Report (PSAR) [B6]. A major element of the safety case is an assessment of the long term post-closure performance of IRUS. To guide the performance assessment, the IRUS

Project Team carried out an analysis to systematically identify and evaluate the safety issues of importance to the facility. The issues-analysis procedure was adapted from a scenario analysis procedure developed and used by groups assessing disposal concepts for transuranic and high level wastes. In this section, the procedures used to perform the issues-analysis for the IRUS facility are presented, as described by [B7] and [B8].

B-4.2. Role of the safety issue analysis in preparing the IRUS PSAR

The IRUS safety case requires an evaluation of how the facility may be expected to perform over thousands of years into the future. The estimated impacts on human health and the environment must be compared to applicable regulatory criteria. After closure, IRUS will be subject to the influence of numerous Features, Events and Processes that will affect the performance of the disposal system. FEPs include the evolving characteristics of the engineered vault and its natural surroundings, perturbing external or internal events that might occur, and the actions of human and non-human biota that might disturb the vault or be affected by the waste it contains.

Additional human-related factors may also be important, such as:

- Limitations of the analysis methods and modelling used in the performance assessment; and
- Evolution of regulatory requirements [e.g. B8].

It was judged that such considerations should also be examined in developing the safety case for IRUS. The FEPs and these additional considerations were together termed safety issues to be addressed in the PSAR and its supporting documentation.

It was deemed essential to use a systematic approach in identifying and evaluating safety issues, to give confidence that all the significant issues for IRUS safety had been identified, and that each had been dealt with appropriately in the safety case. The approach that was adopted for the issue analysis addresses:

- The large number of diverse and interacting factors that may influence the closed vault and its surroundings;
- The extended period of time over which IRUS performance must be assessed to meet regulatory requirements [B9];
- The need to use different tools to address different issues, the results of which must provide a coherent, comprehensive evaluation of IRUS performance. The tools included the NSURE and GENII integrated system model computer codes, which were used to calculate the radiological and non-radiological impacts of releases from IRUS to groundwater, and of human intrusion into the vault;
- Calculations using other software on specific issues such as releases from IRUS to the atmosphere and to a nearby wetland;
- Qualitative evaluations of the significance to safety of diverse events such as meteorite strikes, or artillery fire from the Canadian Forces Base at Petawawa that adjoins the CRL site; and
- The need to delineate in detail the scenarios to be evaluated.

The process used for the safety issue analysis was based on a scenario analysis technique originally developed at Sandia National Laboratories for the Waste Isolation Pilot Project (WIPP) [B10, B11, B12]. The analysis also drew on studies carried out for the Swedish used fuel disposal program [B13, B14 B15] and the Canadian Nuclear Fuel Waste Management

Program [B16], and on a report by an expert group sponsored by the Nuclear Energy Agency of the Organization for Economic Co-operation and Development [B17]. The NEA study generated a FEP classification scheme for deep geological repositories that were used in Step 3 of this analysis (see below).

The process used for the IRUS safety issue analysis consisted of four steps:

Step 1) Identify the safety issues considered potentially important to IRUS performance;
Step 2) Screen the issues to judge their significance to safety, and decide on an appropriate approach to address each issue;
Step 3) Sort the issues as to where they should be dealt with in the documentation for the IRUS Project (e.g., in the PSAR, its supporting documents, the Final Safety Analysis Report (FSAR), or closure documentation).
Step 4) Document the disposition of each issue.

B-4.3. Steps in the safety issue analysis

Step 1) Identify the safety issues considered potentially important to IRUS

Significant efforts had already been made in developing a safety case for IRUS before this safety issue analysis was started [B18, B19]. The information from this earlier work was incorporated into the analysis.

In the light of comments from the regulatory authority on the documentation, and to structure the new safety case, a workshop was held [B20] to introduce to the IRUS Project Team the prior work on scenario analysis for the post-closure assessment in the Canadian Nuclear Fuel Waste Management Program (CNFWMP), [B16]. Lessons learned about the practicality of applying scenario analysis were reviewed, as were the implications of the different scopes of the two projects. The CNFWMP scenario analysis was performed to guide a scoping assessment of a disposal concept, whereas the IRUS Team's analysis was for the specific IRUS design and site in support of a licensing application. The Team identified 219 FEPs for the IRUS disposal system [B21].

This initial collection of issues was supplemented by selecting FEPs documented in other programs [B13, B14, B15, B16, B22], as well as AECB comments on [B19]. Some 351 safety issues were eventually considered to be relevant to the post-closure performance of IRUS.

Over the following three months, bi-weekly meetings of the Project Team were devoted to clarifying the intent of each of the 351 issues.

Step 2) Screen the issues to judge their significance to safety, and decide on an appropriate approach to address each issue.

As a result of this extensive review, 48 of the 351 issues were set aside as being either physically unreasonable, not applicable to IRUS, or covered under other FEPs. The remaining issues were consolidated into 149 more broadly defined issues [B23]. Each of the 149 issues was then classified as either:

— NP — resulting from natural phenomena that might occur in the disposal system;
— HA — connected with human activities involved in the IRUS Project (including the performance assessment itself); or
— WRE — originating in the characteristics of the waste or disposal facility (vault).

The 149 issues were then cross-referenced to the NEA classification scheme and to the CNFWMP classification scheme [B16, B24], and to the comments received from the AECB on Revision 2 of the PSAR. Each issue was described in detail, and approaches to dealing with each issue were decided upon.

Step 3) Sort the issues as to where they should be dealt with in the documentation for the IRUS Project.

Each of the 149 issues was assigned a level of priority for depth of study and location in the Project documentation, depending on its judged importance to safety, the feasibility of significantly improving existing knowledge, and the effort available [B25].

Priority A — To be addressed in the PSAR or its supporting documents, because it might affect the design and construction of IRUS, or the issue had been raised by the AECB in its review of the earlier IRUS safety case, or the FEP had sufficient technical importance that it needed to be addressed now;

- B Important, but could be addressed later in the FSAR;
- C Warranting a few paragraphs in the present document;
- C+ (An interim classification) Requiring further discussion with other experts to see if the issue should be treated as a priority A, B, or C.

Each issue was assigned to one or more individuals on the Project Team to be dealt with. Category "A" issues are discussed in the PSAR itself and/or supporting documents devoted to the topic. Discussions were held with the primary authors of the PSAR to ensure that the issue was addressed in the author's section. The authors of other PSAR sections touching on the issue were asked to refer the reader to the primary discussion. Although priority B issues could be dealt with at a later stage of the IRUS Project, it was found to be convenient to document them in the present report.

Step 4) Document the disposition of each issue

Documentation of the final list of safety issues, including the priority assigned to each issue, and the actions taken to address it. For the safety issues classified as priority "A", a reference is also given to the section of the PSAR or supporting document where the primary discussion of the issue appears.

For priority B and C issues, the documentation constitutes the primary discussion of the issue. Two priority C+ issues, #28a - Buffer degradation and #105 - Erosion (of sand ridge by wind), were eventually classed as priority A issues, and are discussed in the PSAR itself. The remaining 16 C+ priority issues were treated as C priority issues.

B-5. BNFL SCENARIO GENERATION APPROACH

This scenario generation approach was developed concurrent with the ISAM project. Scenario generation is seen by BNFL as one component within a systematic approach to Post-Closure Radiological Safety Assessment (PCRSA) [B26]. Scenario analysis does not try to predict the future; rather, the aim is to identify salient changes, based on analysis of trends, within which variants are explored to investigate the importance of particular sources of uncertainty. The emphasis is therefore on providing meaningful illustrations to assist the decision making process [B27].

BNFL has adopted a systematic approach to allow a rigorous assessment to be undertaken as part of the 2002 Drigg PCRSA. As part of this assessment, relevant uncertainties are considered and transparent and traceable methods of working are adopted. The starting point is therefore a systematic consideration of all FEPs that may be relevant to the Drigg disposal system, , aimed at identifying the potential importance of uncertainties associated with this understanding both now and in the future.

From Fig. B-5, the following elements of a systematic assessment framework can be identify:

- A clear definition of the overall safety case context;
- The use of a comprehensive FEP list as the primary reference point;
- The definition of the extent, nature and content of the process system;
- A structured review and organization of EFEPs to identify relevant scenarios;
- The development and justification of alternative process system conceptualisations;
- The identification, screening and organization of FEPs relevant to the process system behaviour;
- The derivation of representative sets of calculation cases from the selected scenarios and conceptual models; and
- The tracking of information and data through the assessment in an auditable manner.

The systematic assessment approach presented in Fig. B-6 employs a number of form-based procedures and organizational and decision-making tools as aids in systematising the treatment of FEPs, scenarios, models, data and assessment issues. The most important of these tools are:

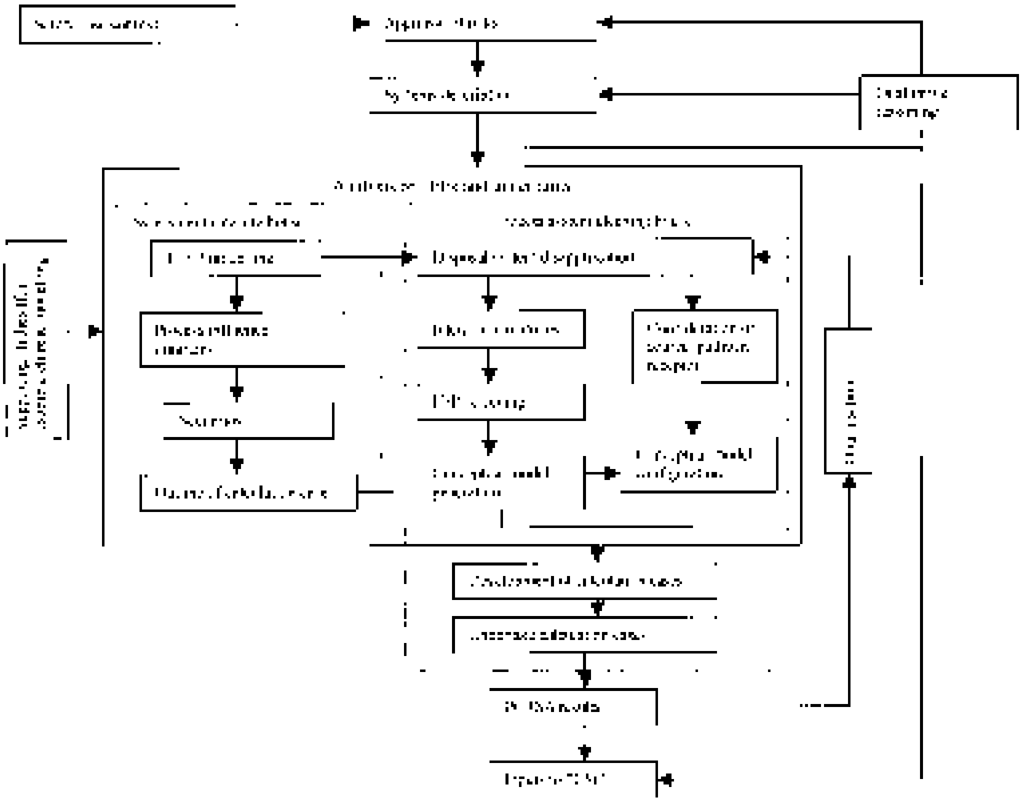


FIG. B-5. Overall Framework for BNFL's Drigg Post-Closure Radiological Safety Assessment.

- — The use of process influence diagrams which show the interdependencies between FEPs;
- — The use of FEP screening proformas to record whether a FEP is included within a model, the associated assumptions and a reference to supporting conceptual model uncertainty forms;
- — The use of interaction matrices for the purpose of describing FEP relationships within the disposal process system;
- — The use of conceptual model uncertainty forms to record nature of conceptual uncertainty, linked assumptions, justification for assumptions, and appraisal of alternative assumptions;
- — The recording of assessment data using parameter input forms;
- — The construction and maintenance of an assessment model flowchart as a tool for organising the available tools, techniques and experts that are used within an assessment; and
- — The use of clearing houses which comprise groups of experts who are charged with advising on how information should be employed in the assessment, model or procedure.

Each of these procedures and tools is discussed in more detail in [B26]. As shown in Fig. B-6, the stages for the systematic derivation of scenarios for the 2002 Drigg PCRSA are:

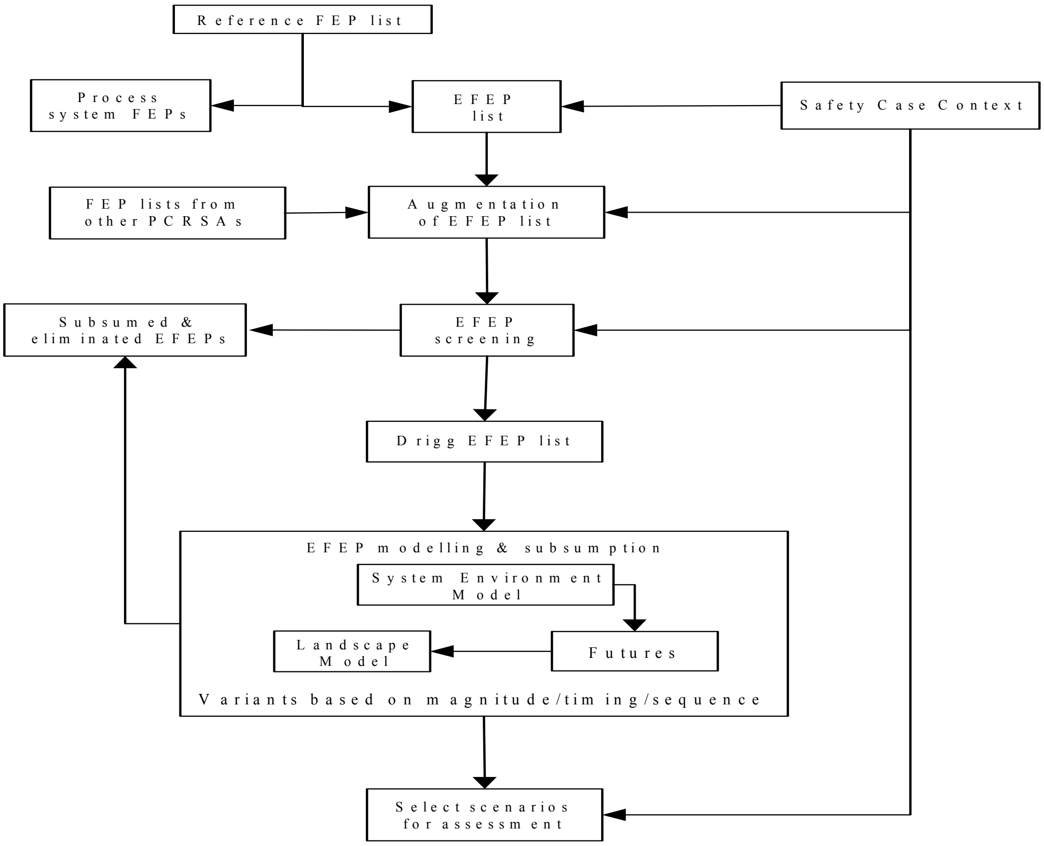


FIG. B-6. Outline Framework for the Derivation of Scenario in the BNFL Scenario Generation Approach.

- — To agree a definition of scenario in relation to the safety case context;
- — To derive an EFEPs list using a comprehensive FEP list;
- — To screen the EFEPs list to derive a Drigg-specific EFEPs list;
- — To develop an EFEPs model for the system environment and for the landscape;

- To use the system environment model to identify a set of qualitatively distinct futures for further analysis;
- To examine the response of the landscape model for each future of the system environment model;
- To examine the response of the disposal process system to the EFEPs represented in the system environment and landscape model; and
- To select representative scenarios for assessment.

The process of EFEP analysis and scenario generation starts with the ISAM FEP list. This list defines EFEPs in broad categories and more detail is considered to be useful for application to Drigg. Information on related EFEPs from other studies has been reviewed and an augmented site specific EFEPs list for Drigg has been produced and documented [B26]. Screening of the augmented EFEP list was carried out by reviewing each EFEP against criteria such as:

- Excluded as physically implausible given the timescale of the assessment;
- Excluded as physically implausible given the site context;
- Excluded due to rate or probability relative to other EFEPs;
- Excluded due to being associated with a global disaster;
- Included elsewhere within the PCRSA (for example as the driver of a more directly relevant EFEP);
- Excluded by regulatory guidance; and
- Excluded by the safety case context.

Futures are considered to be time-histories that may be represented within a scenario. Futures relevant to the 2002 Drigg PCRSA were identified through consideration of interactions between potentially relevant EFEPs. A useful aid to this task was to consider EFEP interactions at an appropriate level of detail using a system environment model, as shown in Fig. B-7.

The landscape model forms a boundary condition between the system environment and the process system. Modelling the response of the landscape to the combined effect of the system environment EFEPs provides an evolving set of boundary conditions to the process system FEPs, shown in Fig. B-8.

Given the location of the Drigg disposal facility, high priority is given to scenarios resulting from environmental evolution associated with phenomena such as climate change and coastal erosion. A range of additional classes of scenarios, e.g. related to future human actions and to meteorite impacts, are also defined from the interaction of the system environment with the process system via the interface of the landscape model [B26].

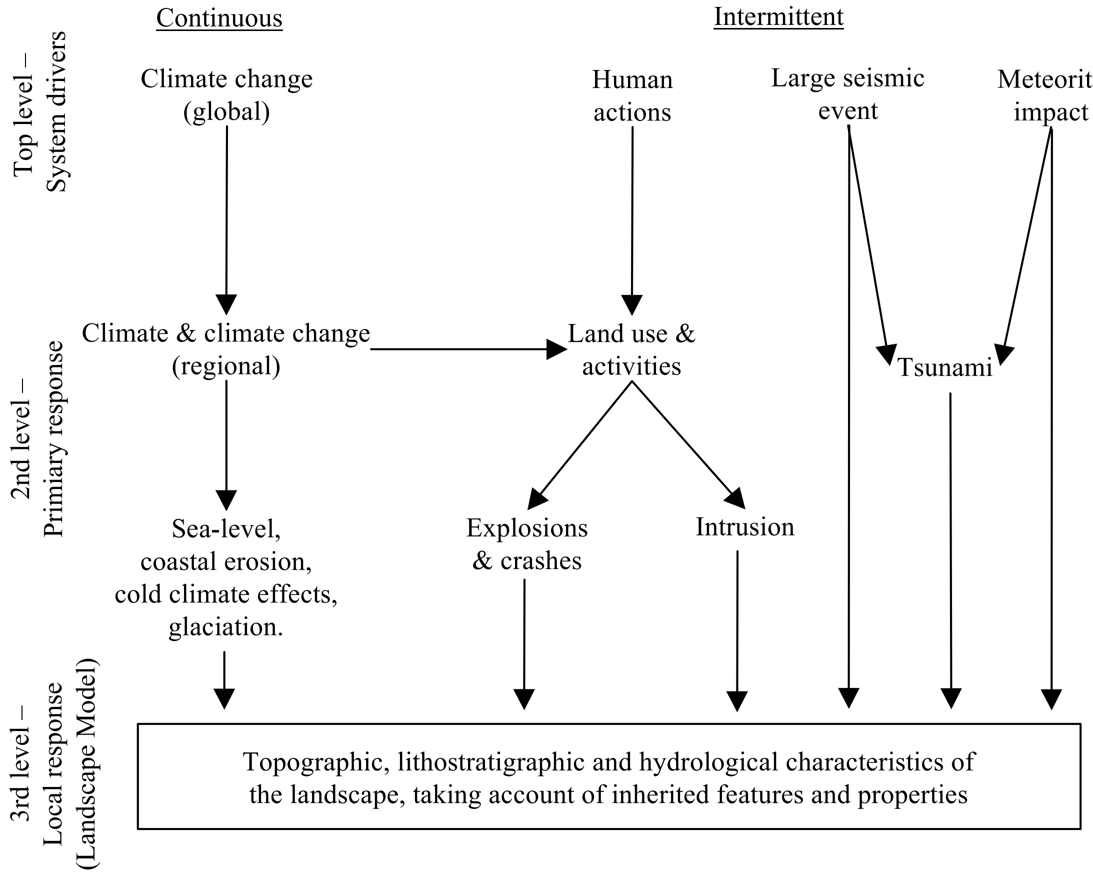


FIG. B-7. The EFEPs System *Environment Model Used in the BNFL Scenario Generation Approach.*

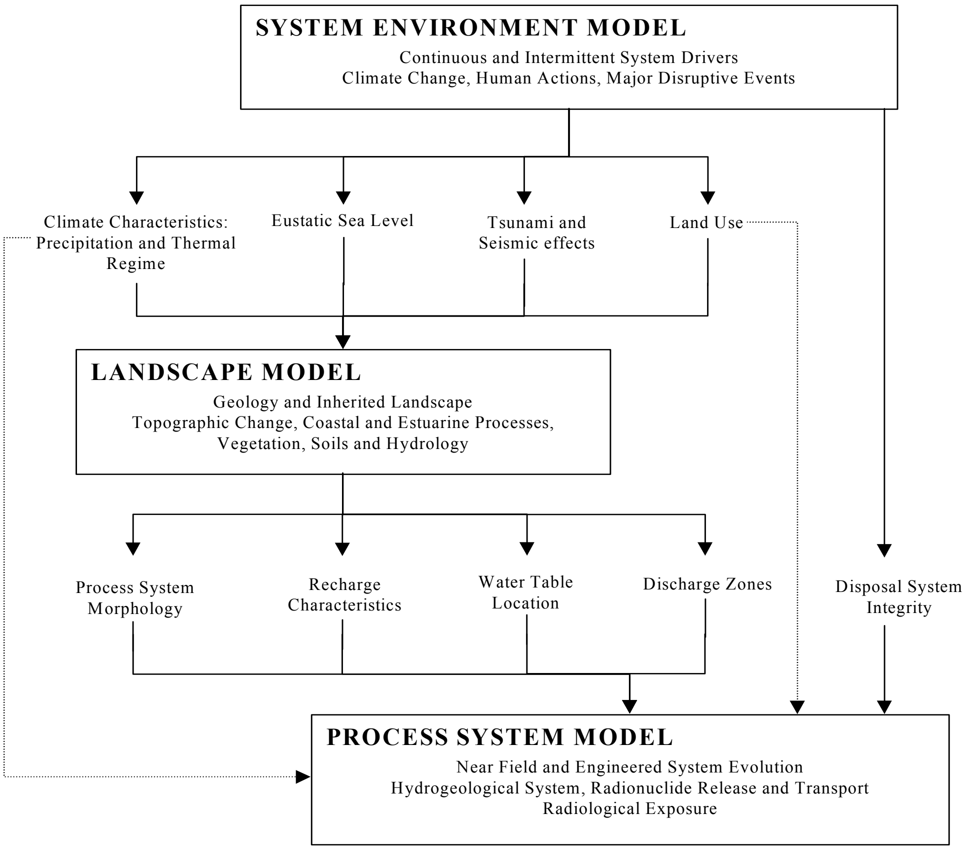


FIG. B-8. Relationship between the System Environment, Landscape and Process System Models in the BNFL Scenario Generation Process.

B-6. NRI SCENARIO GENERATION APPROACH

This scenario generation approach was developed concurrent with the ISAM project.

The safety assessment of the near surface disposal facility at Dukovany, performed in the 2000, is the fourth iteration of the safety assessment. It takes into account not only the latest data relevant to the disposal facility, its inventory and site, but also takes advantage of the results of the IAEA ISAM project.

B-6.1. Scenario generation procedure

The basic structure of the scenario generation procedure is shown in Fig. B-9. The first step is the screening of a modified ISAM FEP list. The modified ISAM FEPs list is divided into 5 blocks – assessment context, external FEPs, near field FEPs, far field FEPs and biosphere FEPs. Based on the general properties of the disposal system those FEPs, which can be excluded from further steps of scenario generation procedure, are identified. Then a new, inventory-, disposal system- and site specific FEPs list is prepared. In parallel with the FEPs list preparation, it is necessary to evaluate the properties of the waste disposal system from the point of view of its main features and safety functions. With the help of basic (top-level) assumptions for scenario development and the disposal system specific FEPs list, it is possible to define the scenarios. Because scenarios represent only the general description of the disposal system evolution, their detailed qualitative analysis is needed. Therefore the scenarios are analysed with an interaction matrix approach. Interaction matrices for each of the evaluated scenarios contain not only the mutual interactions among diagonal elements, but also the pathways of clean/contaminated transport media. Each interaction is linked to FEPs. The last step of the scenario development procedure is the final audit of scenarios against the system specific FEPs list.

B-6.2. Scenario definition

The safety assessment of the Dukovany disposal facility evaluates two scenarios: a normal evolution scenario; and an intrusion and residential scenario. The normal evolution scenario is developed for the assumptions used in the design of the disposal system; i.e. the disposal system evolves in an expected way. Intrusion and residential scenario is an ‘on-site’ scenario – construction of a farmer’s house on the top of the multiple layer cover of the waste disposal facility (residential part of the scenario) and manual excavation of a drinking water well (intrusion). Only rainwater, which penetrates through the engineered barriers to the disposal vaults, is assumed as the main transport media for both scenarios. Basic assumptions for the definition of the scenarios are:

- No human intrusion events for the normal evolution scenario;
- Human intrusion for the intrusion and residential scenario;
- The climate remains as it is at present;
- The operation period of the disposal facility lasts to 2100 AD, then the disposal facility is closed over a 12-13 year period,
- There then follows a 100 years of active institutional control period to 2200 AD and 200 year passive institutional control period to 2400 AD; and
- The biosphere and agriculture practices remain as they are at present.

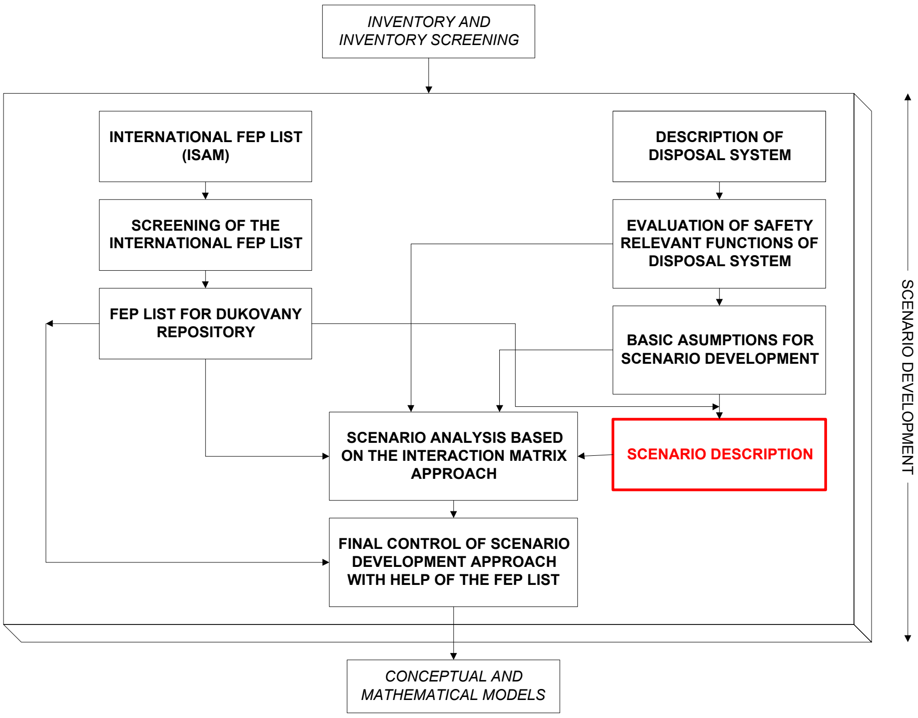


FIG. B-9. Scenario Development Procedure Used in the Dukovany Safety Assessment.

Each scenario is described for all periods of disposal facility’s existence, even though the safety assessment is focussed only on the post-institutional period. The reason for this approach is to define the initial and boundary conditions for the successive part of the scenario.

B-6.3. Description of the normal evolution scenario

The normal evolution scenario of the Dukovany disposal facility during the post-institutional period is graphically illustrated in Fig. B-10 and can be described as follows. After the end of the passive institutional control period (2400 AD), the site can have unlimited use. The disposal vaults will degrade. The multilayer cover will contain preferential pathways (cracks and joints) for the flow of rainfall water due to climatic influences, degradation and erosion processes and plant intrusion. The radioactive waste in immobilization matrices will be exposed to the water. At this time all drums will be corroded and not have any safety function. Depending on the state of the main isolation layer (APC – asphalto-prophylen-concrete) at the top, bottom and the sides of the vaults, the water will first accumulate in the disposal facility (only top and side isolation layer damaged). The contaminated water will flow out to the surface environment round the disposal facility (bathtubbing). The first period of normal evolution scenario (bathtubbing) will last about 100 years, until 2500 AD. Then the underlying APC isolation will become damaged and the contaminated water would start to flow through the unsaturated zone to the aquifer (groundwater transport). The contaminated groundwater will be used as drinking and household water.

B-6.4. Visual representation of the FEP interactions

The interaction matrix shown in Fig. B-11 contains leading diagonal (LDE's) and off-diagonal elements (ODE's). The diagonal elements, building three groups (near field, far field and biosphere), are based on the scenario description and components of the disposal system and their safety functions:

- Waste form
- Drums
- Backfill material
- Vault
- Multiplayer cover
- Unsaturated zone
- aquifer
- soil and sediments
- surface water
- atmosphere
- flora
- fauna

ODE's are derived for contaminant transport in liquid and partly solid phase. The major transport media is the rainwater flowing through the upper part of the vault into the disposal area where it comes into contact with degraded waste. Then the contaminated water flows through the elements of the disposal system into the surrounding biosphere compartments and reaches the man and the environment.

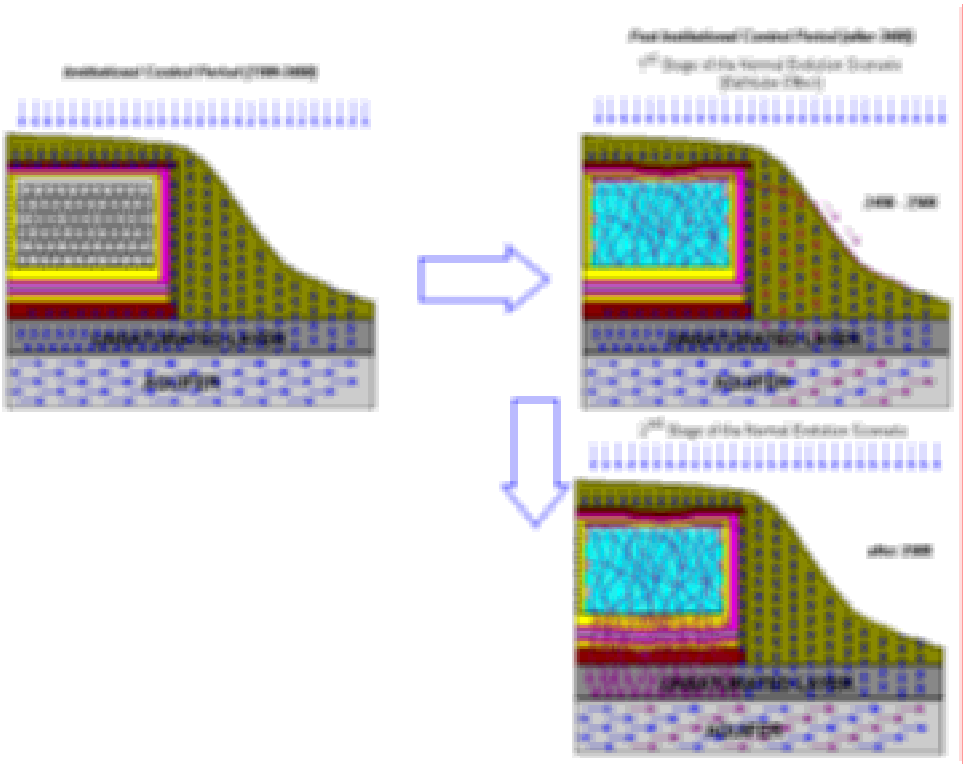


FIG. B-10. Visual Presentation of the Normal Evolution Scenario for the Dukovany Disposal Facility.

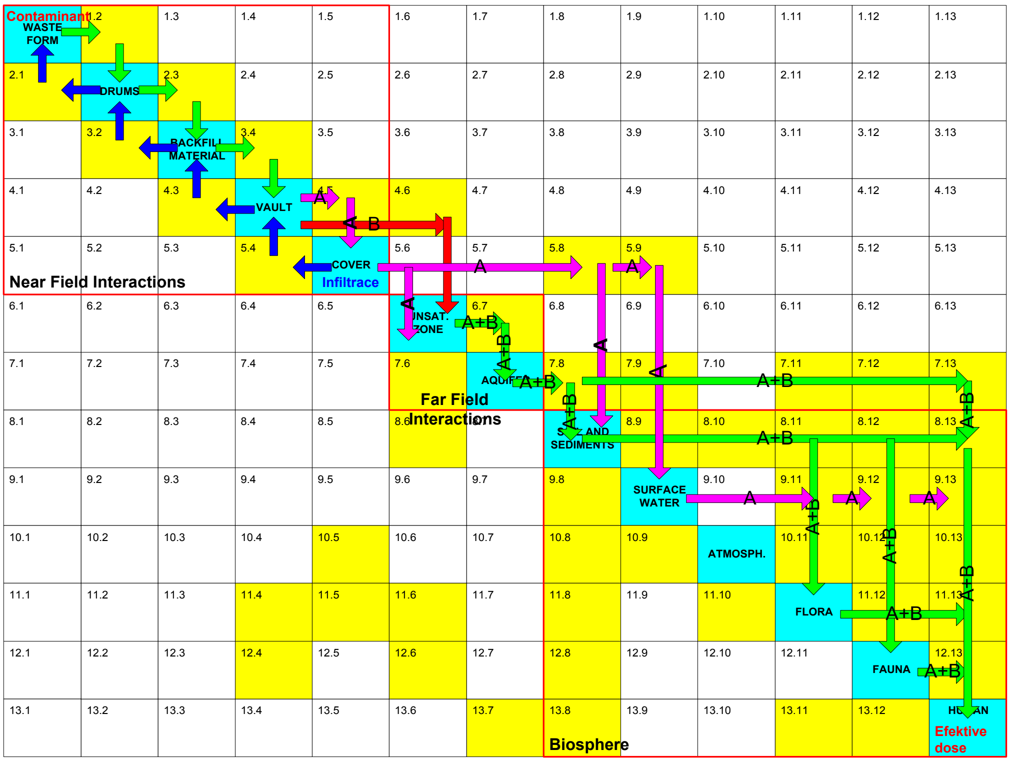


FIG. B-11. Interaction Matrix for the Normal Evolution Scenario for the Dukovany Disposal Facility (A-bathtubbing, B-groundwater transport, C–common for bathtubbing and groundwater transport stages).

B-7. NECSA SCENARIO GENERATION APPROACH

This scenario generation approach was developed concurrent with the ISAM project.

The purpose of Vaalputs as the National Radioactive Waste Disposal Facility (NRWDF) is to provide a long term management solution for radioactive waste in South Africa. At present Vaalputs, situated 100 km from Springbok in the Northern Cape Province is used only for the disposal of low- and intermediate level waste. The disposal concept adopted for Vaalputs is near surface earth trenches. The disposal facility came in operation in 1986 and to date has mainly received waste from the Koeberg Nuclear Power Plant near Cape Town.

Since the selection of Vaalputs as the NRWDF in South Africa, two safety reports have been prepared. Both these reports did not fully address post-closure safety issues. To rectify this shortcoming for the next safety analysis report due in 2002, a comprehensive post-closure safety assessment has been prepared taking on board the experience and results obtained from the ISAM project.

The primary reference point for the definition of exposure scenarios for Vaalputs is the assessment context, the ISAM FEPs list, the adoption of a Process System related approach and a detailed system description. In this section, the approach followed for scenario generation in preparing the Vaalputs safety assessment is presented.

B-7.1. Definition of the process system

A primary feature of the scenario generation framework is the classification of potentially relevant FEPs into two categories: those that are considered in physical models of the behaviour of the disposal system (Internal FEPs) and those that are treated as external FEPs (EFEPs). EFEPs are those that influence the system, in other words they act on the system rather than to be an intrinsic part of it. For this purpose, the Process System approach, as originally defined in [B27] was very useful.

The Process System comprised of *internal* FEPs (and their interdependencies) *within* the disposal system that can directly or indirectly influence the fate and transport of radionuclides from the source to the accessible environment. Given that the Process System consists of those FEPs "*...that can be predicted with at least some degree of determinism...*" it was assumed that it pertains to those FEPs associated with the *anticipated normal evolution conditions*, i.e. how the disposal system would be expected to evolve with time. Fundamental considerations in developing scenarios using this approach include the identification of the *boundary* of the Process System, the important components either side of the boundary and their interdependencies. In practice, the boundaries are defined by distinguishing between the Process System and the FEPs external to it.

B-7.1.1. Source-pathway-receptor analysis

A description of the Process System domain provides a basis to identify the potential sources, pathways and receptors for the Vaalputs disposal system. These sources, pathways and receptors were divided into the near field, geosphere/atmosphere and biosphere, respectively, that describe the key facets controlling the potential migration of radionuclides from the facility to humans and the environment.

B-7.1.2. Process system FEPs

The Process System does not represent any scenario *per se*. It merely represents the "*… organized assembly of all FEPs…under anticipated normal evolution conditions of the system".* The ISAM FEPs list was consequently screened for Process System FEPs. These were limited to Level 2 (DISPOSAL SYSTEM DOMAIN: ENVIRONMENTAL FACTORS) and Level 3 (RADIONUCLIDE/CONTAMINANT FACTORS) FEPs, because the Process System is more concerned with the internal components than the external components. Criteria used for the screening process include the assessment context, site description, and probability of occurrence. Justifications were provided for those FEPs screened from the list.

B-7.1.3. Lower level division of the process system

The division of the Process System into the three distinct spheres (i.e. the near field, geosphere and biosphere) and the identification of a set of higher-level Process System FEPs, facilitate further division of the Process System. This division, schematically illustrated in Fig. B-12, resulted in the sub-division of the system into definable components that are generally features or conceptual entities. This process advanced in steps, the aim being to break the system down in a regular and ordered manner so that each level contains components of a similar magnitude and complexity. The division stops when the system has been described in sufficient detail to allow all relevant FEPs to be identified. Before the division, definitions were provided of what is meant by the terms near field, geosphere and biosphere.

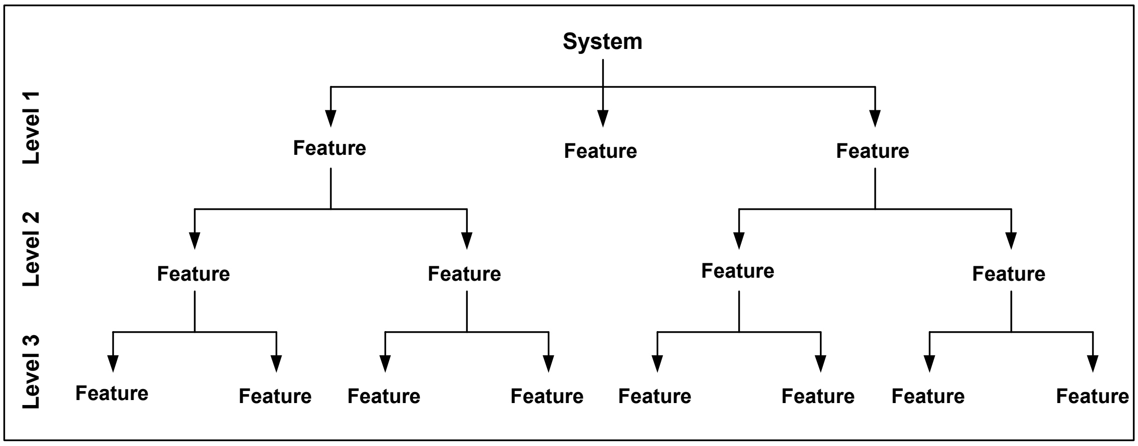


FIG. B-12. Division of the Process System into Lower Levels of Features Important to the Post-Closure Safety Assessment (after [B26]).

B-7.1.4. Visual representation of the process system

The next step in the definition of the Process System was to identify more detailed FEP and FEP interactions associated with the Process System. This required a tool more suitable for visual representation of the FEPs and the interdependencies that exist between FEPs in a logical, traceable and systematic way. The methods that are suitable for this purpose include event or fault trees, Process Influence Diagrams (PID) and the Interaction Matrix (IM). The IM approach, illustrated for the Level I division of the Process System in Table B-2, was used in the scenario generation for the Vaalputs safety assessment.

An IM was compiled for each of the Level I components of the Process System, with the features identified in the lower level division of the Level I components as diagonal elements and the interactions or influences of these features on the off-diagonal elements (processes and events). Explanations were provided of what is meant with each diagonal element, including a correlation with the FEPs list.

TABLE B-2. AN INTERACTION MATRIX FOR THE LEVEL I COMPONENTS OF THE VAALPUTS PROCESS SYSTEM

	1	**2**	**3**
1	**Near field**	Near field on geosphere	Near field on biosphere
2	Geosphere on near field	**Geosphere**	Geosphere on biosphere
3	Biosphere on near field	Biosphere on geosphere	**Biosphere**

B-7.2. Definition of the reference system

The Vaalputs Process System constitutes an organized assembly of FEPs expected under normal evolution conditions of the system, i.e. how the system will evolve assuming everything evolves goes according to design. It does not consist of conceptual and mathematical models necessary to analyse the performance of the Process System. For this purpose the *Reference System* was defined, which referred to a calculational case based on the normal evolution conditions of the system that are suitable for conceptual and mathematical model development. The Process System forms the nucleus of the Reference System, which implies that the Reference System excludes any EFEPs.

Generally, the Process System comprises of a comprehensive list of FEPs identified to be of importance for the migration of radionuclides through the system to eventually pose a dose to human beings. However, depending on the stage of the life cycle of the disposal facility, the level of information available on these FEPs may vary. This lack of information will obviously influence the level of detail that can be included in the analysis of the Process System, i.e. in the definition of the Reference System. If it is an existing facility, for example, then the level of detail that can be included in the Reference System will depend on the availability of information on FEPs identified during the definition of the Process System.

B-7.2.1. Advantages of defining the reference system

In the post-closure safety assessment of a radioactive waste disposal system, there are several advantages for defining a Reference System, i.e., a calculational case of the Process System independently of the influence of external factors [B28]. Although unrealistic in neglecting external environmental change (e.g., geological or climatical), for example, the relative simplicity of such a calculation means that it represents a practical basis for exploring sensitivities to parameter and modelling uncertainties. It constitutes a useful benchmark against which the significance of other results can be compared. Analysis of the Reference System provides a basis for evaluating the potential significance of conceptual model uncertainties and/or alternative engineering options. Variant realisations of the Reference System can be envisaged, in which different initial conditions, or different representations of Process System FEPs, are used to investigate the effects of different assumptions on system performance. A series of Reference System examples can therefore be anticipated as part of the overall suite of assessment calculations. With the Reference System properly defined and evaluated, it becomes a useful reference framework to assess the significance of alternative scenarios.

B-7.2.2. Description of the reference system

The current iteration of the Vaalputs post-closure safety assessment is the first to go through a detailed FEPs analysis. It was therefore expected that some FEPs exist, for which no or little information is available, notwithstanding the fact that Vaalputs went through a detailed site selection and characterization process. It was also uncertain how important these FEPs would be in terms the performance of the system. However, this level of uncertainty could be addressed through the definition of the Reference System. The consequence of these uncertainties, however, is that certain assumptions have to be made in defining the Reference System. For this purpose an initial *conceptual understanding* of radionuclide movement through the disposal system under normal evolution conditions was developed. Generally this could be in the form of a flow diagram or a written description of the evolution of the Reference System during the various periods of importance.

For the Vaalputs safety assessment, the Reference System description consisted of a high level description of the expected temporal evolution of the system, its safety-related features, their function and any assumptions made in defining the Reference System. For this purpose, both the FEPs selected (or not selected) in the Process System definition and the assumptions made in defining the assessment context were particularly useful. Reference was made to these FEPs and assumptions in the description.

Generally, the Reference System description should cover the operational period, the institutional control period (active and passive) and the post-institutional control period. At some stage, the safety related features in the near field would fail to meet their function, and therefore the lifetime/performance of these features should also be described. The operational period is included in the description to clarify the status of the facility at the end of the operational period and hence rule out possible “what if” questions. In particular, questions such as ‘why’, ‘when’ and ‘how’ need to be asked when considering the failure of the safety features.

As mentioned above, the Reference System does not consider the influence of any EFEPs. This means that human intrusion activities were excluded from the description. In addition, climate conditions and biosphere practices were assumed to remain as present day.

B-7.2.3. Visual representation of the reference system

In the definition of the Vaalputs Process System, an IM was used to visually represent the features, events and processes associated with the normal evolution of the near field, geosphere and biosphere. The simplifying assumptions that were incorporated into the Reference System would influence the FEPs of importance to the Reference System and consequently the interactions between the FEPs. A revised IM was consequently compiled, focusing on the FEPs associated with the Reference System Description. From this IM conceptual and mathematical models could be developed to evaluate the performance of the Reference System.

B-7.3. Alternative evolution scenarios

The Vaalputs Process System was defined as an organized assembly of FEPs expected under normal evolution conditions of the system, i.e. how the system would evolve assuming everything goes according to plan and design. The Reference System represents a calculational case of the Process System that is suitable for conceptual and mathematical model development. The Process System and consequently the Reference System considered the evolution of the system without the influence of external factors.

To generate alternative evolution scenarios it was necessary to determine what factors can influence the Process System in such a way that it will alter the normal evolution of the system. For this purpose the ISAM FEPs list was again used, because in the development of the list an attempt was made to include a comprehensive list of external scenario-generating FEPs.

The External FEPs, of which the majority will come from Layer 1 acts from outside the temporal and spatial boundaries of the Process System to influence the normal evolution of the disposal system as a function of time. The choice of the FEPs to be scenario generating ones is entirely qualitatively. Also, a single scenario can represent several similar external FEPs. The intent is to capture the key issues that external FEPs can impose on the Process System, without explicitly modelling all possibilities. At a high level, these may be categorized as follows:

- Geological processes and events;
- Climatic processes and events; and
- Future human actions and events.

B-7.3.1. Screening criteria to identify external factors

The first step to define a set of alternative evolution scenarios for Vaalputs was to screen the external (scenario-generating) factors in the ISAM FEPs list for those FEPs applicable to the Vaalputs post-closure safety assessment. Criteria that can be used for the purpose of the screening includes [B28]:

- Physically implausible given the time scale of the assessment (e.g., orogeny and volcanic activity);
- Physically implausible given the site context (e.g., geothermal effects);
- Rate or probability small relative to other EFEPs (e.g., large meteorite impact);
- Global disaster (e.g., extreme global warming creating a tropical/desert climate);
- Included elsewhere (e.g., human impacts on climate change);
- Excluded by regulatory guidance (e.g., technological development); and
- Excluded by assessment context (e.g., species evolution).

Those FEPs carried forward should be considered at a more detailed level in order to assess their relative importance to the development of representative scenarios. Justifications were provided for those FEPs excluded from the original list.

B-7.3.2. Grouping of EFEPs into alternative evolution scenarios

After careful examination of the EFEPs selected in the screening of the FEPs list, it was clear that the following three classes of scenarios could be identified for the Vaalputs post-closure safety assessment:

- Environmental evolution scenarios, which take account of the alternative natural evolution of the system environment and its subsequent influence on the Vaalputs disposal facility;

- Future human action scenarios such as those which may result in intrusion into the Vaalputs disposal facility; and
- Scenarios based on intermittent events, such as those involving explosions or crashes, which may result in the gross disruption of the Vaalputs disposal facility.

In previous assessments of Vaalputs, environmental evolution scenarios were included only to a certain extent, while intermittent events were considered explicitly. The latter were consequently not considered for this iteration of the safety assessment. Future human action or intrusion scenarios were not evaluated in the past. At this stage it is uncertain what the performance of the facility would be under environmental change and therefore a high priority should be given to the assessment of scenarios resulting from natural conditions associated with phenomenon such as climate change.

Vaalputs is a near surface facility with no intrusion resistance capability. It is therefore expected that future human actions can result in a significant potential exposure. It is proposed that these scenarios be assessed separately from the environmental evolution scenarios described above. Such an approach is not uncommon for the assessment of future human actions [B26], due to the speculative nature, in which they are treated.

Five alternative evolution scenarios were defined for the Vaalputs post-closure safety assessment following the grouping of the screened EFEPs. Explanations and justifications were provided for the grouping of the EFEPs, as well as a conceptual description of the possible consequence of such a grouping of events on the normal evolution of the system. The alternative evolution scenarios defined for Vaalputs are:

- Environmental Evolution Scenario A: Geological Change Scenario;
- Environmental Evolution Scenario B: Climate Change Scenario;
- Future Human Action Scenario C: Human Intrusion Scenario;
- Future Human Action Scenario D: Societal Change Scenario; and
- Future Human Action Scenario E: Archaeological Actions Scenario.

B-7.3.3. Visual representation of the alternative scenarios

The alternative evolution scenarios will not only influence the FEPs to consider, but also the values of parameters to use in the consequence analysis. To facilitate model development and to visually represent the FEP and FEP interactions associated with a scenario, an IM is compiled for each scenario.

B-8. ENEA SCENARIO GENERATION APPROACH

This scenario generation approach was developed concurrent with the ISAM project.

In Italy a considerable amount of radioactive wastes have been produced over the past thirty years of the nuclear programme. Since 1996, a major effort has been undertaken by ENEA (Italian National Agency for Energy and Environment) to provide the country with a disposal facility for LLW. A near surface LLW disposal facility based on a vault design is being considered, for a national total inventory of around 100 000 m^3 of conditioned waste.

Initially, two sites belonging to governmental establishments were first investigated. A general site selection process covering the whole national territory was started in 1997, which complies with governmental policy to promote potential sites candidatures via a volunteer process.

So far, a Geographical Information System (GIS) based methodology has been developed to produce a *Suitable Areas National Map* (SANM), in which suitable areas for the location of the LLW disposal facility are identified and evaluated, using an exclusion criteria and a point count system model appropriately developed for a suitability index calculation. The exclusion criteria applied for the location of the suitable areas in the SANM can be readily described in terms of FEPs. Therefore, the key point of the ENEA approach is the use of ISAM FEPs list not only for defining scenarios but also to approach and carried out the site selection process. Another consequence of this approach is that site selection and scenario development processes are related by means of the use of a common FEPs list. This results in a more comprehensive, robust and defensible approach to the disposal facility related issues, because of the possibility to take into account the performance assessment problems during the site selection step of the near surface LLW disposal project.

The five step approach that has been used to develop the scenarios is described in the following sub-sections.

B-8.1. Use of siting exclusion criteria to screen the FEPs list

The construction of the disposal facility is supposed to be in suitable areas defined in the SANM by means of the adoption of certain exclusion criteria. These exclusion criteria can be used to help screen the FEPs in the ISAM FEP list. The process is summarized in Table B-3.

TABLE B-3. The FEPs exclusion criteria for the setting up of the Suitable Areas National Map (SANM) in Italy.

Exclusion criteria	FEPs screened out	FEPs minimized
Islands	0.09 – Regulatory requirements and exclusion	
Areas within 50 kilometres from the national inland borders	0.09 - Regulatory requirements and exclusion	
Environmentally protected areas	0.09 - Regulatory requirements and exclusion 2.4.04 – Habits (non – diet-related behaviour) 2.4.11 – Leisure and other uses of environment	
Areas included within a certain distances from the urbanized perimeter of towns	1.4.11 – Social and institutional development 2.4.04 – Habits (non – diet-related behaviour) 2.4.11 - Leisure and other uses of environment	2.4.10 – Urban and industrial land and water use
Areas included within a certain distances from transportation network	1.4.11 - Social and institutional development	2.4.10 - Urban and industrial land and water use
Areas with elevation higher then 800 m a.s.l.;	1.3.04 – Periglacial effect 1.3.05 – Local glacial and ice sheet effects	2.3.12 – Erosion and deposition

	2.3.01 – Topography and morphology	
Areas with slope higher than 30%	2.3.01 - Topography and morphology	2.3.12 – Erosion and deposition
Flat areas around rivers corresponding to plio-pleistocenic and holocenic alluvial deposits	1.3.03 – Sea level change 2.3.10 - Meteorology	1.2.07 – Erosion and sedimentation
Areas with seismicity equal or higher than IX degree of the Mercalli's ranking system	1.2.03 - Seismicity 1.2.04 – Volcanic and magmatic activity	

B-8.2. Consideration of the assessment context

The following components of the assessment context have been considered for defining the *design scenario*:

- The purposes for which the assessment will be undertaken is, primarily, the evaluation and comparison of sites in terms of the disposal facility- geosphere-biosphere system safety performance (FEP 0.08 considered);
- The effects and consequences on the critical group due to the disposal facility construction will be calculated in terms of annual individual dose or annual individual risk (FEP 0.01 considered);
- The time period over which the annual individual dose and/or the annual individual risk will be calculated will be 10000 years (FEP 0.02 considered);
- The assessment will only consider the spatial domain which will be necessary to model in order to develop an understanding of the movement of contaminants in the Disposal facility surrounding environment (FEP 0.03 considered);
- The assessment will only assess post closure safety of the disposal facility. The disposal facility will be considered successfully closed after its operational period. No possibility of recovering the wastes is expected after the disposal facility is closed. A 300 years institutional control period will be adopted. In this way FEP 0.04 is considered whilst FEPs 1.1.02, 1.1.03, 1.1.04, 1.1.05, 1.1.06, 1.1.07, 1.1.08, 1.1.09, 1.1.10, 1.1.11, 1.1.12 and 1.1.13 are screened out.
- Human technology and behaviour is assumed to remain the same for the next 10.000 years (FEP 0.05 and 0.06 considered);
- The following equation will be used for the individual risk calculation (FEP 0.07 considered):
- *(dose consequence) × (probability of exposure) × (probability of fatal cancer per unit dose)*
- A 0.3 $mSvy^{-1}$ dose limit will be adopted in the PA analysis. The risk limit will be $1.5\times10^{-5}\,y^{-1}$ (FEP 0.09);
- The assessment will be carried out by means of a mathematical model and a computer code. A conservative approach in the definition and evaluation of the models input data will be used whenever there is insufficient or unreliable data from the quantitative/qualitative point of view. A procedure for the treatment of uncertainty based on a sensitivity analysis will have to be defined and applied to the model for its validation (FEP 0.10 considered).

B-8.3. Consideration of external factors

It is assumed that all the geological, geomorphological, hydrological and hydrogeological investigations that will be carried out at the sites will be considered suitable to screen out the FEP 1.1.01. The geological, geomorphological and climatic features of the sites are assumed to be constant (FEPs of categories 1.2 and 1.3 and FEP 1.4.01 screened out).

So far, the possibility of a human intrusion event in the design and barrier failure scenarios has not been considered (FEPs 1.4.02, 1.4.03, 1.4.04, 1.4.05, 1.4.06, 1.4.07, 1.4.08, 1.4.09, 1.4.10, 1.4.11 screened out).

B-8.4. Consideration of disposal system domain: environmental factors

Wastes and engineered features: For the preliminary assessment, the disposal facility inventory contains only those radionuclides that are considered important in terms of initial activity, half-life (considering the time period over which the assessment will be carried out), radiotoxicity and their sorption properties in the far and near field (FEP 2.1.01 considered).

The simulation model will have to be set up with the specific aim of giving the assessor the flexibility to alter the hydraulic properties of the waste containers, backfill materials and engineered barrier system. The design scenario will have to be developed taking into consideration the possibility of a slow degradation of the disposal facility multi-barrier engineered system once the institutional control period has ceased (remaining layer 2.1 FEPs considered).

Geological environment: For the assessment it will be considered that transport of radionuclides is a consequence of infiltration of rain water through the disposal facility cover, with following migration of the pollutants in the groundwater flow system. Unsaturated and saturated zones of the disposal facility and underlying aquifer are characterized by a porous flow governed by the Darcy's flow. (all FEPs of layer 2.2 screened out except 2.2.05 and 2.2.07).

Surface environment: The preliminary assessment model for each evaluated site shall consider the following features:

- Superficial aquifer characteristics (FEP 2.3.03 considered);
- Superficial water body characteristics (FEP 2.3.04 considered);
- Coastal environment characteristics (FEP 2.3.05), also in relationship with marine features (FEP 2.3.06 considered);
- Hydrological characteristics (FEP 2.3.10 considered); and
- Infiltration characteristics (FEP 2.3.11 considered).

The *remaining* FEPs of layer 2.3 will be screened out.

Human behavior: The dose and risk calculations will have to take into account the intake of water by humans of the exposed group (FEP 2.4.03 considered).

The remaining FEPs of layer 2.4 will be screened out essentially because it is assumed that areas, which are relatively undeveloped agriculturally in the analysed areas for the disposal facility location, will remain the same in the next 10000 years.

B-8.5. Consideration of contaminant characteristics

In the assessment and the scenario development it will be considered that radionuclides will remain stable in terms of radioactive decay and in-growth (FEP 3.1.01 screened out).

Radionuclides sorption characteristics will be considered by means of the K_d parameter of the waste container, backfill, engineered barrier materials and environmental compartments (FEP 3.2.03 considered).

Migration and fate of radionuclides will result from rainwater infiltration through the disposal facility cover and engineered barrier system, with following advective mobilization of contaminants in the groundwater flow system (FEP 3.2.07 considered).

The remaining FEPs of layer 3 will be screened out.

B-8.6. Selected scenarios

With reference to the FEPs examination reported in the previous sub-sections, two scenarios have been investigated: a *design scenario* and a *barrier failure scenario*. A *human intrusion scenario* is expected to be introduced in the next stage of the study.

Design Scenario: During the institutional control period all the components of the disposal facility are kept in complete working order. No contaminant leaching is expected to occur during this period.

After the 300 years institutional control period, a gradual degradation of the engineered barrier system is expected. In terms of hydraulic barrier effect, this means that after 10000 years the efficiency of the engineered barrier system is reduced by 30%. This estimation is derived from the analysis of the cement degradation process in a radioactive waste disposal facility environment reported in [B29].

Doses to the critical group will be calculated based on an intake of 2 ld^{-1} of groundwater, abstracted from a well located 1000 m downstream the disposal facility. Depending on the geographical, hydrological, hydrogeological and land use characteristics of individual sites, doses will also be calculated for all relevant radionuclide transport pathways.

Barrier Failure Scenario: This scenario assumes that a barrier failure event could arise soon after closure of the Disposal facility. Three options are considered:

- Failure after one year;
- Failure after 299 years; and
- Failure after 400 years.

The failure will cause the mobilization into the groundwater flow system of 2% of the total inventory at the annual average infiltration rate for a period of one year. In the first two cases, in which failure occurs during institutional control, the damage will be repaired and the leaching process will be arrested.

The features and evolution after the failure and the dose calculation approach used for this scenario are identical to those already described for the *design scenario*.

B-9. CPHR SCENARIO GENERATION APPROACH

This scenario generation approach was developed concurrent with the ISAM project.

Taking into account the current scenarios generation methodologies, the type of data used and the interest for making the process more transparent and traceable, it is possible to development a database application to allow the management of the FEPs in a simple way. Some stages in the scenario methodology can be implemented in a database application in order to facilitate the process, and make it more traceable.

Centro de Protección e Higiene de las Radiaciones (CPHR) developed a MS Access application in order to support the scenarios generation process. This database was successfully used for practical purposes in the Regional Training Course on Management of Waste from Nuclear Applications, which was held in Havana, October 1999. The use of a database allows all the processes in the approach used to generate scenarios to become more transparent. The database helps document the scenario generation stage, facilitating the work of the experts and allowing the subsequent review.

B-9.1. Methodology of the scenario generation and justification process

CPHR followed the methodology showed in Fig. B-13, which includes the principal elements adopted in several scenario generation approaches. Adopting a systematic approach can reduce the principal scenario uncertainties and identify the more important factor to take into account regarding the safety. The steps include:

- Identifying a comprehensive list of features, events, and processes based on the ISAM FEPs List;
- Screening the comprehensive FEPs list;
- Building and justifying of the scenarios; and
- Obtaining the final scenarios for the safety assessment.

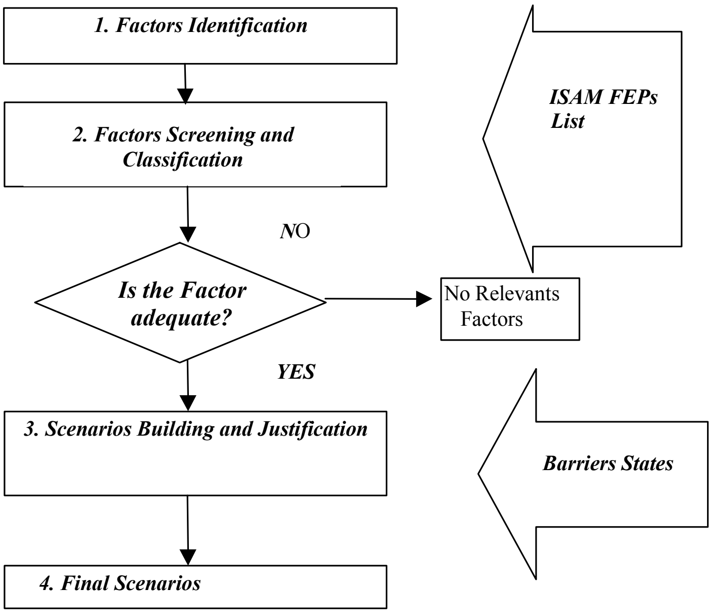


FIG. B-13. CPHR's Scenario Generation Methodology.

B-9.2. Identifying a comprehensive list of features, events, and processes

The ISAM FEPs List was used as the basis for the database. It has fields like: layer name, category, FEPs number, definition and examples.

B-9.3. FEPs screening

To screen the FEPs the following procedure is followed (Fig. B-14).

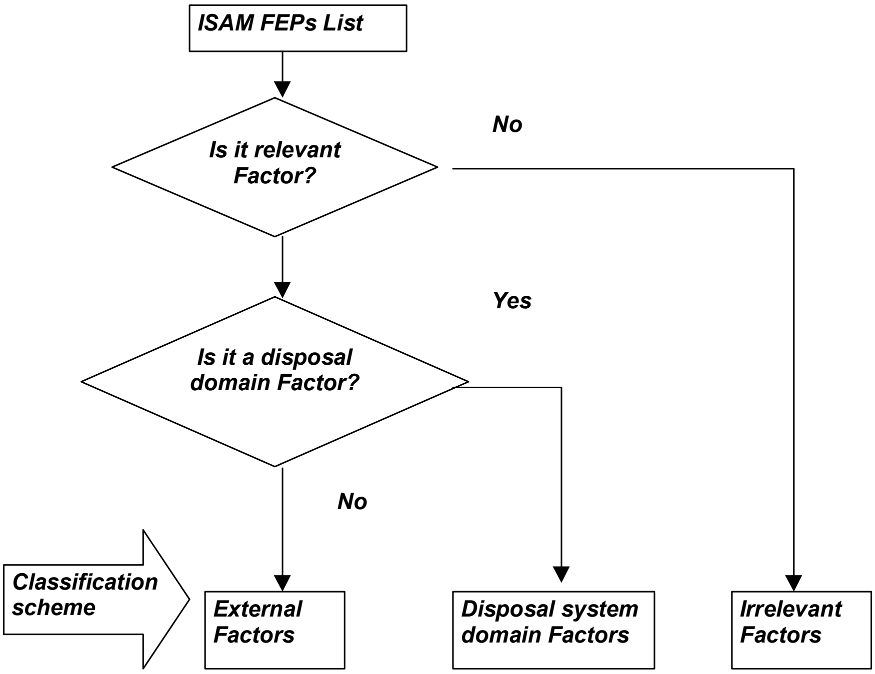


FIG. B-14. CPHR's FEPs Screening and Classification.

- Identify, from the ISAM FEPs List, those FEPs relevant for the safety of disposal system, and screen them according to criteria such as probability, consequences and assessment context. A rejected FEPs List is obtained, which can be re-screened again, if required;and
- Classify the relevant FEPs as external or disposal system domain factors; this scheme is similar to adopted in the ISAM FEPs List. The external FEPs are FEPS with causes or origins outside the disposal system domain, i.e. natural or human factors of a more global nature and their immediate effects. Included in this term are decisions related to disposal facility design, operation and closure since these are outside the temporal bound of the disposal system domain. Often these FEPs are not influenced by disposal domain processes. The disposal domain factors are FEPs that occur in the spatial and temporal disposal system domain. These factors affect the evolution of the physical, chemical, biological and human conditions of the disposal domain.

For this stage, the database included a FEPs screening form (Fig. B-15) in order to facilitate this process. This form shows the complete ISAM FEPs List including different fields (Layer, category, definition, examples, etc) and the user can select whether the current FEP is important or not for the system according the screening criteria adopted. A justification window is also available to include the reasons or criteria adopted for the selection.

This procedure is repeated for the all FEPs and finally two Lists are obtained (relevant and not relevant factors) which can be re-screening again in order to reduce any errors or uncertainties in the selection process. There is the possibility to save the obtained FEPs List in external files for discussion and peer review by experts. Finally a revised FEPs List will be obtained which can affect the safety of the disposal system, according the criteria determined.

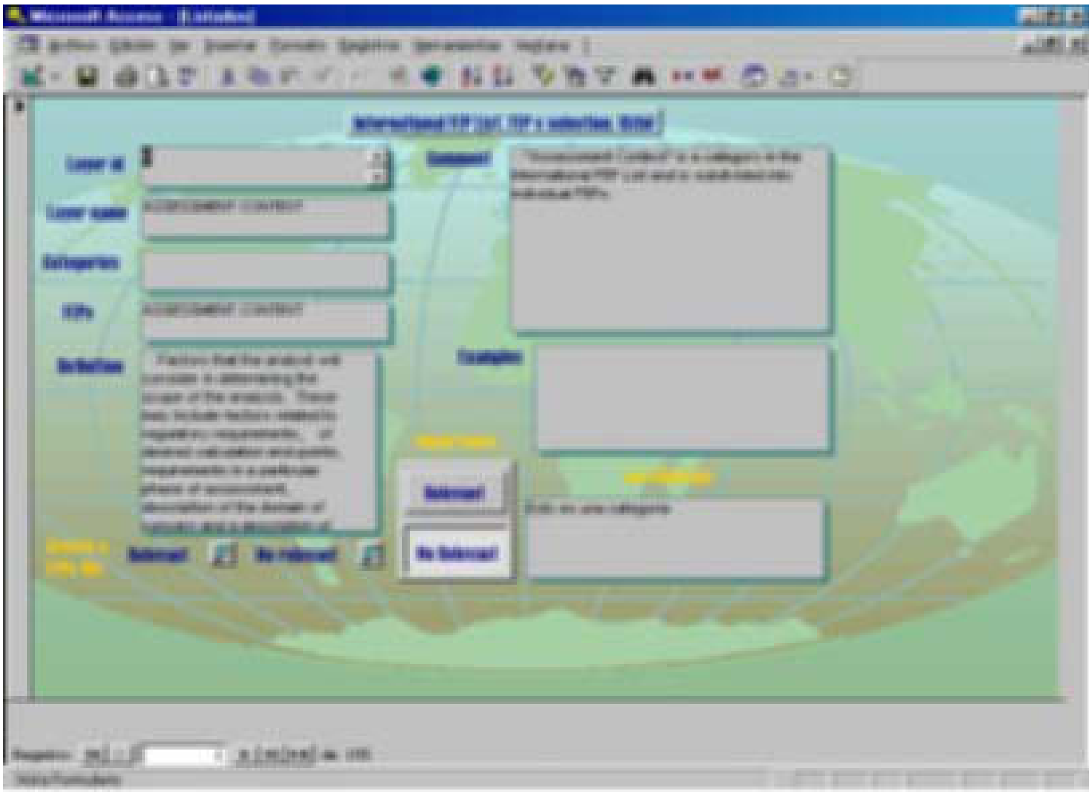


FIG. B-15. CPHR's FEPs Screening Form.

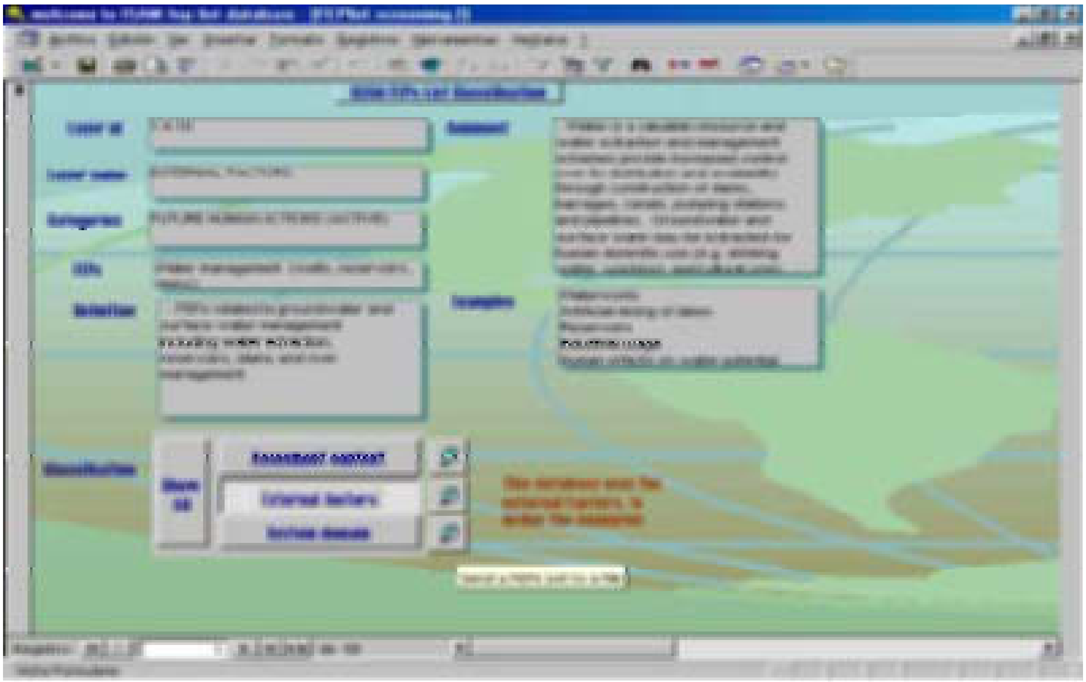


FIG. B-16. CPHR's FEPs Classification Form.

B-9.5. Scenarios generation

For scenario generation stage, CPHR recognized that the disposal facility is a multi-barrier system, the evolution of which can be characterized by the state of the barriers. For each barrier, a number of FEPs or combination of so called external FEPs, can be found which define the state of the barrier. Three components of the system are defined:

- Near field (including the engineer barrier, the waste form, container);
- Far field (the geological host surrounds the disposal facility); and
- Biosphere (human environment, external activities, etc).

For each system component, it is assumed that there are three possible states of the barriers: normal; altered or bypassed (short circuited). In the first state, the barrier maintains all its characteristics as a barrier. In the second one, the barrier is affected but the main protective functions are kept. In the last one, the barrier is not longer a protection element in the system.

The database includes a scenarios form (Fig. B-17), where the previous selected FEPs can be organized according to the barriers that they affect. There are a group of bottoms in the scenario form, in order to define the barriers that the specific FEPs affect and how they affect them.

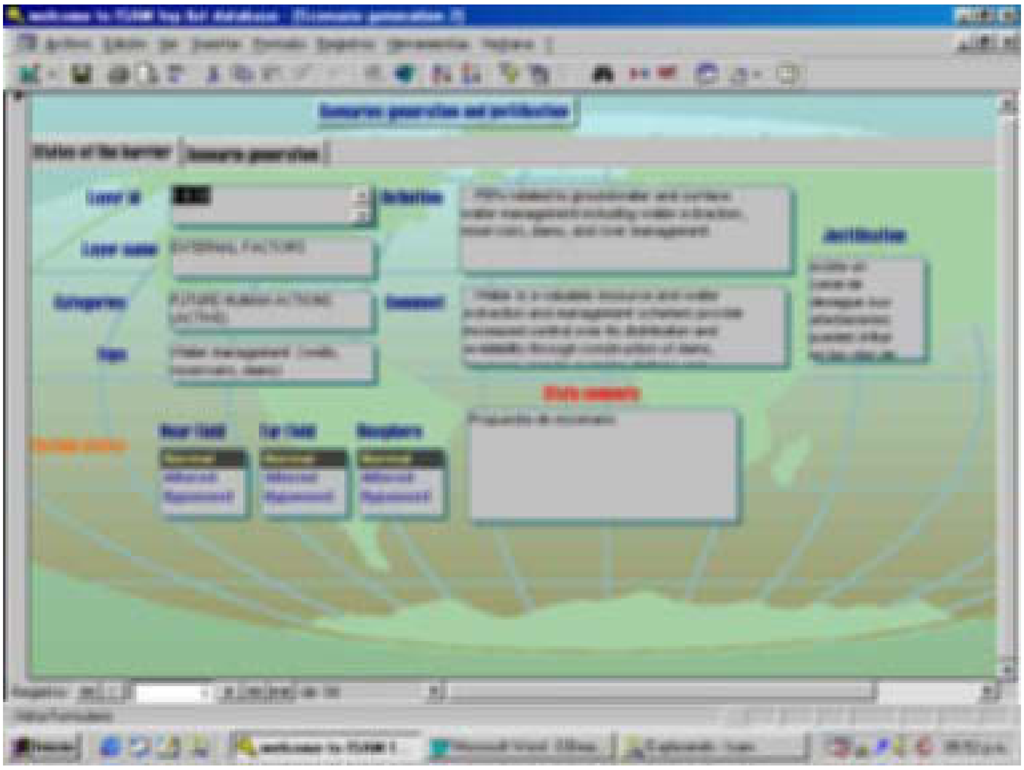
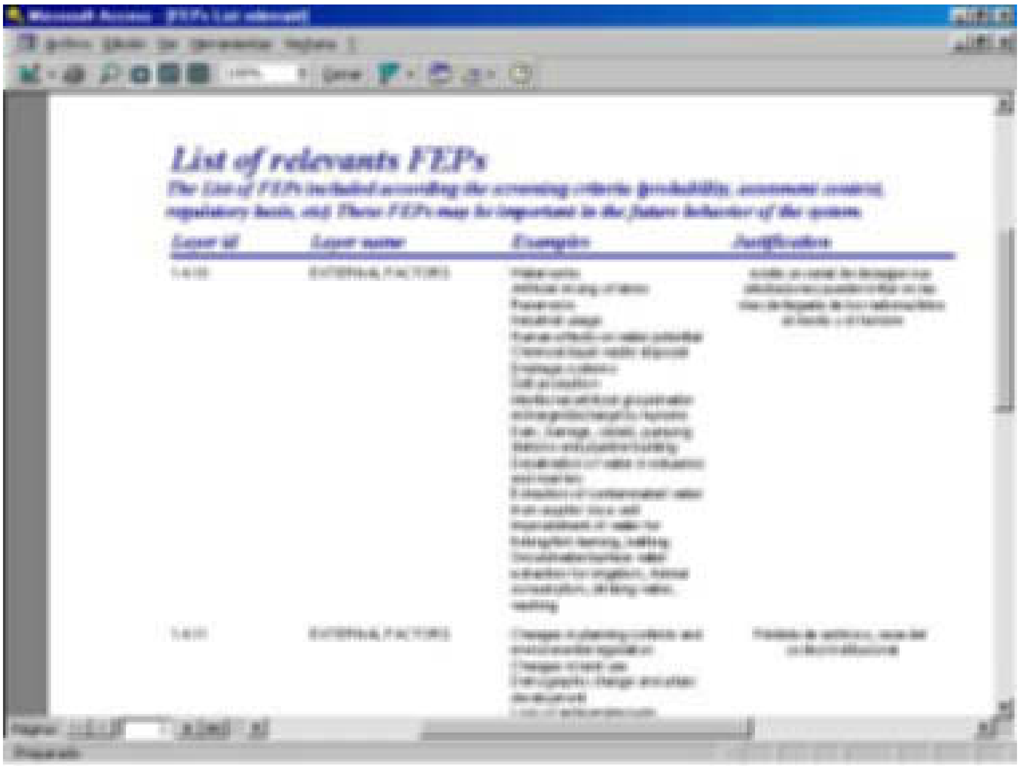


FIG. B-17. CPHR's Scenarios Generation Form.

There are considered to be three barriers (near field, far field and biosphere) and each one has three possible states, therefore 27 (3x3x3=27) different combination or scenarios for the system can be obtained. Of course only the logical combinations of scenarios will be adopted for final evaluation. The scenarios selected can be saved as an independent file for review.

Finally the database includes several reports (see for example Fig. B-18), which can be printed for documentation purpose and make the scenario generation process traceable.



List of relevants FEPs

FIG. B-18. Example of CPHR's Database Report.

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APPENDIX C:
ISAM LIST OF FEATURES EVENTS AND PROCESSES (FEPS)

The FEP records are printed in classification scheme order. FEP names and scheme numbers are in bold, definitions are in normal type, comments and examples are in italics.

ASSESSMENT CONTEXT 0

Definition: Factors that the analyst will consider in determining the scope of the analysis. These may include factors related to regulatory requirements, definition of desired calculation end-points, requirements in a particular phase of assessment, description of the domain of concern and a description of the target groups in the assessment. Decisions at this point will affect the phenomenological scope of a particular phase of assessment, i.e. what “physical FEPs” will be included.

Comment*: "Assessment Context" is a category in the International FEP List and is subdivided into individual FEPs.*

Assessment endpoints 0.01

Definition: The long term human *health and environmental effects or risks that may arise from the disposed wastes and repository. These FEPs include health or environmental effects of concern in an* assessment (what effect and to whom/what), and health or environmental effects ruled to be of no concern.

Comment: *From the disposed radioactive waste to the health impact to humans, various indicators and associated criteria can be defined to serve as assessment endpoints. Which one to choose, will depend on the purpose of the assessment. The indicator most frequently considered is the radiation dose or risk to man, often represented by the annual dose rate or risk to a member of a “critical group” of potentially most exposed individuals (see FEP 0.06).*

Key concepts, examples, and related FEPs

Annual individual dose

Annual individual risk

Collective doses

Lifetime individual dose

Collective effective dose

Lifetime individual risk

Radionuclide concentration in the environment

Flux through engineered barriers

Flux from geosphere to biosphere

Increase in radiation levels in the environment

Release or concentration of non-radiological toxic contaminants

Dose to biota other than man

Collective risk

Timescales of concern 0.02

Definition: The time periods over which the disposed wastes and repository may present some significant human health or environmental hazard.

Comment: *These may correspond to the timescale over which the safety of the disposed wastes and repository is estimated or discussed. In some countries national regulations set a limit up to which quantitative assessment is required, with more qualitative arguments to demonstrate safety being sufficient at later times.*

Key concepts, examples, and related FEPs

Until peak doses occur

> 60 000 years

500 – 10 000 years

10 000 – 60 000 years

0 – 500 years

Spatial domain of concern 0.03

Definition: The domain over which the disposed wastes and repository may present some significant human health or environmental hazard.

Comment: *This may correspond to the spatial domain over which the safety of the disposed wastes and repository is estimated, or the domain which is necessary to model in order to develop an understanding of the movement of contaminants and exposures. This may be limited by the purpose of the assessment, for example if the performance of a component of the total system have to be assessed.*

Key concepts, examples, and related FEPs

Description of the spatial domain of concern

Repository assumptions 0.04

Definition: The assumptions that are made in the assessment about the construction, operation, closure and administration of the repository.

Comment: *For example, most post-closure assessments make the assumption that a repository has been successfully closed, although, in practice such decisions may be delayed or be the subject of uncertainty*

Key concepts, examples, and related FEPs

Description of the construction, operation, closure and operation of the repository

Repository has been successfully closed

Waste emplacement configuration has change

Change in volume of disposed waste

Change in repository design

Future human action assumptions 0.05

Definition: The assumptions made in the assessment concerning general boundary conditions for assessing future human actions.

Comment: *For example, it can be expected that human technology and society will develop over the timescales of relevance for repository safety assessment. However, this development is unpredictable. Therefore, it is usual to make some assumptions in order to constrain the range of future human activities that are considered.*

Key concepts, examples, and related FEPs

Only present day technologies will be considered

Description of general human society

Only technologies practised in the past will be considered

Description of human society development

The past is an accurate reflection of the future

Future human behaviour (target group) assumptions	0.06

Definition: The assumptions made concerning potentially exposed individuals or population groups that are considered in the assessment.

Comment: *Doses or risks are usually estimated for critical groups (individuals or groups) thought to be representative of the individuals or population groups that may be at highest risk or receive the highest doses as a result of the disposed wastes and repository. This is the accepted approach for assessing radiological risk or dose to members of the public resulting from a source of radioactive release to the environment. To assess the doses or risks at times in the far future, when the characteristics of potentially exposed populations are unknown, a hypothetical critical group, or groups, is/are usually defined*

Key concepts, examples, and related FEPs

Description of an actual critical group

Description of a hypothetical critical group

Dose response assumptions	0.07

Definition: Those assumptions made in an assessment in order to convert received dose to a measure of risk to an individual or population.

Comment: *Usually this will refer to individual human dose response, e.g. by a dose-risk conversion factor where the factor is the probability of a specified health effect per unit of radiation exposure. If other organisms are considered then a risk to individual organisms or a species might be considered. The variation of a given response or human health effect (e.g. cancer incidence, cancer mortality) with the amount of radiation dose an individual or a group of individuals received is referred to as the dose-response relation. It is not possible to determine the shape of the dose response curve at low doses with any precision, because the incidence of health effects is very low. A linear dose-response relation with no dose threshold is generally assumed cautious (See ICRP 60).*

Key concepts, examples, and related FEPs

None

Assessment purpose	0.08

Definition: The purpose for which the assessment is being undertaken.

Comment: *The aim of the assessment is likely to depend on the stage in the repository development project at which the assessment is carried out and may also affect the scope of assessment*

Key concepts, examples, and related FEPs

Site selection

Demonstrate regulatory compliance

Concept design

Demonstrate the feasibility of a disposal concept

Rehabilitation of contaminated site

Public confidenceSystem optimization

Regulatory requirements and exclusions	0.09

Definition: The specific terms or conditions in the national regulations or guidance related to all stages of the repository that will influence the post closure safety assessment.

***Comment:** Regulatory requirements and exclusions may be expressed in terms of release, dose or risk limits or targets to individuals or populations effective over a specified timescale; they may also make demands about procedures following closure of the repository. In some regulations, the long term scenarios to be assessed are specified, or some scenarios or events are specifically ruled out of consideration.*

Key concepts, examples, and related FEPs

Independence of safety from control

Optimization

Effects in the future

Environmental protection standards

Quality assurance

Quality control

Multi-factor safety case

Radiological protection standards

Model and data issues	0.10

Definition: Model and data issues in the context of a safety assessment, refers to general (i.e. methodological) issues affecting the assessment modelling process and use of data during the process.

***Comment:** A post-closure safety assessment is an attempt to quantify the exposure or risk posed by a radioactive waste disposal site to future generations of humanity and their environment. Intrinsically, to do this one can say that the observations needed for the safety assessment of a site should be carried out for the life span of the proposed disposal facility. However, this is neither physically possible nor desirable. The only viable approach to perform a complete radiological safety assessment is to try to obtain as much observational data as possible, on a limited time scale, and then simulate the future behaviour of the disposal system through what is known as a model.*

Key concepts, examples, and related FEPs

Treatment of uncertainty

Method of handling site data

Assessment philosophy

Modelling studies

☐ *Model and data reduction/simplification*

Data availability

Application of conservatism

EXTERNAL FACTORS	1

Definition: FEPs with causes or origin outside the disposal system domain, i.e. natural or human factors of a more global nature and their immediate effects. Included in this category are decisions related to repository design, operation and closure since these are outside the temporal boundary of the disposal system domain for post-closure assessment.

***Comment:** "External Factors" is a category in the International FEP List and is divided into sub-categories.*

REPOSITORY ISSUES 1.1

Definition: Decisions on designs and waste allocation (repository type), and also events related to site investigation, operations and closure (site context).

Comment: *"Repository Issues" is a sub-category of External Factors in the International FEP List and is divided into individual FEPs.*

Site investigation 1.1.01

Definition: FEPs related to the investigations that are carried out at a potential repository site in order to characterize the site both prior to repository excavation and during construction and operation.

Comment: *Site investigation activities provide detailed site specific performance assessment data and information necessary for the safety case to demonstrate the suitability of the site and to establish baseline conditions*

<u>Key concepts, examples, and related FEPs</u>

Geography and demography

Meteorology and climatology (regional and local)

Geology and seismology

Hydrology characteristics

Geotechnical characteristics

Aquifer tests

Investigative boreholes

Biosphere characteristics

Natural resources

Geochemical characteristics

Ecological features

Pre-operational monitoring programme

Hydrogeology characteristics

Geohydrological characteristics

Geomorphology characteristics

Design, repository 1.1.02

Definition: FEPs related to the design of the repository including both the safety concept, i.e. the general features of design and how they are expected to lead to a satisfactory performance, and the more detailed engineering specification for excavation, construction and operation.

Comment: *The repository design and construction is established in a general way in the disposal concept for the repository which is based on expected host lithology characteristics, waste and backfill characteristics, construction technology, and economics. Repository design includes the principle design features that are designed to provide long term isolation of disposed waste, minimize the need for continued active maintenance after site closure, and improve the site's natural characteristics in order to protect public health and the environment. There may, nevertheless, be a range of engineering design and construction options still open. As the repository project proceeds, and more detailed site specific information becomes available, the range of options may be constrained and decisions will be made. At any stage, repository safety assessments may only analyse a subset of the total range of option. (See FEP 1.103).*

<u>Key concepts, examples, and related FEPs</u>

The general repository design features (e.g. host lithology, waste form, backfill, waste packages, construction technology, etc.)

The principle design criteria or considerations for normal and abnormal conditionOperational monitoring programme

Construction, repository 1.1.03

Definition: FEPs related to the construction (e.g., excavation) of shafts, tunnels, disposal galleries, silos, trenches, vaults, etc. of a repository, as well as the stabilisation of these openings and installation/assembly of structural elements according to the design criteria.

Comment:*. Repository construction refers to the implementation of the design considerations and specifically to the construction of features of the repository necessary to provide long term isolation of disposed waste, minimize the need for continued active maintenance after site closure, and improve the site's natural characteristics in order to protect public health and the environment. In addition, it includes the construction methods. (See FEP 1.102).*

Key concepts, examples, and related FEPs

Drilling of borehole

Excavation of trenches, holes, vaults

Construction equipment

Construction of walls, floors, mounds, layers of mounds

Site plans, engineering drawing, and construction specifications

Control and diversion of water

Site preparations

Emplacement of wastes and backfilling 1.1.04

Definition: FEPs related to the placing of wastes (usually in containers) at their final position within the repository and placing of buffer and/of backfill materials in the disposal zone.

Comment: *Some waste types and inventories may require special waste emplacement arrangements to simplify the disposal practice, to ensure safety or to ensure structure stability in the repository area. The backfill material is used to refill excavated portions of the repository or any void spaces left unfilled after waste has been emplaced (see also FEP 1.1.07).*

Key concepts, examples, and related FEPs

Emplacement method

Waste emplacement configuration

Filling of void spaces between the containers and in the rest of the repository

Covering of waste in-between containers

Closure, repository 1.1.05

Definition: FEPs related to the cessation of waste disposal operations at a site, the backfilling and sealing of boreholes type facilities, and the capping and covering of trenches, vaults, etc.

Comment: *The term closure refers to the status of, or an action directed at a disposal facility at the end of its operational life. A disposal facility is placed under permanent closure usually after completion of waste emplacement, by covering a near surface disposal facility, by backfilling and/or sealing of a borehole type facility, and termination and completion of activities in any associated structure. The intention of repository capping and sealing is to prevent infiltrating water as well as human access to the wastes. Individual sections of a repository may be closed in sequence, but closure usually refers to final closure of the whole repository, and will probably include removal of surface installations. The schedule and procedure for capping, sealing and closure may need to be considered in the assessment.*

Key concepts, examples, and related FEPs

Trench/vault capping

Site stabilisation

Cover construction

Backfilling of boreholes

Removal of surface structures

Closure procedures

Decontamination and decommissioning plan

Post-operational monitoring programme

Closure compartments

Records and markers, repository 1.1.06

Definition: FEPs related to the retention of records of the content and nature of a repository after closure and also the placing of permanent markers at or near the site.

Comment: *It is expected that records will be kept to allow future generations to recall the existence and nature of the repository following closure. In some countries, the use of site markers has been proposed where the intention is that the location and nature of the repository might be recalled even in the event of a lapse of present-day administrative controls.*

Key concepts, examples, and related FEPs

Records of the content and nature of the repository

Disposal unit and boundary markers

Archive of the records

Site markers

Waste allocation 1.1.07

Definition: FEPs related to the choices on allocation of wastes to the repository, including waste type(s) and amount(s).

Comment: *The waste type and waste allocation is established in a general way in the repository disposal concept. There may, however, be a number of options concerning these factors. Final decisions may not be made until the repository is operating and will be subject to regulation. In safety assessments, assumptions may need to be made about future waste arisings and future waste allocation strategies (see also FEP 1.1.04).*

Key concepts, examples, and related FEPs

Waste allocation description

Future waste arisings

Future waste allocation strategies

Projected inventories

Waste acceptance criteria for the repository

Quality control 1.1.08

Definition: FEPs related to quality assurance and control procedures and tests during the design, construction and operation of the repository, as well as the manufacture of the waste forms, containers and engineered features.

Comment: *It can be expected that a range of quality control measures will be applied during construction and operation of the repository, as well as to the manufacture of the waste forms, containers etc. In an assessment these may be invoked to avoid analysis of situations which, it is expected, can be prevented by quality control. There may be specific regulations governing quality control procedures, objectives and criteria.*

Key concepts, examples, and related FEPs

Defects in construction of disposal system

Defects in the construction of container

Improper or faulty waste emplacement and backfilling

Defects during the conditioning of the waste

Defects in cap constructions

Schedule and planning	1.1.09

Definition: FEPs related to the sequence of events and activities occurring during repository excavation, construction, waste emplacement and sealing.

Comment: *Relevant events may include phased construction of units and emplacement of wastes, backfilling, sealing, capping and closure of sections of the repository after wastes are emplaced, and monitoring activities to provide data on the transient behaviour of the system or to provide input to the final assessment. The sequence of events and time between events may have implications for long term performance, e.g. decline of activity and heat production from the wastes, material degradation, chemical and hydraulic changes during a prolonged "open" phase.*

Key concepts, examples, and related FEPs

Phased construction of units

Planning of monitoring activities to provide data on the transient behaviour of the system

Phased emplacement of wastes, backfilling, sealing, capping and closure of sections of the repository

Administrative control, repository site	1.1.10

Definition: FEPs related to measures to control events at or around the repository site, both during the operational period and after closure.

Comment: *The responsibility for administrative control of the site before closure of the repository during the construction and operational phases, and subsequently following closure of the repository may not be the same. Furthermore, the type of administrative control may vary depending on the stage in the repository lifetime.*

Key concepts, examples, and related FEPs

None

Monitoring of repository	1.1.11
Definition: FEPs related to any monitoring that is carried out during operations or following closure of sections of, or the total, repository. This includes monitoring for operational safety and also monitoring of parameters related to the long term safety and performance.	
Comment: *The extent and requirement for such monitoring activities may be determined by repository design and host lithology, regulations and public pressure.*	
Key concepts, examples, and related FEPs *Pre-operational monitoring programme* *Post-operational monitoring programme* *Operational monitoring programme*	

Accidents and unplanned events	1.1.12
Definition: FEPs related to accidents and unplanned events during construction, waste emplacement and closure, which might have an impact on long term performance or safety.	
Comment:**.** *Accidents are events that are outside the range of normal operations although the possibility that certain types of accident may occur should be anticipated in repository operational planning. Unplanned events include accidents but could also include deliberate deviations from operational plans.*	
Key concepts, examples, and related FEPs *Deviations from operations in response to an accident* *Unexpected waste arising during operations* *Increase in waste delivery* *Reduction in waste delivery* *Unexpected geological event* *Earlier than anticipated container failure* *Earlier than anticipated cap failure* *Deliberate deviations from operational plans*	

Retrievability	1.1.13
Definition: FEPs related to any special design, emplacement, operational or administrative measures that might be applied or considered in order to enable or ease retrieval of wastes.	
Comment: *Designs may specifically allow for retrieval or rule it out. In some cases, an interim period might be planned, between waste emplacement and final repository closure, during which time retrieval is possible.*	
Key concepts, examples, and related FEPs *None*	

GEOLOGICAL PROCESSES AND EFFECTS	1.2
Definition: Processes arising from the wider geological setting and long term processes	
Comment*. "Geological Processes and Effects" is a sub-category of External Factors in the International FEP List and is divided into individual FEPs.*	

Orogeny and related tectonic processes at plate boundaries

1.2.01

Definition: Rock deformation and translation (commonly referred to as tectonics) of this nature arises when rock masses belonging to different plateseither collide against each other or slide past each other. Literally speaking, orogeny is the process of formation of mountains, often occurring over periods of a few million years, but up to several tens of millions of years.

***Comment:** By present geological usage, orogeny is the process by which structures within mountain areas were formed through processes that include thrusting, folding and faulting in the lithosphere. The latter h is the name given to the rigid, outermost layer of the earth, made up predominantly of solid rock which are affected by processes such as metamorphism, plutonism, and, at great depth (>10 km), by plastic folding. .*

The term folding is generally used to imply the shortening of strata that results from the formation of fold structures on a broad scale, and sometimes has the connotation of general deformation of which the actual folding is only a part. A fault is a fracture in the Earth's crust accompanied by displacement of one side of the fracture relative to the other, from a few cm to several kilometres. Orogenic belts are typically characterized by compressive reverse faults as this lead to crustal shortening and duplication of geological formations. Transform faults typically occur where crustal plates slide past each other without colliding (e.g. the St. Andrea fault in California) and the relative displacement can be in the order of thousands of kilometers. Fractures and joints may be caused by compressional or tenisonal forces in the earth crust but do not present displacement between the rocks on each side. These forces may result in the reactivation of of existing faults or, less likely, in the generation of new ones

It is important to acknowledge that orogenic processes experience periods of quiescence alternating with periods of paroxismand that such periods are not necessaily synchronous along the whole length of an orogenic belt.

***Implications to near surface disposal systems:** This type of movements should be considered with great care since orogenic processes can lead, in areas of active collision (e.g. Chile, Turkey, Iran, Morocco) to the propagation of fault and thrust planes up to the surface. In such events (see seismicity) extreme ground fracturing, faulting could lead to breakage of containment barriers*

Key Concepts, examples, and related FEPs

Collision of the Earth's crustal plates

Transcurrent, strike-slip faults

Thrusts: low-angle reverse faults;

Subduction zones

Faulting and folding of lithosphere: Thin skinned tectonics vs. Thick skinned tectonics

Metamorphism, anatexis (partial melting/ migmatization), and plastic folding in the inner and deeper layer

Granitic to granodioritic batholiths; calc-alkaline igneous activity

Orogeny,

Neotectonics

Anorogenic and within-plate tectonic processes (Deformation, elastic, plastic or brittle)

1.2.02

Definition: FEPs related to the physical deformation of geological structures in the interior of continental or oceanic plates in response to stress fields generated either at plate margins or in regions of anomalous stress. This includes mainly faulting and fracturing of rocks and, less frequently, also their compression and folding rocks.

***Comment.** The term folding is generally used for the compression of strata in the formation of fold structures on a broad scale, and sometimes has the connotation of general deformation of which the actual folding is only a part. A fault is a fracture in the Earth's crust accompanied by displacement of one side of the fracture relative to the other, from a few centimetres to a few kilometres on scale. Fractures may be caused by compressional or tensional forces in the Earth's crust. Such forces may result in the activation of existing faults and, less likely, the generation of new faults.*

***Implications to near surface disposal systems:** Within the timescales of concern, deformation is unlikely to have an effect on near surface disposal systems*

Key Concepts, examples, and related FEPs

Faulting: normal, extensional faults
Extrusion
Neotectonics
Alkaline volcanism, volcanoes
Dyke swarms
Fractures
Fracturing
Compression of rocks
Rifting, rift valleys
Horst and grabens
Jointing, master joints
Hot springs
Basin and range
Continental; break- up
Uplift axes
Stress field
Cross-fabrics

Seismicity 1.2.03

Definition: FEPs related to seismic events and the potential for seismic events. Rapid relative movements within the Earth’s crust, usually along existing faults or geological interfaces cause a seismic event. The accompanying release of energy may result in ground movement and/or rupture, e.g. earthquakes.

Comment: *Seismic events may result in changes in the physical properties of rocks due to stress changes and induced hydrological changes. Seismic events are most common in tectonically active or volcanically active regions at crustal plate margins, less commonly they also occur in the interior of continental/oceanic plates. The seismic waves that are generated by a tectonic or volcanic disturbance of the ocean floor may result in a seismic (giant) sea wave, known as a tsunami. These may be amplified by submarine soft sediment slumps along steep continental margins. In extreme cases, soil liquefaction has been reported in areas where soils and sedimentary strata of appropriate moisture content and composition are subjected to strong seismic shaking.*

Key Concepts, examples, and related FEPs

Change in the physical properties of rocks due to stress changes
Hydrological changes
Faulting
Tsunami
Earthquakes
Seismic swarms
Soil liquefaction
Aftershocks

Volcanic and magmatic activity 1.2.04

Definition: FEPs related to volcanic and magmatic activities. Magma is molten, mobile rock material, generated below the Earth’s crust, which gives rise to igneous rocks when solidified. Magmatic activity occurs when there is intrusion of magma into the crust. A volcano is a vent or fissure in the Earth’s surface through which molten or part-molten materials (lava) may flow, and ash and hot gases be expelled.

Comment: *The high temperatures and pressures associated with volcanic and magmatic activity may result in permanent changes in the surrounding rocks; this process is referred to as metamorphism but is not confined to volcanic and magmatic activity (see FEP 1.2.05). Intrusive magmatic activity refers to the process of emplacement of magma in pre-existing rock. Extrusive magmatic activity refers to the process whereby magma are ejected onto the surface of the Earth.*

Key Concepts, examples, and related FEPs

- *Temperature and pressure rise*
- *Change in surrounding rocks*
- *Slope tilting*
- *Intrusive magmatic activity*
- *Extrusive magmatic activity*
- *Lava flows*
- CO_2 *emissions*
- *Pyroclastic explosion / flow / cloud*
- *Fumaroles*
- *Hydrothermal alteration*

Metamorphism 1.2.05

Definition: FEPs induced by the mineralogical and structural adjustment of solid rock to physical and chemical conditions, which have been imposed by the action of heat (T>200 C) and pressure at great depths (usually several kilometres) beneath the Earth’s surface or near magmatic activity.

Comment: *Metamorphic processes are unlikely to be important at typical repository depths, but past metamorphic history of a host lithology may be very important to understanding its present-day characteristics.*

Implications to near surface disposal systems: *Within the timescales of concern, metamorphism is unlikely to have an effect on near surface disposal systems.*

Key Concepts, examples, and related FEPs

- *Metamorphic history of a host lithology*

Hydrothermal activity 1.2.06

Definition: FEPs associated with high temperature groundwater, including processes such as density-driven groundwater flow and hydrothermal alteration of minerals in the rocks through which the high temperature groundwater flows.

Comment: *Groundwater temperature is determined by the large-scale geological and petrophysical properties of the rock formations (e.g. radiogenic heat formation, thermal conductivity), as well as the hydrogeological characteristics (e.g. hydraulic conductivity) of the rock and by the tectonic environment. (neotectonic deformation, extension).*

Implications to near surface disposal systems: *Within the timescales of concern, hydrothermal activity is unlikely to have an effect on typical near surface disposal systems.*

Key Concepts, examples, and related FEPs

- *Hydrothermal synthesis*
- *Density driven groundwater flow*
- *Hydrothermal alterations of minerals in the rocks*
- *Hydrothermal metamorphism*
- *Scalding springs*

Erosion and sedimentation

1.2.07

Definition: FEPs related the large-scale (geological) removal and accumulation of rocks and sediments, with associated changes in topography and geological/hydrogeological conditions of the repository host lithology.

Comment: *Erosion is the process or group of processes whereby the earthy and rocky materials of the Earth's crust are loosened, dissolved, or worn away, and simultaneously removed from one place to another, by natural agencies that include weathering, solution, corrosion, and transportation. Compare FEP 2.3.12, which is concerned with more local processes over shorter periods of time. Sedimentation is the act or process of forming or accumulating sediment in layers, including such processes as the separation of rock particles from the material from which the sediment is derived, the transportation of these particles to the site of deposition or settling of the particles, the chemical and other (diagenetic) changes occurring in the sediment, and the ultimate consolidation of the sediment into solid rock.*

Implications to near surface disposal systems: *Within the timescales of concern, large scale erosion and sedimentation are unlikely to have an effect on near surface disposal systems.*

<u>Key Concepts, examples, and related FEPs</u>

Change in topography, uplift
Deposition of sediment
Stream erosion
Coastal erosion
Changes in geological conditions
Changes in hydrogeological conditions

Diagenesis and pedogenesis

1.2.08

Definition: The processes by which deposited sediment, at or near the Earth's surface are formed into rocks by compaction, cementation and crystallisation, i.e. under conditions of temperature and pressure normal to the upper few kilometres of the earth's crust.

Comment: *Diagenesis include all the chemical, physical, and biological changes, modifications, or transformations undergone by a sediment after its initial deposition, and during and after its lithification, exclusive or surficial alteration (weathering) and metamorphism. It embraces those non-destructive or reconstructive processes (e.g., consolidation, compaction, cementation, reworking, authigenesis, replacement, solution, precipitation, crystallisation, oxidation, reduction, leaching, hydration, polymerisation, adsorption, bacterial action, and formation of concretions) that occur under conditions of pressure and temperature that are normal to the surficial or outer part of the Earth's crust.*

Pedogenesis represents the mode of origin of soils, with reference to the factors responsible for the formation of "solum", or true soil, from unconsolidated parent material. Pedogenesis may have an effect on the behaviour of near surface disposal systems as it involves geohydrologic, atmospheric and biological processes (burrowing animals, plant roots activity/invasion) operation at or near surface on time scales of few hundred to thousands of years

Implications to near surface disposal systems: *Within the timescales of concern, diagenesis is unlikely to have an effect on near surface disposal systems*

<u>Key Concepts, examples, and related FEPs</u>

None

Salt diapirism and dissolution 1.2.09

Definition: The long term evolution of salt formations. Diapirism is the lateral or vertical intrusion or upwelling of either buoyant or non-buoyant rock into overlying strata (the overburden) from a source layer. Dissolution of the salt may occur where the evolving salt formation is in contact with groundwater with salt content below saturation.

Comment: *Diapirism is most commonly associated with salt formations where a salt diapir comprises a mass of salt that has flowed in a ductile manner from a source layer and pierces or intrudes into the over-lying rocks. The term can also be applied to magmatic or migmatic intrusion.*

Implications to near surface disposal systems: *Within the timescales of concern, salt diapirism and dissolution are unlikely to have an effect on near surface disposal systemt.*

Key Concepts, examples, and related FEPs

Diapirism
Brine pockets

Hydrological/hydrogeological response to geological changes 1.2.10

Definition: FEPs related to changes in the hydrological or hydrgeological regime arising from the large-scale geological changes listed in FEPs 1.2.01 to 1.2.09.

Comment: *These could include changes of hydrological boundary conditions due to effects of erosion on topography, changes of hydraulic properties of saturated and unsaturated zones due to changes in rock stress or fault movements, or a change in the geochemical behaviour of the saturated and unsaturated zones. In and below low-permeability geological formations, hydrogeological conditions may evolve very slowly and often reflect past geological conditions, i.e. be in a state of disequilibrium*

Key Concepts, examples, and related FEPs

Geochemical change
Changes in hydraulic properties
Changes of hydrological boundary conditions

CLIMATIC PROCESSES AND EFFECTS 1.3

Definition: Processes related to global climate change and consequent regional effects.

Comment: "Climatic Processes and Effects" is a sub-category of External Factors in the International FEP List and is divided into individual FEPs.

Climate change, global 1.3.01

Definition: FEPs related to the possible future, and evidence for past, long term change of global climate. This is distinct from resulting changes that may occur at specific locations according to their regional setting and also climate fluctuations, c.f. FEP 1.3.02.

Comment: *The last two million years of the Quaternary have been characterized by glacial/interglacial cycling. According to the Milankovitch Theory, the Quaternary glacial/interglacial cycles are caused by long term changes in seasonal and latitudinal distribution of incoming solar radiation which are due to the periodic variations of the Earth's orbit about the Sun (Milankovitch cycles). The direct effects are magnified by factors such as changes in ice, vegetation and cloud cover, and atmospheric composition.*

Key Concepts, examples, and related FEPs

Description of global climate changes
Changes in ice, vegetation and cloud cover
Isostatic movement (c.f. FEP 1.3.03)
Changes in atmospheric composition
Greenhouse effect
Glaciation (large scale)
Eustatic change (c.f. FEP 1.3.03)

Climate change, regional and local — 1.3.02

Definition: FEPs related to the possible future changes, and evidence for past changes, of climate at the repository site. This is likely to occur in response to global climate change, but the changes will be specific to situation, and may include shorter-term fluctuations, c.f. FEP 1.3.01.

Comment: *Climate is characterized by a range of factors including temperature, humidity, precipitation and pressure as well as other components of the climate system such as oceans, ice and snow, biota and the land surface. The Earth's climate varies by location and for convenience broad climate types have been distinguished in assessments, e.g. tropical, savannah, mediterranean, temperate, boreal and tundra. Climatic changes lasting only a few decades are referred to as climatic fluctuations. These are unpredictable at the current state of knowledge although historical evidence indicates the degree of past fluctuations.*

Key Concepts, examples, and related FEPs

Climate fluctuations
Description of regional and local climate change
Increase/decrease in temperature
Increase/decrease in precipitation)

Sea level change — 1.3.03

Definition: FEPs related to changes in sea level, which may occur as a result of global (eustatic) change and regional geological change, e.g. isostatic movements.

Comment: *The component of sea-level change involving the interchange of water between land ice and the sea is referred to as eustatic change. As ice sheets melt so the ocean volume increases and sea levels rise. Sea level at a given location will also be affected by vertical movement of the land mass, e.g. depression and rebound due to glacial loading and unloading, referred to as isostatic change (c.f. FEP 1.3.01).*

Key Concepts, examples, and related FEPs

Flooding
Saline intrusion into repository or geosphere
Change in the hydrogeological regime

Periglacial effects

1.3.04

Definition: FEPs related to the physical processes and associated landforms in cold but ice-sheet-free environments. This may be at the immediate margins of former and existing glaciers and ice sheets or an environment in which frost actions is dominant.

Comment: *An important characteristic of periglacial environments is the seasonal change from winter freezing to summer thaw with large water movements and potential for erosion. The frozen subsoils are referred to as permafrost. Meltwater of the seasonal thaw is unable to percolate downwards due to permafrost and saturates the surface materials, this can result in a mass movement called solifluction (literally soil-flow). Permafrost layers may isolate the deep hydrological regime from surface hydrology, or flow may be focused at "taliks" (localized unfrozen zones, e.g. under lakes, large rivers or at regions of groundwater discharge).*

Key Concepts, examples, and related FEPs

Large water movement

Erosion

Strong seasonal influences

Soil flow (movement) – solifluction

Permafrost

Saturation of surface materials

Glacial and ice sheet effects, local

1.3.05

Definition: FEPs related to the effects of glaciers and ice sheets within the region of a repository, e.g. changes in the geomorphology, erosion, meltwater and hydraulic effects. This is distinct from the effect of large ice masses on global and regional climate, c.f. FEPs 1.3.01, 1.3.02.

Comment: *Erosional processes (abrasion, over-deepening) associated with glacial action, especially advancing glaciers and ice sheets, and with glacial meltwaters beneath the ice mass and at the margins, can lead to morphological changes in the environment e.g. U-shaped valleys, hanging valleys, fjords and drumlins. Depositional features associated with glaciers and ice sheets include moraines and eskers. The pressure of the ice mass on the landscape may result in significant and even depression of the regional crustal plate.*

Key Concepts, examples, and related FEPs

Erosional processes (abrasion, over-deepening)

Hydrogeological change

Transportation and depositional processes and features (Moraines Eskers)

Morphological changes (Hanging valleys, Fjords, Drumlins)

Depression of the regional crustal plate

Warm climate effects (tropical and desert)

1.3.06

Definition: FEPs related to warm tropical and desert climates, including seasonal effects, and meteorological and geomorphological effects special to these climates.

Comment: *Regions with a tropical climate may experience extreme weather patterns (monsoons, hurricanes), that could result in flooding, storm surges, high winds etc. with implications for erosion and hydrology. The high temperatures and humidity associated with tropical climates result and soils are generally thin. In arid climates, total rainfall, erosion and recharge may be dominated by infrequent storm events.*

Key Concepts, examples, and related FEPs

Extreme weather patterns

Monssons

Harricanes

Flooding

Storm surges

Alkali flats

Infrequent storm events

High rainfall

High winds

Effective recharge

Change in hydrological regime

Rapid biological degradation

Erosion

Hydrological/hydrogeological response to climate changes

1.3.07

Definition: FEPs related to changes in the hydrological and hydrogeological regime, e.g. recharge, sediment load and seasonality, in response to climate change in a region.

Comment: *The hydrology and hydrogeology of a region is closely coupled to climate. Climate controls the amount of precipitation and evaporation, seasonal ice cover and thus the soil water balance, extent of soil saturation, surface runoff and groundwater recharge. Vegetation and human actions may modify these responses.*

Key Concepts, examples, and related FEPs

Change in groundwater recharge

Change in sediment load

Change in soil water balance

Change in regional precipitation/infiltration/evaporation

Change in seasonal ice cover

Change in surface runoff

Increase in groundwater velocity

Creation of local ponds

Ecological response to climate changes

1.3.08

Definition: FEPs related to changes in ecology, e.g. vegetation, plant and animal populations, in response to climate change in a region.

Comment: *The ecology of an environment is linked to climate. Ecological adaptation has allowed flora and fauna to survive and exploit even the most hostile of environments. For example, cacti have evolved to survive extreme heat and desiccation of the desert environment, and certain plant species complete their entire lifecycle over very short time periods following rare rain events in the desert. Some tree and plant species have evolved to survive natural events such as forest fires, and may require them to complete their lifecycle*

Key Concepts, examples, and related FEPs

Desert formation

Change in vegetation

Change in animal life

Ecological adaptation

Human response to climate changes 1.3.09

Definition: FEPs related to changes in human behaviour, e.g. habits, diet, size of communities, in response to climate change in a region.

***Comment:** Human response is closely linked to climate. Climate affects the abundance and availability of natural resources such as water, as well as the types of crops that can be grown. The more extreme a climate, the greater the extent of human control over these resources is necessary to maintain agricultural productivity, e.g. through the use of dams, irrigation systems, controlled agricultural environments (greenhouses).*

Key Concepts, examples, and related FEPs

Change in human habits

Effect of climate change on food chain

Change in agricultural activities/products

Increase/decrease in usage of irrigation systems

Change in population density

Change in diet

Effect of climate change on water availability

Construction of dams

Other geomorphologic changes 1.3.10

Definition: FEPs related to geomorphologic (also known as physiography) changes on a regional and local scale, i.e. the general configuration of the Earth's surface.

***Comment:** Geomorphology refers to the classification, description, nature, origin and development of present landforms and their relationships to underlying structures, and of the history of geologic changes as recorded by these surface features. The term is especially applied to the generic interpretation of landforms, but has also been restricted to features produced only by erosion and deposition.*

Key Concepts, examples, and related FEPs

Denudation

FUTURE HUMAN ACTIONS (ACTIVE) 1.4

Definition: Human actions and regional practices, in the post-closure period, that can potentially affect the performance of the engineered and/or geological barriers, e.g. intrusive actions, but not the passive behaviour and habits of the local population, c.f. 2.4.

***Comment:** Human Actions (Active)" is a sub-category of the External Factors in the International FEP List and is divided into individual FEPs.*

Human influences on climate 1.4.01

Definition: FEPs related to human activities that could affect the change of climate either globally or in a region.

***Comment:** These activities could be intentional or unintentional, with an indirect influence more than a direct influence on the climate.*

Key Concepts, examples, and related FEPs

De-forestation

Emissions of 'greenhouse' gases such as CO_2 *and* CH_4

Motivation and knowledge issues (inadvertent/deliberate human actions) 1.4.02

Definition: FEPs related to the degree of knowledge of the existence, location and/or nature of the repository. Also, reasons for deliberate interference with, or intrusion into, a repository after closure with complete or incomplete knowledge.

Comment: *Some future human actions e.g. see FEPs 1.4.03 and 1.4.04, could directly impact upon the repository performance. Many assessments distinguish between:*

- *inadvertent actions, which are actions taken without knowledge or awareness of the repository, and*
- *deliberate actions, which are actions that are taken with knowledge of the repository's existence and location, e.g. deliberate attempts to retrieve the waste, malicious intrusion and sabotage.*

Intermediate cases, of intrusion with incomplete knowledge, could also occur.

<u>Key Concepts, examples, and related FEPs</u>

Human intrusion (instigate mechanical processes

Incomplete knowledge intrusion)

Deliberate actions e.g. war, sabotage, waste recovery, malicious intrusion

Inadvertent actions e.g. exploratory drilling, resource mining, archaeological intrusion

Drilling activities (human intrusion) 1.4.03

Definition: FEPs related to any type of drilling activity near the repository.

Comment: *These activities may be taken with or without knowledge of the repository and in fact is a subgroup of FEP 1.4.02.*

<u>Key Concepts, examples, and related FEPs</u>

Exploratory and/or exploitation drilling for natural resources and raw materials

Drilling for research or site characterization studies

Water well drilling

Drilling for waste injection

Drilling for hydrothermal resources

Extraction of valuable components of the disposed waste

Mining and other underground activities (human intrusion) 1.4.04

Definition: FEPs related to any type of mining or excavation activity carried out near the repository.

Comment: *These activities may be taken with or without knowledge of the repository and in fact is a subgroup of FEP 1.4.02.*

Key Concepts, examples, and related FEPs

Resource mining;

Excavation for industry;

Geothermal energy production

Mine drillings

Shaft construction, underground construction and tunnelling

Recovery of repository materials (re-use of waste)

The presence of mine galleries - after closure

Malicious intrusion, sabotage or war

Injection of liquid wastes and other fluids

Scientific underground investigation

Underground nuclear testing

Un-intrusive site investigation

1.4.05

Definition: FEPs related to airborne, geophysical or other surface-based investigation of a repository site after repository closure

Comment: *Such investigation, e.g. prospecting for geological resources, might occur after information of the location of a repository had been lost. The evidence of the repository itself, e.g. discovery of an old shaft, might itself prompt investigation, including research of historical archives.*

Key Concepts, examples, and related FEPs

Prospecting for geological resources

Investigation of an old shaft

Research of historical archives

Surface excavations

1.4.06

Definition: FEPs related to any type of human activities during surface excavations that can potentially affect the performance of the engineered and/or natural (geological) barriers, or the exposure pathways.

Comment: *This FEP relates to the surface environment. Strictly speaking, excavation refers to an act or process of removing soil and or rock materials from one location and transporting them to another. This may include, for example, digging, blasting, breaking, loading and hauling, which may result in direct human intrusion in the case of a near surface repository.*

Key Concepts, examples, and related FEPs

Quarrying, trenching, ploughing

Digging, blasting, breaking, loading, hauling

Recycling of materials

Dredging of sediments in estuaries

Excavation for construction (earthworks)

Excavation for storage or disposal

Shallow excavations for site investigations

Excavation for military purposes

Pollution

1.4.07

Definition: FEPs related to any type of human activities associated with pollution that can potentially affect the performance of the engineered and/or natural (geological) barriers, or the exposure pathways.

Comment: *As used here, it refers to the alteration of the chemical composition of the surface environment in the vicinity of the repository, in such a way that the performance of the disposal system is influenced.*

Key Concepts, examples, and related FEPs

Acid rain

Chemical liquid waste disposal

Soil pollution

Soil fertilization

Groundwater pollution

Site development

1.4.08

Definition: FEPs related to any type of human activities during site development that can potentially affect the performance of the engineered and/or natural (geological) barriers, or the exposure pathways

Comment: *As used here, site development refers to alterations to the surface environment after memory of the repository has been lost. These alterations may result in direct human intrusion in the near surface facility, or to an alteration of the host lithology or topography.*

Key Concepts, examples, and related FEPs

Site occupation

Levelling of hills (e.g., airport lay out)

Construction of roads, houses, buildings, dams, etc.

Human modification of the site drainage

Residential, industrial, transport and road construction

Land reclamation/extension

Archaeology

1.4.09

Definition: FEPs related to any type of human activities associated with archaeology that can potentially affect the performance of the engineered and/or natural (geological) barriers, or the exposure pathways.

Comment: *As used here, the FEP refers to archaeological investigations in the surface environment.*

Key Concepts, examples, and related FEPs

Archaeological, inadvertent human intrusion

Archaeological artefacts find during construction

Water management (wells, reservoirs, dams)

1.4.10

Definition: FEPs related to groundwater and surface water management including water extraction, reservoirs, dams, and river management.

Comment: *Water is a valuable resource and water extraction and management schemes provide increased control over its distribution and availability through construction of dams, barrages, canals, pumping stations and pipelines. Groundwater and surface water may be extracted for human domestic use (e.g. drinking water, washing), agricultural uses (e.g. irrigation, animal consumption) and industrial uses. Extraction and management of water may affect the movement of radionuclides to and in the surface environment.*

Key Concepts, examples, and related FEPs

Waterworks

Artificial mixing of lakes

Reservoirs

Industrial usage

Human effects on water potential

Chemical liquid waste disposal

Intentional artificial groundwater recharge/discharge by humans

Dam, barrage, canals, pumping stations and pipeline building

Desalination of water in estuaries and marines

Drainage systems

Extraction of contaminated water from aquifer via a well

Impoundment of water for fishing/fish farming, bathing

Groundwater/surface water extraction for irrigation, animal consumption, drinking water, washing

Salt production

Social and institutional developments

1.4.11

Definition: FEPs related to changes in social patterns and degree of local government, planning and regulation.

Comment: *The decisions made in future concerning social and institutional development may have a significant influence on the disposal system, e.g., if a change in land use is promulgated or a change in the regulatory requirements.*

Key Concepts, examples, and related FEPs

Loss of archives/records, loss/degradation of societal memory

Changes in planning controls and environmental legislation

Demographic change and urban development

Changes in land use

Change in regulatory requirements

Change in institutional control

Technological developments

1.4.12

Definition: FEPs related to future developments in human technology and changes in the capacity and motivation to implement technologies. This may include retrograde developments, e.g. loss of capacity to implement a technology.

Comment: *Of interest are those technologies that might change the capacity of man to intrude deliberately or otherwise into a repository, to cause changes that would affect the movement of contaminants, to affect the exposure or its health implications. Technological developments are likely but may not be predictable especially at longer times into the future. In most assessments, assumptions are made to limit the scope of consideration.*

Key Concepts, examples, and related FEPs

Retrograde developments

Loss of capacity to implement technology

Remedial actions 1.4.13

Definition: FEPs related to actions that might be taken following repository closure to remediate problems with a waste repository that, either, was not performing to the standards required, had been disrupted by some natural event or process, or had been inadvertantly or deliberately damaged by human actions.

Comment:

Key Concepts, examples, and related FEPs

None

Explosions and crashes 1.4.14

Definition: FEPs related to deliberate or accidental explosions and crashes such as might have some impact on a closed repository, e.g. underground nuclear testing, aircraft crash on the site, acts of war.

Comment:

Key Concepts, examples, and related FEPs

Intrusions by war, sabotage, terrorism

Underground nuclear testing

Likelihood of crashes onto surface facilities, e.g. plane crashes

DISPOSAL SYSTEM DOMAIN: ENVIRONMENTAL FACTORS 2

Definition: Features and processes occurring within that spatial and temporal (post-closure) domain whose principal effect is to determine the evolution of the physical, chemical, biological and human conditions of the domain that are relevant to estimating the release and migration of radionuclides and consequent exposure to man.

Comment: *"Disposal System Domain: Environmental Factors" is a category in the International FEP List and is divided into sub-categories.*

WASTES AND ENGINEERED FEATURES

2.1

Definition: Features and processes within the waste and engineered components of the disposal system. (output – source term characteristics)

Comment: *"Wastes and Engineered Features" is a sub-category of Disposal Domain:Environmental Factors in the International FEP List and is divided into individual FEPs.*

Note that FEPs 2.1.01 to 2.1.06 describe the features in the disposal system, in other words, a description of the system as it is constructed, whereas FEPs 2.1.07 to 2.1.11 describe the processes or the changes in the disposal system.

Inventory, radionuclide and other material

2.1.01

Definition: FEPs related to the total content of the repository of a given type of material, substance, element, individual radionuclides, total radioactivity or inventory of toxic substances.

Comment: *The FEP often refers to content of radionuclides but the content of other materials, e.g. steels, other metals, concrete or organic materials, could be of interest.*

Key Concepts, examples, and related FEPs

Radionuclide content

Concrete or organic material content

Steel and other metal content

Waste form materials, characteristics and degradation processes

2.1.02

Definition: FEPs related to the physical, chemical, biological characteristics of the waste form at the time of disposal and as they may evolve in the repository, including FEPs which are relevant specifically as waste degradation processes.

Comment: *The waste form will usually be conditioned prior to disposal, e.g. by solidification and inclusion of grout materials. the waste form is a component of the waste package. The waste characteristics will evolve due to various processes that will be affected by the physical and chemical conditions of the repository environment. Processes that are relevant specifically as waste degradation processes, as compared to general evolution of the near field, are included in this FEP.*

Key Concepts, examples, and related FEPs

Physical degradation

Chemical degradation

Solid matrix of resin, bitumen, cement

Ash

Cloves, clothing, plastics, paper wood

Spent sources

Activated metal

Sludges, evaporation residue, compacted solids, filters

Container materials, characteristics and degradation/failure processes 2.1.03

Definition: FEPs related to the physical, chemical, biological characteristics of the container at the time of disposal and as they may evolve in the repository, including FEPs that are relevant specifically as container degradation/failure processes.

Comment: *The container refers to the vessel into which the waste form is placed for handling, transportation, storage and or disposal. It is also the outer barrier protecting the waste from external intrusions. The container is a component of the waste package.*

<u>Key Concepts, examples, and related FEPs</u>

- *Container degradation/failure processes*
- *Metal drums*
- *Concrete containers*
- *Stainless steel containers*
- *Lead containers*

Buffer/backfill materials, characteristics and degradation processes 2.1.04

Definition: FEPs related to the physical, chemical, biological characteristics of the buffer and/or backfill at the time of disposal and as they may evolve in the repository, including FEPs that are relevant specifically as buffer/backfill degradation processes. (Effect on hydrology / flow)

Comment: *Buffer and backfill are sometimes used synonymously. In some HLW/spent fuel concepts, the term buffer is used to mean material immediately surrounding a waste container and having some chemical and/or mechanical buffering role whereas backfill is used to mean material used to fill other underground openings. However, in ILW/LLW concepts the term backfill is used to describe the material placed between waste containers, which may have a chemical role. Buffer/backfill materials may include clays, cement and mixtures of cement with aggregates, e.g. of crushed rock.*

The buffer/backfill characteristics will evolve due to various processes that will be affected by the physical and chemical conditions of the repository environment. Processes, which are relevant specifically as buffer/backfill degradation processes, as compared to general evolution of the near field, are included in this FEP.

<u>Key Concepts, examples, and related FEPs</u>

- *Buffer/backfill degradation processes*
- *Bentonite clay*
- *Clay, cement, sand, soil*
- *Mixture of clay and crushed rock*

Engineered barrier system characteristics and degradation processes 2.1.05

Definition: FEPs related to the design, physical, chemical, hydraulic etc. characteristics of the cavern/tunnel/shaft seals at the time of sealing and closure and also as they may evolve in the repository, including FEPs which are relevant specifically as cavern/tunnel/shaft seal and cap degradation processes. (Effect on hydrology / flow – change over time).

Comment: *Cavern/tunnel/shaft seal and cap failure may result from gradual degradation processes, or may be the result of a sudden event. The importance is that alternative routes for groundwater flow and radionuclide transport may be created along the various layers and tunnels and/or shafts and associated EDZ (see FEP 2.2.01).*

Key Concepts, examples, and related FEPs

Engineered caps (cover)

Cover degradation

Intrusion resistance caps

Cap materials: clay, concrete

Other engineered features materials, characteristics and degradation processes	2.1.06

Definition: FEPs related to the physical, chemical, biological characteristics of the engineered features (other than containers, buffer/backfill, caps and seals) at the time of disposal and also as they may evolve in the repository, including FEPs which are relevant specifically as degradation processes acting on the engineered features.

Comment: *Examples of other engineered features are rock bolts, shotcrete, tunnel liners, silo walls, any services and equipment not removed before closure. The engineered features, materials and characteristics will evolve due to various processes that will be affected by the physical and chemical conditions of the repository environment. Processes which are relevant specifically as degradation processes acting on the features, as compared to general evolution of the near field, are be included in this FEP.*

Key Concepts, examples, and related FEPs

Trenches, holes, vaults

Walls, floors, mounds, layers of mounds

Rock bolts, tunnel liners, silo walls

Reduction in flow through structures due to impermeable membrane and subsequent degradation of impermeable membrane

Cut-off walls

Degradation processes

Mechanical processes and conditions (in wastes and EBS)	2.1.07

Definition: FEPs related to the mechanical processes that affect the wastes, containers, seals and other engineered features, and the overall mechanical evolution of near field with time. This includes the effects of hydraulic and mechanical loads imposed on wastes, containers and repository components by the surrounding geology.

Comment:

Key Concepts, examples, and related FEPs

Waste and container compression

Container collapse

Buffer swelling pressure

Material volume changes

Subsidence as a result of compression of waste and cover layers

Fracture formation in vault, backfill, joints, cover materials, host geology (local fractures)

Container movement

Differential behaviour of joints

Tunnel roof or lining collapse

Hydraulic/hydrogeological processes and conditions (in wastes and EBS) 2.1.08

Definition: FEPs related to the hydraulic/hydrogeological processes that affect the wastes, containers, seals and other engineered features, and the overall hydraulic/hydrogeological evolution of near field with time. This includes the effects of hydraulic/hydrogeological influences on wastes, containers and repository components by the surrounding geology.

Comment:

Key Concepts, examples, and related FEPs

Failure of drainage system

Failure of cut-off walls

Failure of cap/cover

Modification of pore water by cover caused by chemical

Interaction of vault material with pore water

pH change

Osmotic effects

Infiltration and movement of fluids in the repository environment

Resaturation/desaturation of the repository or its components

Failure of the joints

Bathtubbing

Fracturing of concrete components

Effect of cap+cover+backfill

Influence of climate change

Influence of saline intrusion

Gas mediated water flow

Interaction of backfill with pore water

pH change

Redox change

Sulphate attack

Effect of chelating agents

Redox potential change

Mineralization

Modefication of pore water by cover

Interaction of container material with pore water

Matrix corrosion

Gas generation

Polymer degradation (high integrity containers)

Mineralization change

Osmotic effect

Interaction of vault materials with host groundwater

Carbonation

Water flow and contaminant transport paths within the repository

Induced fluid effects caused by temperature change

-Pressure change

-Natural convection

-Viscosity

Reduction in flow through structures due to grouting

holoride attack

Sulphate attack

Colloid formation

Chemical/geochemical processes and conditions (in wastes and EBS) 2.1.09

Definition: FEPs related to the chemical/geochemical processes that affect the wastes, containers, seals and other engineered features, and the overall chemical/geochemical evolution of near field with time. This includes the effects of chemical/geochemical influences on wastes, containers and repository components by the surrounding geology.

Comment:

Key Concepts, examples, and related FEPs

Chemical interaction of backfill with pore water

pH changes

Redox changes

Sulphate attack

Chemical interaction of waste with pore water

Metallic corrosion processes (general and pitting)

Polymer degradation (resins)

Osmotic effects

Induced galvanic metallic corrosion

Polymer degradation (high integrity containers)

Chemical interaction of backfill with containers (including overpacks)

Induced galvanic metallic corrosion

Osmotic effects

Chemical interaction of vault materials with pore water

pH changes

Redox potential changes

Chemical interaction of vault materials with host groundwater

Carbonation

Chloride attack

Sulphate attack

Chemical interaction of containers (including overpacks) with pore water

Metallic corrosion

Polymer degradation (high integrity containers)

Osmotic effects

Chemical interaction of waste with containers

Precipitation/dissolution reactions

Evolution of redox (Eh) and acidity/alkalinity (pH) etc.

Silting/pore closure

Geochemical changes

Polymer degradation (high integrity containers)

Chemical interaction of non-radioactive waste components with radioactive waste components

pH changes

Redox potential changes

Change in chemical reaction rate caused by temperature change

Electrochemical processes

Chemical conditioning and buffering processes

Biological/biochemical processes and conditions (in wastes and EBS)	2.1.10

Definition: FEPs related to the biological/biochemical processes that affect the wastes, containers, seals and other engineered features, and the overall biological/biochemical evolution of near field with time. This includes the effects of biological/biochemical influences on wastes, containers and repository components by the surrounding geology.

Comment:

Key Concepts, examples, and related FEPs

Microbial growth and poisoning

Microbially/biologically mediated processes

Effect of organic material

Microbial/biological effects of evolution of redox (Eh) and acidity/alkalinity (pH) , etc.

Effect of organic materials

Change in microbial caused by change in temperature

Thermal processes and conditions (in wastes and EBS) 2.1.11

Definition: FEPs related to the thermal processes that affect the wastes, containers, seals and other engineered features, and the overall thermal evolution of the near field with time. This includes the effects of heat on wastes, containers and repository components from the surrounding geology.

Comment:

Key Concepts, examples, and related FEPs

Temperature evolution

Differential elastic response

Non-elastic response

Fracture aperture changes caused by the temperature change

Change in microbial activity

Radiogenic, chemical and biological heat production from the wastes

Chemical heat production from engineered features, e.g. concrete hydration

Change in chemical reaction rates e.g. corrosion

Temperature dependence of physical/chemical/ biological/hydraulic processes, e.g. corrosion and re-saturation

Fluid pressure, density viscosity changes

Induced chemical changes caused by the temperature change

Gas sources and effects (in wastes and EBS) 2.1.12

Definition: FEPs within and around the wastes, containers and engineered features resulting in the generation of gases and their subsequent effects on the repository system.

Comment: *Gas production may result from degradation and corrosion of various waste, container and engineered feature materials, as well as radiation effects. The effects of gas production may change local chemical and hydraulic conditions, and the mechanisms for radionuclide transport, i.e. gas-induced and gas-mediated transport.*

Key Concepts, examples, and related FEPs

Explosion

Pressurisation

Radiation effects

Gas generation

Corrosion

Decomposition of organic matter (microbial)

Degradation of vault, overpacks or backfill (instigate mechanical processes)

Chemical interaction of containers (including overpacks) with pore water

Chemical interaction of waste with containers

Chemical interaction of backfill with containers (including overpacks)

Radiation effects (in wastes and EBS) 2.1.13

Definition: FEPs related to the effects that result from the radiation emitted from the wastes that affect the wastes, containers, seals and other engineered features, and the overall radiogenic evolution of the near field with time.

Comment: *Examples of relevant effects are ionization, radiolytic decomposition of water (radiolysis), radiation damage to waste matrix or container materials, helium gas production due to alpha decay.*

Key Concepts, examples, and related FEPs

Radiolysis

Decay product gas generation

Irradiation effects on metals, concrete

Polymer degradation (resins and high integrity containers)

Concrete degradation

Metallic degradation

Nuclear criticality	2.1.14

Definition: FEPs related to the possibility and effects of spontaneous nuclear fission chain reactions within the repository.

Comment: *A chain reaction is the self-sustaining process of nuclear fission in which each neutron released from a fission triggers, on average, at least one other nuclear fission. Nuclear criticality requires a sufficient concentration and localized mass (critical mass) of fissile isotopes (e.g. U-235, Pu-239) and also presence of neutron moderating materials in a suitable geometry; a chain reaction is liable to be damped by the presence of neutron absorbing isotopes (e.g. Pu-240).*

Key Concepts, examples, and related FEPs

Radiological criticality

Extraneous materials	2.1.15

Definition:

Comment:

Key Concepts, examples, and related FEPs

None

GEOLOGICAL ENVIRONMENT	2.2

Definition: The features and processes of the geological environment surrounding the repository including, for example, the hydrogeological, geomechanical and geochemical features and processes, both in pre-emplacement state and as modified by the presence of the repository and other long term changes.

Comment: *" Geological Environment" is a sub-category in the International FEP List and is divided into individual FEPs.*

Note that FEPs 2.2.01 to 2.2.06 describe the features in the disposal system, in other words, a description of the features of the system as it is constructed, whereas FEPs 2.2.07 to 2.2.11 describe the processes or the changes in the disposal system..

Disturbed zone, host lithology 2.2.01

Definition: FEPs related to the host lithology zone around the repository or any other underground openings that may be mechanically disturbed during construction, and the properties and characteristics as they may evolve both before and after repository closure.

Comment: *The disturbed zone may have different properties to the undisturbed host lithology, e.g. opening of fractures or change of hydraulic properties due to stress relief.*

Key Concepts, examples, and related FEPs

Fracture formed by the construction

Change of hydraulic properties due to stress relief

Host lithology 2.2.02

Definition: FEPs related to the properties and characteristics of the lithology in/on which the repository is sited (excluding the zone disturbed by the construction) as they may evolve both before and after repository closure. In most cases, this FEP will be associated with the unsaturated zone.

Comment: *Relevant properties include thermal and hydraulic conductivity, compressive and shear strength, porosity etc. In most cases, this FEP will be associated with the unsaturated zone (See FEP 2.2.03).*

Key Concepts, examples, and related FEPs

Thermal and hydraulic conductivity

Porosity

Description of the host lithology

Compressive and shear strength

Lithological units, other 2.2.03

Definition: FEPs related to the properties and characteristics of the lithology other than the host lithology as they may evolve both before and after repository closure.

Comment: *These lithological units are those that make up the region in which the repository is located. These units are identified in the geological investigations of the region. Each geological unit is characterized according to its geometry and its general physical properties and characteristics. Details concerning inhomogeneity and uncertainty associated with each unit are included in the characterization. In most cases, this FEP will be associated with the saturated zone (See FEP 2.2.02).*

Key Concepts, examples, and related FEPs

Non-uniform stratigraphy

Heterogeneity

Description of the lithology units

Discontinuities, large scale (in geosphere) 2.2.04

Definition: FEPs related to the properties and characteristics of discontinuities in and between the saturated and unsaturated zones, including faults, shear zones, intrusive dykes and interfaces between different rock types.

Comment:

Key Concepts, examples, and related FEPs

Fault	*Shear zones*	*Interfaces between different rock types*
Intrusive dykes		

Contaminant transport path characteristics (in geosphere) 2.2.05

Definition: FEPs related to the properties and characteristics of smaller discontinuities and features within saturated and unsaturated zones that are expected to be the main paths for contaminant transport through the geosphere, as they may evolve both before and after repository closure.

Comment: *Groundwater flow and contaminant transport through rocks may occur in a variety of systems depending on the rock characteristics. Porous flow is predominantly through pores in the medium or through the interstitial spaces between small grains of materials. Fracture flow is predominantly along fractures in the rock which represent the only connected open spaces. Changes in the contaminant transport path characteristics due to the repository construction or its chemical influence etc. are included.*

Key Concepts, examples, and related FEPs

Fracture flow	*Fracture-matrix interaction*	*Porous flow*

Mechanical processes and conditions (in geosphere) 2.2.06

Definition: FEPs related to the mechanical processes that affect the saturated and unsaturated zones, and the overall evolution of conditions with time. This includes the effects of changes in condition, e.g. rock stress, due to the excavation, construction and long term presence of the repository.

Comment:

Key Concepts, examples, and related FEPs

Subsidence	*Upliftment*

Hydraulic/hydrogeological processes and conditions (in geosphere) 2.2.07

Definition: FEPs related to the hydraulic and hydrogeological processes that affect the saturated and unsaturated zones, and the overall evolution of conditions with time. This includes the effects of changes in condition, e.g. hydraulic head, due to the excavation, construction and long term presence of the repository.

Comment: *The hydrogeological regime is the characterization of the composition and movement of water through the relevant geological formations in the repository region and the factors that control this. This requires knowledge of the recharge and discharge zones, the groundwater flow systems, saturation, and other factors that may drive the hydrogeology, such as density effects due to salinity gradients or temperature gradients. Changes of the hydrogeological regime due to the construction and/or presence of the repository are included.*

Key Concepts, examples, and related FEPs

Saline intrusion
Darcy flow
Non-Darcy flow
Fracture flow
Groundwater discharge to surface water, Soil, Estuary, Seas, Wells
Channelling and preferential flow pathways
Aquifer(groundwater) discharge/recharge (e.g. well)
Saturated/unsaturated conditions
Flow between two aquifers
Infiltration
Flow direction

Chemical/geochemical processes and conditions (in geosphere) 2.2.08

Definition: FEPs related to the chemical and geochemical processes that affect the saturated and unsaturated zones, and the overall evolution of conditions with time. This includes the effects of changes in condition, e.g. Eh, pH, due to the excavation, construction and long term presence of the repository.

Comment: *The hydrochemical regime refers to the groundwater chemistry in the geological formations in the repository region, and the factors that control this. This requires knowledge of the groundwater chemistry including speciation, solubility, complexants, redox (reduction/oxidation) conditions, rock mineral composition and weathering processes, salinity and chemical gradients. Changes of the hydrochemical regime due to the construction and/or presence of the repository are included.*

Key Concepts, examples, and related FEPs

pH change
Redox potential changes
pH effects of cement on the environment, soil, etc
Mineralization changes
Effect of non-radioactive solute plume

Biological/biochemical processes and conditions (in geosphere) 2.2.09

Definition: FEPs related to the biological and biochemical processes that affect the saturated and unsaturated zones, and the overall evolution of conditions with time. This includes the effects of changes in condition, e.g. microbe populations, due to the construction and long term presence of the repository.

Comment:

Key Concepts, examples, and related FEPs

Generating of chelating agents
Influences on pH
Influences on redox potential
Change in microbe population
Microbiology-enhanced mobility

Thermal processes and conditions (in geosphere)	**2.2.10**
Definition: FEPs related to the thermal processes that affect the saturated and unsaturated zones, and the overall evolution of conditions with time. This includes the effects of changes in condition, e.g. temperature, due to the construction and long term presence of the repository.	
Comment: *Geothermal regime refers to sources of geological heat, the distribution of heat by conduction and transport (convection) in fluids, and the resulting thermal field or gradient. Changes of the geothermal regime due to the construction and/or presence of the repository are included*	
Key Concepts, examples, and related FEPs *Bio-heat* *Chemical reactions* *Change in temperature*	

Gas sources and effects (in geosphere)	2.2.11
Definition: FEPs related to natural gas sources and production of gas within the geosphere and also the effect of natural and repository produced gas on the geosphere, including the transport of bulk gases and the overall evolution of conditions with time.	
Comment: *Gas movement in the geosphere will be determined by many factors including the rate of production, gas permeability and solubility, and the hydrostatic pressure regime.*	
Examples *Natural gas intrusion*	

Undetected features (in geosphere)	2.2.12
Definition: FEPs related to natural or man-made features within the geology that may not be detected during the site investigation.	
Comment: *Examples of possible undetected features are fracture zones, brine pockets or old mine workings. Some physical features of the repository environment may remain undetected during site surveys and even during pilot tunnel excavations. The nature of the geological environment will indicate the likelihood that certain types of undetected features may be present and the site investigation may be able to place bounds on the maximum size or minimum proximity to such features.*	
Key Concepts, examples, and related FEPs *Boreholes (drillings)* *Mine shafts or mine galleries* *Faults, shear zones, Breccia pipes, Lava tubes, Intrusive dykes* *Gas or brine pockets*	

Geological resources

2.2.13

Definition: FEPs related to natural resources within the geosphere, particularly those that might encourage investigation or excavation at or near the repository site.

Comment: *Geological resources could include oil and gas, solid minerals, water, and geothermal resources. For a near surface repository, quarrying of near surface deposits, e.g. sand, gravel or clay, may be of interest*

Key Concepts, examples, and related FEPs

Oil and gas
Solid minerals
Water
Sand, gravel, clay

SURFACE ENVIRONMENT

2.3

Definition: The features and processes within the surface environment, including near surface aquifers and unconsolidated sediments but excluding human activities and behaviour, see 1.4 and 2.4..

Comment: *Surface Environment" is a sub-category in the International FEP List and is divided into individual FEPs*

Note that FEPs 2.3.01 to 2.3.06 describe the features in the disposal system, in other words, a description of the features of the system as it is constructed, whereas FEPs 2.3.07 to 2.3.11 describe the processes or the changes in the disposal system..

Topography and morphology

2.3.01

Definition: FEPs related to the relief and shape of the surface environment and its evolution.

Comment: *This FEP refers to local land form and land form changes with implications for the surface environment, e.g. plains, hills, valleys, and effects of river and glacial erosion thereon. In the long term, such changes may occur as a response to geological changes, see 1.3.*

Key Concepts, examples, and related FEPs

Land forms
Hills
Valleys
Plains

Soil and sediment

2.3.02

Definition: FEPs related to the characteristics of the soils and sediments and their evolution.

Comment: *Different soil and sediment types, e.g. characterized by particle-size distribution and organic content, will have different properties with respect erosion/deposition and contaminant sorption etc.*

Key Concepts, examples, and related FEPs

Soil and sediment development
Soil conversion

Aquifers and water-bearing features, near surface	2.3.03

Definition: FEPs related to the characteristics of aquifers and water-bearing features within a few metres of the land surface and their evolution.

Comment: *Aquifers are water-bearing features geological units or near surface deposits that yield significant amounts of water to wells or springs. The presence of aquifers and other water-bearing features will be determined by the geological, hydrological and climatic factors.*

Key Concepts, examples, and related FEPs

Weathered aquifer

Sandy aquifer

Fractured aquifer

Description of aquifers in repository region

Lakes, rivers, streams and springs	2.3.04

Definition: FEPs related to the characteristics of terrestrial surface water bodies and their evolution.

Comment: *Streams, rivers and lakes often act as boundaries on the hydrogeological system. They usually represent a significant source of dilution for materials (including) radionuclides entering these systems, but in hot dry environments, where evaporation dominates, concentration is possible.*

Key Concepts, examples, and related FEPs

Description of lakes, rivers, streams and springs in the repository region

Coastal features	2.3.05

Definition: FEPs related to the characteristics of coasts and the near shore, and their evolution. Coastal features include headlands, bays, beaches, spits, cliffs and estuaries.

Comment: *The processes operating on these features, e.g. active erosion, deposition, longshore transport, determine the development of the system and may represent a significant mechanism for dilution or accumulation of materials (including radionuclides) entering the system.*

Key Concepts, examples, and related FEPs

Description of the coastal features in the repository region

Headlands, Bays, Beaches, Spits

Cliffs, Estuaries

Coastal erosion

Saline intrusion

Salinity changes

Sedimentation

Resuspension

Volatilisation

Coastal surge

Storm

tsunami

Groundwater discharge to estuary, shore

Bioturbation

Tidal currents

Sea spray

Behaviour of coastal waters and marine sediment

Estuarine changes

Temperature change

Recharge

Bed-load processes

Flooding

Plant/animal uptake/metabolism

Sand dune encroachment

Coastal currents

Description of coastal features in vicinity of repository

Beach development

Marine features 2.3.06

Definition: FEPs related to the characteristics of seas and oceans, including the seabed, and their evolution. Marine features include oceans, ocean trenches, shallow seas, and inland seas.

Comment: *Processes operating on these features such as erosion, deposition, thermal stratification and salinity gradients, determine the development of the system and may represent a significant mechanism for dilution or accumulation of materials (including radionuclides) entering the system.*

Key Concepts, examples, and related FEPs

Ocean trenches, shallow seas
inland seas, Oceans
Sedimentation
Resuspension
Volatilisation
Tidal currents
Marine currents
Marine sediment transport and deposition
Groundwater discharge towards sea
Sea spray
Sediment transport
Sea currents
Temperature change
Vertical mixing and isolation
Salinity changes
Plant/animal uptake/metabolism
Bed-load processes
Description of marine features in vicinity of repository
Recharge

Atmosphere 2.3.07

Definition: FEPs related to the characteristics of the atmosphere, including capacity for transport, and their evolution.

Comment:

Key Concepts, examples, and related FEPs

Physical transport of gases
Chemical and photochemical reactions
Aerosols and dust in the atmosphere

Vegetation 2.3.08

Definition: FEPs related to the characteristics of terrestrial and aquatic vegetation both as individual plants and in mass, and their evolution.

Comment:

Key Concepts, examples, and related FEPs

Chemical changes caused by plants
Description of the vegetation in vicinity of repository

Animal populations 2.3.09

Definition: FEPs related to the characteristics of the terrestrial and aquatic animals both as individual animals and as populations, and their evolution.

Comment:

Key Concepts, examples, and related FEPs

Animal diets

External contamination of animals

Description of the animal population in vicinity of repository

Meteorology 2.3.10

Definition: FEPs related to the characteristics of weather and climate, and their evolution.

Comment: *Meteorology is characterized by precipitation, temperature, pressure and wind speed and direction. The variability in meteorology should be included so that extreme events such as drought, flooding, storms and snow melt are identified.*

Key Concepts, examples, and related FEPs

Rainfall

Snowfall

Flooding related to high precipitation

Storms related to strong winds

Climate fluctuation

Dew-freezing cycles

Wet-dry cycles

Seasonality

Hurricanes

High rainfall / Flooding

Temperature

Tsunamis

Hydrological regime and water balance (near-surface) 2.3.11

Definition: FEPs related to near surface hydrology at a catchment scale and also soil water balance, and their evolution.

Comment: *The hydrological regime is a description of the movement of water through the surface and near surface environment. It includes the movement of materials associated with the water such as sediments and particulate. Extremes such as drought, flooding, storms and snowmelt may be relevant.*

Key Concepts, examples, and related FEPs

Surface run-off to marines/estuaries

River flow to marines/estuaries

Evaporation

Evapotranspiration

Infiltration

Groundwater discharge to surface water, soils, estuaries/marines

Water discharge/recharge processes that effecting radionuclide content

Stream silting

Change in lake or reservoir levels

Alkali flats

Stream and river flow changes

River meander

Stream flow

Erosion and deposition 2.3.12

Definition: FEPs related to all the erosional and depositional processes that operate in the surface environment, and their evolution.

Comment: *Relevant processes may include fluvial and glacial erosion and deposition, denudation, eolian erosion and deposition. These processes will be controlled by factors such as the climate, vegetation, topography and geomorphology.*

Key Concepts, examples, and related FEPs

Deposition

Wind erosion related to storms

Erosion related to flooding

Erosion related to glaciation

Coastal erosion due to rise and fall of lea level (Greenhouse effect)

Landsliding (instigate mechanical processes)

Erosion (instigate mechanical processes)

Erosion by wave action, landslides or rockfalls

Agriculture erosion

Erosion of cover

Weathering

Ecological/biological/microbial systems 2.3.13

Definition: FEPs related to living organisms and relations between populations of animals, plants and their evolution.

Comment: *Characteristics of the ecological system include the vegetation regime, and natural cycles such as forest fires or flash floods that influence the development of the ecology. The plant and animal populations occupying the surface environment are an intrinsic component of its ecology. The wide range of processes that define the ecological system regulates their behaviour and population dynamics. Human activities have significantly altered the natural ecology of most environments.*

Key Concepts, examples, and related FEPs

Ecological and biological features

Chemical changes caused by micro-organisms

Chemical changes caused by plants

Animal/Plant intrusion 2.3.14

Definition: Animal and plant intrusion leading to vault or trench disruption.

Comment:

Key Concepts, examples, and related FEPs

Seeds

Burrowing animals

Root intrusion (instigate mechanical processes)

Bio-intrusion by plants and animals

Animal intrusion (instigate mechanical processes)

HUMAN BEHAVIOUR	2.4
Definition: The habits and characteristics of the individuals or populations, e.g. critical groups, to whom exposures are calculated, not including intrusive or other activities which will have an impact on the performance of the engineered or geological barriers, see 1.4.	
Comment: *"Human Behaviour (passive)" is a sub-category in the International FEP List and is divided into individual FEPs.*	

Human characteristics (physiology, metabolism)	2.4.01
Definition: FEPs related to characteristics, e.g. physiology, metabolism, of individual humans.	
Comment: *Physiology refers to body and organ form and function. Metabolism refers to the chemical and biochemical reactions, which occur within an organism, or part of an organism, in connection with the production and use of energy.*	
Key Concepts, examples, and related FEPs *Physiological and metabolism description of humans that will be the subject of the assessment*	

Adults, children, infants and other variations	2.4.02
Definition: FEPs related to considerations of variability, in individual humans, of physiology, metabolism and habits.	
Comment: *Children and infants, although similar to adults, often have characteristic differences, e.g. metabolism, respiratory rates, habits (e.g. pica, ingestion of soil) which may lead to different exposure characteristics.*	
Key Concepts, examples, and related FEPs *None*	

Diet and fluid intake	2.4.03
Definition: FEPs related to intake of food and water by individual humans and the compositions and origin of intake.	
Comment:*. The human diet refers to the range of food products consumed by humans.*	
Key Concepts, examples, and related FEPs *Diet* — *Description of the human diet and assumptions regarding quantities/volume*	

Habits (non-diet-related behaviour) 2.4.04

Definition: FEPs related to non-diet related behaviour of individual humans, including time spent in various environments, pursuit of activities and uses of materials.

Comment: *The human habits refer to the time spent in different environments in pursuit of different activities and other uses of materials. Agricultural practices and human factors such as culture, religion, economics and technology will influence the diet and habits. Smoking, ploughing, fishing, and swimming are examples of behaviour that might give rise to particular modes of exposure to environmental contaminants.*

Key Concepts, examples, and related FEPs

Human habits

Resource usage

Storage of products

Ventilation

Location of shielding factors

Impoundment of water

Fishing/fish farming

Bathing

Description of human habits and behaviour

Air filtration

Community characteristics 2.4.05

Definition: FEPs related to characteristics, behaviour and lifestyle of groups of humans that might be considered as target groups in an assessment.

Comment: *Relevant characteristics might be the size of a group and degree of self-sufficiency in food stuffs/diet. For example, hunter/gathering describes a subsistence lifestyle employed by nomadic or semi-nomadic groups who roam relatively large areas of land hunting wild game and/or fish, and gathering native fruits, berries, roots and nuts, to obtain their dietary requirements.*

Key Concepts, examples, and related FEPs

Demographic changes

General human society description

Food and water processing and preparation 2.4.06

Definition: FEPs related to treatment of foodstuffs and water between raw origin and consumption.

Comment: *Once a crop is harvested or an animal slaughtered it may be subject to a variety of storage, processing and preparational activities prior to human or livestock consumption. These may change the radionuclide distribution and/or content of the product. For example, radioactive decay during storage, chemical processing, washing losses and cooking losses during food preparation.*

Water sources may be treated prior to human or livestock consumption, e.g. chemical treatment and/or filtration.

Key Concepts, examples, and related FEPs

Water filtration

Food processing

Dwellings	2.4.07
Definition: FEPs related to houses or other structures or shelter in which humans spend time.	
Comment: *Dwellings are the structures which humans live in. The materials used in their construction and their location may be significant factors for determining potential radionuclide exposure pathways.*	
<u>Key Concepts, examples, and related FEPs</u> *Construction of buildings, houses* *Ventilation* *Location and shielding factors* *Site occupation*	

Wild and natural land and water use	2.4.08
Definition: FEPs related to use of natural or semi-natural tracts of land and water such as forest, bush and lakes.	
Comment: *Special foodstuffs and resources may be gathered from natural land and water, which may lead to significant modes of exposure.*	
<u>Key Concepts, examples, and related FEPs</u> *Natural and semi-natural environments*	

Rural and agricultural land and water use (incl. fisheries)	2.4.09
Definition: FEPs related to use of permanently or sporadically agriculturally managed land and managed fisheries.	
Comment: *An important set of processes are those related to agricultural practices, their effects on land form, hydrology and natural ecology, and also their impact in determining uptake through food chains and other exposure paths.*	
<u>Key Concepts, examples, and related FEPs</u> *Use of land for agriculture* *Ploughing* *Land use change* *Fertilization* *Fishing/ fish farming in estuaries/marines*	

Urban and industrial land and water use	2.4.10
Definition: FEPs related to urban and industrial developments, including transport, and their effects on hydrology and potential contaminant pathways.	
Comment: *Human populations are concentrated in urban areas in modern societies. Significant areas of land may be devoted to industrial activities. Water resources may be diverted over considerable distances to serve urban and/or industrial requirements.*	

Key Concepts, examples, and related FEPs

Water works
Urban and industrial environments
Water extraction through wells
Water extraction for irrigation
De-salination of water
Human water extraction

Leisure and other uses of environment 2.4.11

Definition: FEPs related to leisure activities, the effects on the surface environment and implications for contaminant exposure pathways.

Comment: *Significant areas of land, water, and coastal areas may be devoted to leisure activities. e.g. water bodies for recreational uses, mountains/wilderness areas for hiking and camping activities.*

Key Concepts, examples, and related FEPs

Recreational land use
Impoundment of water for bathing
Beach development

RADIONUCLIDE/CONTAMINANT FACTORS 3

Definition: FEPs that take place in the disposal system domain that directly affect the release and migration of radionuclides and other contaminants, or directly affect the dose to members of a critical group from given concentrations of radiotoxic and chemotoxic species in environmental media.

Comment: *"Disposal System Domain: Radionuclide Factors" is a category in the International FEP List and is divided into sub-categories..*

CONTAMINANT CHARACTERISTICS 3.1

Definition: The characteristics of the radiotoxic and chemotoxic species that might be considered in a postclosure safety assessment.

Comment: *"Contaminant Characteristics" is a sub-category in the International FEP List and is divided into individual FEPs.*

Radioactive decay and in-growth 3.1.01

Definition: Radioactivity is the spontaneous disintegration of an unstable atomic nucleus resulting in the emission of sub-atomic particles. Radioactive isotopes are known as radionuclides. Where a parent radionuclide decays to a daughter radionuclide so that the population of the daughter radionuclide increases this is known as in-growth.

Comment: *In post-closure assessment models, radioactive decay chains are often simplified, e.g. by neglecting the shorter-lived radionuclides in transport calculations, or adding dose contributions from shorter-lived radionuclides to dose factors for the longer-lived parent in dose calculations*

Key Concepts, examples, and related FEPs

Production of aqueous progeny
Radon emanation

Chemical/organic toxin stability	3.1.02
Definition: FEPs related to chemical stability of chemotoxic species.	
Comment:	
<u>Key Concepts, examples, and related FEPs</u> *None*	

Inorganic solids/solutes	3.1.03
Definition: FEPs related to the characteristics of inorganic solids/solutes that may be considered.	
Comment:	
<u>Key Concepts, examples, and related FEPs</u> *Source terms content*	

Volatiles and potential for volatility	3.1.04
Definition: FEPs related to the characteristics of radiotoxic and chemotoxic species that are volatile or have the potential for volatility in repository or environmental conditions.	
Comment: *Some radionuclides may be isotopes of gaseous elements (e.g. Kr isotopes) or may form volatile compounds. Gaseous radionuclides or species may arise from chemical or biochemical reactions, e.g. metal corrosion to yield hydrogen gas and microbial degradation of organic material to yield methane and carbon dioxide.*	
<u>Key Concepts, examples, and related FEPs</u> *None*	

Organics and potential for organic forms	3.1.05
Definition: FEPs related to the characteristics of radiotoxic and chemotoxic species that are organic or have the potential to form organics in repository or environmental conditions.	
Comment:	
<u>Key Concepts, examples, and related FEPs</u> *Source term content*	

Noble gases 3.1.06

Definition: FEPs related to the characteristics of noble gases.

Comment: *Radon and thoron are special cases, see FEP 3.3.08.*

Key Concepts, examples, and related FEPs

None

CONTAMINANT RELEASE/MIGRATION FACTORS 3.2

Definition: The processes that directly affect the release and/or migration of radionuclides in the disposal system domain.

Comment: *"Release/Migration Factors" is a sub-category in the International FEP List and is divided into individual FEPs.*

Dissolution, precipitation and crystallisation, contaminant 3.2.01

Definition: FEPs related to the dissolution, precipitation and crystallisation of radiotoxic and chemotoxic species under repository or environmental conditions.

Comment: *Dissolution is the process by which constituents of a solid dissolve into solution. Precipitation and crystallisation are processes by which solids are formed out of liquids. Precipitation occurs when chemical species in solution react to produce a solid that does not remain in solution. Crystallisation is the process of producing pure crystals of an element, molecule or mineral from a fluid or solution undergoing a cooling process.*

Key Concepts, examples, and related FEPs

Chemical reactions caused by dissolution and precipitation of radionuclides

Change in mineralization

Caused by chemical interaction of vault material with pore water

Caused by chemical interaction of backfill with pore water

Caused by chemical interaction of non-radioactive waste with radioactive waste

Caused by a change in temperature

Speciation and solubility, contaminant 3.2.02

Definition: FEPs related to the chemical speciation and solubility of radiotoxic and chemotoxic species in repository or environmental conditions.

Comment: *The solubility of a substance in aqueous solution is an expression of the degree to which it dissolves. Factors such as temperature and pressure affect solubility, as do the pH and redox conditions. These factors affect the chemical form and speciation of the substance. Thus different species of the same element may have different solubilities in a particular solution. Porewater and groundwater speciation and solubility are very important factors affecting the behaviour and transport of radionuclides*

Key Concepts, examples, and related FEPs

Species equilibrium change cased by change in temperature

Solubility change cased by change in temperature

Solubility

Solubility change caused by chemical interaction between waste and pore water

Sorption/desorption processes, contaminant 3.2.03

Definition: FEPs related to sorption/desorption of radiotoxic and chemotoxic species in repository or environmental conditions.

Comment: *Sorption describes the physico-chemical interaction of dissolved species with a solid phase. Desorption is the opposite effect. Sorption processes are very important for determining the transport of radionuclides in groundwater. Sorption is often described by a simple partition constant (K_d) which is the ratio of solid phase radionuclide concentration to that in solution. This assumes that sorption is reversible, reaches equilibrium rapidly, is independent of variations in water chemistry or mineralogy along the flow path, the solid-water ratio, or concentrations of other species. More sophisticated approaches involve the use of sorption isotherms.*

Key Concepts, examples, and related FEPs

Sorption

Chemical reactions caused by adsorption or desoption

Anion exclusion effects

Effect of sorption

Caused by chemical interaction of waste with pore water

Caused by chemical interaction of non-radioactive waste with radioactive waste

Sorption change cased by change in temperature

Colloids, contaminant interactions and transport with 3.2.04

Definition: FEPs related to the transport of colloids and interaction of radiotoxic and chemotoxic species with colloids in repository or environmental conditions.

Comment: *Colloids are particles in the nanometre to micrometre size range which can form stable suspensions in a liquid phase. Metastable solid phases are unstable thermodynamically but exist due to the very slow kinetics of their alteration into more stable products. Colloids are present in groundwaters and may also be produced during degradation of the wastes or engineered barrier materials.*

Colloids may influence radionuclide transport in a variety of ways: retarding transport by sorption of aqueous radionuclide species and subsequent filtration; or, enhancing transport by sorption and transport with flowing groundwater

Key Concepts, examples, and related FEPs

Colloid formation

Caused by chemical interaction of waste with pore water

Caused by chemical interaction of backfill with pore water

Colloid transport

Caused by chemical interaction of non-radioactive waste with radioactive waste

Chemical/complexing agents, effects on contaminant speciation/transport 3.2.05

Definition: FEPs related to the modification of speciation or transport of radiotoxic and chemotoxic species in repository or environmental conditions due to association with chemical and complexing agents.

Comment: *This FEP refers to any chemical agents that are present in the repository system and the effects that they may have on the release and migration of radionuclides from the repository environment. Chemical agents may be present in the wastes or in repository materials or introduced, e.g. from spillage during repository construction and operation, e.g. oil, hydraulic fluids, organic solvents. Chemical agents may be used during construction and operation, e.g. in drilling fluids, as additives to cements and grouts etc.*

Key Concepts, examples, and related FEPs
Effects of chelating agents *Caused by chemical interaction of waste with pore water* *Caused by chemical interaction of backfill with pore water* *Caused by chemical interaction of non-radioactive waste with radioactive waste* *Microbial*

Microbial/biological/plant-mediated processes, contaminant	3.2.06
Definition: FEPs related to the modification of speciation or phase change due to microbial/biological/plant activity.	
Comment: *Microbial activity may facilitate chemical transformations of various kinds.*	
Key Concepts, examples, and related FEPs *Microbial-enhanced mobility*	

Water-mediated transport of contaminants	3.2.07
Definition: FEPs related to transport of radiotoxic and chemotoxic species in groundwater and surface water in aqueous phase and as sediments in surface water bodies.	
Comment: *Water-mediated transport of radionuclides includes all processes leading to transport of radionuclides in water. Radionuclides may travel in water as aqueous solutes (including dissolved gases), associated with colloids (see FEP 3.2.04) or, if flow conditions permit, with larger particulates/sediments.*	
Key Concepts, examples, and related FEPs *Multiphase transport processes* *Surface water aqueous transport* *Transport by surface run-off* *Transport in water bodies* *Percolation* *Capillary rise* *Groundwater transport* *Infiltration* *Dual flow systems* *Advection, i.e. movement with the bulk movement of the fluid (in fractures, failed joints and matrix)* *Molecular diffusion, i.e. random movement of individual atoms or molecules within the fluid* *Dispersion, i.e. the spread of spatial distribution with time due to differential advection* *Matrix diffusion, i.e. the diffusion or micro-advection of solute/colloids etc. into non-flowing pores* *Transport of colloids* *Percolation, i.e. movement of the fluid under gravity* *Transport processes between surface water and porous media* *Isotopic dilution.* *Mass dilution* *Discharge of radionuclides to sea* *Fracture-matrix interaction* *Discharge of radionuclides to foreshore* *Transport of suspended sediment*	

Solid-mediated transport of contaminants 3.2.08

Definition: FEPs related to transport of radiotoxic and chemotoxic species in solid phase, for example large-scale movements of sediments, landslide, solifluction and volcanic activity.

Comment:

Key Concepts, examples, and related FEPs

Resuspension/deposition
Land slides
Rock falls
Rain splash
Transport by suspended sediments (sedimentation)
Erosion
Solid material release
Solid phase transport by water
Wet Deposition
Washout

Gas-mediated transport of contaminants 3.2.09

Definition: FEPs related to transport of radiotoxic and chemotoxic species in gas or vapour phase or as fine particulate or aerosol in gas or vapour.

Comment: *Radioactive gases may be generated from the wastes, e.g. C-14-labelled carbon dioxide or methane. Radioactive aerosols or particulates may be transported along with non-radioactive gases, or gases may expel contaminated groundwater ahead of them*

Key Concepts, examples, and related FEPs

Gas mediated water flow
Gaseous release
Atmospheric gas transport
Gas phase processes
Diffusion
Atmospheric aerosol transport
Barometric pumping
Overpressurization

Atmospheric transport of contaminants 3.2.10

Definition: FEPs related to transport of radiotoxic and chemotoxic species in the air as gas, vapour, fine particulate or aerosol.

Comment: *Radionuclides may enter the atmosphere from the surface environment as a result of a variety of processes including transpiration, suspension of radioactive dusts and particulates or as aerosols. The atmospheric system may represent a significant source of dilution for these radionuclides. It may also provide exposure pathways e.g. inhalation, immersion.*

Key Concepts, examples, and related FEPs

Sea spray
Aerosol transport due to waves, wind

Animal, plant and microbe mediated transport of contaminants 3.2.11

Definition: FEPs related to transport of radiotoxic and chemotoxic species as a result of animal, plant and microbial activity.

Comment: *Burrowing animals, deep rooting species and movement of contaminated microbes are included*

Key Concepts, examples, and related FEPs

Discharge of radionuclides to soil layer (biotic intrusion)

Animal/Plant intrusion

Transport mediated by flora and fauna

Uptake and desorption

Bioturbation

Intake and emission by animals

Human-action-mediated transport of contaminants 3.2.12

Definition: FEPs related to transport of radiotoxic and chemotoxic species as a direct result of human actions.

Comment:. *Human-action-mediated transport of contaminants includes processes such as drilling into or excavation of the repository, the dredging of contaminated sediments from lakes, rivers and estuaries and placing them on land. Earthworks and dam construction may result in the significant movement of solid material from one part of the biosphere to another. Ploughing results in the mixing of the top layer of agricultural soil, usually on an annual basis.*

Key Concepts, examples, and related FEPs

Dredging of sediments

Ploughing

Water abstraction

Foodchains, uptake of contaminants in 3.2.13

Definition: FEPs related to incorporation of radiotoxic and chemotoxic species into plant or animal species that are part of the possible eventual food chain to humans.

Comment: *Plants may become contaminated either as a result of direct deposition of radionuclides onto their surfaces or indirectly as a result of uptake from contaminated soils or water via the roots. Animals may become contaminated with radionuclides as a result of ingesting contaminated plants, or directly as a result of ingesting contaminated soils, sediments and water sources, or via inhalation of contaminated particulates, aerosols or gases.*

Key Concepts, examples, and related FEPs

Plant/animal uptake in a marine/estuarine

External contamination of animals

Crops and natural and semi-natural flora and fauna

Internal transfer of radionuclides within animals

EXPOSURE FACTORS **3.3**

Definition: Processes and conditions that directly affect the dose to members of the critical group, from given concentrations of radionuclides in environmental media.

Comment: *Exposure Factors" is a sub-category in the International FEP List and is divided into individual FEPs.*

Drinking water, foodstuffs and drugs, contaminant concentrations in	3.3.01
Definition: FEPs related to the presence of radiotoxic and chemotoxic species in drinking water, foodstuffs or drugs that may be consumed by human.	
Comment:	
<u>Key Concepts, examples, and related FEPs</u> *Internal transfer of radionuclides within animals* *Crops and natural and semi-natural flora and fauna*	

Environmental media, contaminant concentrations in	3.3.02
Definition: FEPs related to the presence of radiotoxic and chemotoxic species in environmental media other than drinking water, foodstuffs or drugs.	
Comment:*. The comparison of calculated contaminant concentrations in environmental media with naturally-occurring concentrations of similar species or species of similar toxic potential, may provide alternative or additional criteria for assessment less dependent on assumptions of human behaviour.*	
<u>Key Concepts, examples, and related FEPs</u> *None*	

Non-food products, contaminant concentrations in	3.3.03
Definition: FEPs related to the presence of radiotoxic and chemotoxic species in human manufactured materials or environmental materials that have special uses, e.g. clothing, building materials, peat.	
Comment: *Contaminants may be concentrated in non-food products to which humans are exposed. For example, building materials, natural fibres or animal skins used in clothing, and the use of peat for fuel.*	
<u>Key Concepts, examples, and related FEPs</u> *None*	

Exposure modes	3.3.04
Definition: FEPs related to the exposure of man (or other organisms) to radiotoxic and chemotoxic species.	
Comment:	

Key Concepts, examples, and related FEPs

Direct radiation from airborne plumes of radioactive materials

Injection through wounds

Cutaneous absorption of some species.

External exposure through water or sediment

Dermal exposure

Immersion in contaminated water bodies

Ingestion (internal exposure) from drinking or eating contaminated water or foodstuffs

Inhalation (internal exposure) from inhaling gaseous or particulate radioactive materials

External exposure as a result of direct irradiation from radionuclides deposited on, or present on, the ground, buildings or other objects.

Dosimetry	3.3.05

Definition: FEPs related to the dependence between radiation or chemotoxic effect and amount and distribution of radiation or chemical agent in organs of the body.

Comment: *Dosimetry involves the estimation of radiation dose to individual organs, tissues, or the whole body, as a result of exposure to radionuclides. The radiation dose will depend on: the form of exposure, e.g. ingestion or inhalation of radionuclides leading to internal exposure or proximity to concentrations of radionuclides leading to external exposure; the metabolism of the radioelement and physico-chemical form if inhaled or ingested, which will determine the extent to which the radionuclide may be taken up and retained in body tissues; and the energy and type of radioactive emissions of the radionuclide which will affect the distribution of energy within tissues of the body.*

Key Concepts, examples, and related FEPs

None

Radiological toxicity/effects	3.3.06

Definition: FEPs related to the effect of radiation on man or other organisms.

Comment: *Radiation effects are classified as somatic (occurring in the exposed individual), genetic (occurring in the offspring of the exposed individual), stochastic (the probability of the effect is a function of dose received), non-stochastic (the severity of the effect is a function of dose received and no effect may be observed below some threshold).*

Key Concepts, examples, and related FEPs

None

Non-radiological toxicity/effects	3.3.07

Definition: FEPs related to the effects of chemotoxic species on man or other organisms.

Comment:

Key Concepts, examples, and related FEPs

None

Radon and radon daughter exposure **3.3.08**

Definition: FEPs related to exposure to radon and radon daughters.

Comment: *Radon and radon daughter exposure is considered separately to exposure to other radionuclides because the behaviour of radon and its daughter, and the modes of exposure, are different to other radionuclides.*

Radon (Rn-222) is the immediate daughter of radium (Ra-226). It is a noble gas with a half-life of about 4 days and decays through a series of very short-lived radionuclides (radon daughters), with half-lives of 27 minutes or less, to a lead isotope (Pb-210) with a half-life of 21 years. The principal mode of exposure is through the inhalation of radon daughters attached to dust particles, which may deposit in the respiratory system.

Key Concepts, examples, and related FEPs

Radon emanation

APPENDIX D: EXAMPLE ANALYTICAL SOLUTIONS AND INTEGRAL TRANFORM TECHNIQUES

D-1. EXAMPLE ANALYTICAL SOLUTIONS

Tables D.1 and D.2 contain a selection analytical solutions of ordinary and partial differential equations used in the definition of mathematical models for groundwater flow and radionuclide transport under fixed flow conditions. They are based on the contributions of ISAM participants. The information has been transcribed from participants' contributions, however, it has not been possible to check the contributions for accuracy against the original references cited within the ISAM project. The reader should be aware of this potential limitation, and is recommended to consult the original references.

TABLE D.1 ORDINARY DIFFERENTIAL EQUATIONS

Types of Equation	Equation	Solution
First order linear homogeneous differential equation	$dY(t)/dt= - K\ Y(t)$ where K is a constant	$Y(t)=C_1\ e^{-Kt}$ Where C_1 is a constant determined by the boundary condition
First order homogeneous non linear differential equation	$dY(t)/dt= - K(t)\ Y(t)$	$Ye^{\int Kdt} = C_1$ Where C_1 is a constant determined by the boundary condition
First order non homogeneous non Linear differential equation	$dY(t)/dt= - K(t)\ Y(t) +Q(t)$	$Ye^{\int Kdt} =\int Q[e^{\int Kdt}]\ dt + C_1$ Where C_1 is a constant determined by the boundary condition
Second order linear homogeneous differential equation	$d^2Y(t)/dt^2 + a\ dY(t)/dt + bY(t)=0$ where a and b are real constants	m_1 and m_2 are the roots of equation: $m^2+am +b=0$ there are 3 different solutions as follows: Case 1: $m_1=m_2$ and real $Y(t)=C_1e^{m_1t} +C_2\ t\ e^{m_2t}$ Where C_1 and C_2 are constants determined by the boundary conditions Case 2: m_1 different from m_2 and real $Y(t)=C_1e^{m_1t} +C_2\ e^{m_2t}$ Where C_1 and C_2 are constants determined by the boundary conditions Case 3: m_1 different from m_2 and imaginary $m_1=p+qi$, $m_2=p-qi$ $Y(t) =\{e^{pt}\}(C_1 \cos qt + C_2 \sin qt)$ Where $p=-a/2$, $q= (b-a^2/4)^{1/2}$

TABLE D.2 PARTIAL DIFFERENTIAL EQUATIONS

Equation and Initial/Boundary Conditions	Solution
$\mathbf{R}\,\partial C/\partial t=\mathbf{D}\,\partial^2 C/\partial x^2 - \mathbf{v}\,\partial C/\partial x$ $C(x,0)=C_1$ $C(0,t)= C_0 \quad 0<t<t_0$ $C(0,t) = 0$ for $t > t_0$ $\partial C/\partial x\ (\infty,t) = 0$ $x \in (0, \infty)$ Where v, C_0 and C_1 are constants	$C(x , t) = C_1+ (C_0-C_1)\ A(x,t) \quad 0<t<t_0$ and $C(x , t) = C_1+ (C_0-C_1)\ A(x,t) - C_0\ A(x ,t-t_0)\ t>t_0$ Where: $A(x,t) = (1/2)\ \mathrm{erfc}\ \{[Rx-vt]/[2(DRt)^{1/2}]\}+$ $(1/2) \exp(vx/D)\ \mathrm{erfc}\{[Rx+vt]/[2(DRt)^{1/2}]\}$ [E1]
$\mathbf{R}\,\partial C/\partial t=\mathbf{D}\,\partial^2 C/\partial x^2 - \mathbf{v}\,\partial C/\partial x$ $C(x,0)=C_1$ $C(0,t)= C_0 \quad 0<t<t_0 \quad C(0,t)= 0$ for $t > t_0$ $\partial C/\partial x\ (L,t) = 0$ $x \in (0, L)$ Where v, C_0 and C_1 are constants	$C(x , t) = C_1+ (C_0-C_1)\ A(x,t) \quad 0<t<t_0$ And $C(x , t) = C_1+ (C_0-C_1)\ A(x,t) - C_0\ A(x ,t-t_0)\ t>t_0$ Where: $A(x,t)= 1 - \sum \{(2\beta_m)\sin(\beta_m x/L)\exp[(vx/2D)-v^2t/(4DR) -$ $(\beta^2{}_m Dt/L^2R)]\}\ [\beta^2{}_m + (vL/2D)^2 + (vL/2D)]$ where the eingenvalues β_m are the positive roots of the equation: $\beta_m \mathrm{Cot}\ (\beta_m)+ (vL/2D) =0$
$\mathbf{R}\,\partial C/\partial t=\mathbf{D}\,\partial^2 C/\partial x^2 - \mathbf{v}\,\partial C/\partial x$ $C(x,0)=C_1+C_2\ e^{-\alpha x}$ $C(0,t)= C_0 \quad 0<t<t_0$ $C(0,t)= 0$ for $t > t_0$ $\partial C/\partial x\ (\infty,t) = 0$ $x \in (0, \infty)$ Where v, C_0, C_1 and C_2 are constants	$C(x , t) = C_1 + (C_0-C_1)\ A(x,t) + C_2\ B(x,t) \quad 0<t<t_0$ and $C(x , t) = C_1 + (C_0-C_1)\ A(x,t) - C_0\ A(x ,t-t_0) + C_2\ B(x,t) \quad t>t_0$ Where $A(x,t) = (1/2)\mathrm{erfc}\{[Rx-vt]/[2(DRt)^{1/2}]\}+$ $(1/2)[\exp(vx/D)]\mathrm{erfc}\{[Rx+vt]/[2(DRt)^{1/2}]\}$ and $B(x,t) = (1/2)\exp[\alpha^2Dt/R +\alpha vt/R - \alpha x]*$ $\{2-\mathrm{erfc}\{[Rx-(v+2\alpha D)t]/[2(DRt)^{1/2}]\} - [\exp(vx/D+2\alpha$ $x)]\mathrm{erfc}\{[Rx+(v+2\alpha D)t]/[2(DRt)^{1/2}]\}\}$
$\mathbf{R}\,\partial C/\partial t=\mathbf{D}\,\partial^2 C/\partial x^2 - \mathbf{v}\,\partial C/\partial x$ $C(x,0)=C_1$ $C(0,t)= Ca + C_b\ e^{-\lambda t}$ $\partial C/\partial x\ (\infty,t) = 0$ $x \in (0, \infty)$	$C(x,t)=C_1 +(C_a-C_1)A(x,t) + C_b\ B(x,t)$ Where: $A(x,t)= (1/2)\mathrm{erfc}\{[Rx-vt]/[2(DRt)^{1/2}]\}+$ $(1/2)[\exp(vx/D)]\mathrm{erfc}\{[Rx+vt]/[2(DRt)^{1/2}]\}$ and

Equation and Initial/Boundary Conditions	Solution
Where v, C_0, C_1 and C_2 are constants	$B(x,t) = e^{-\lambda t} \Big\{ (1/2)\exp[(v-y)x/2D]\ \mathrm{erfc}\{[Rx-yt]/[2(DRt)^{1/2}]\} +$ $[(1/2)\ \exp[(v+y)x/(2D)]\mathrm{erfc}\{[Rx+yt]/[2(DRt)^{1/2}]\}\Big\}$ and $y= v(1- 4\lambda DR/v^2)^{1/2}$
$\partial C/\partial t=[D_h/R_t]\partial^2 C/\partial z^2 -$ $[V_f/R_t]\ \partial C/\partial z-\lambda C$ Movement of a radiotracer in a semi-infinite column. $t \le 0$ $z\ge 0$ $C=0$ $t > 0$ $z=0$ $C=C_0$ $z = \infty$ $C=0$	$C(z,t)= (C_o/2)\exp(V_f.z/2R_tD_h).$ $(\exp(-z\beta).\mathrm{erfc}\{\{z-[(V_f/R_t)^2+4\lambda D_h/R_t]^{1/2}t\}/2[D_ht/R_t]^{1/2}\}$ $+\exp(z\beta).\mathrm{erfc}\{\{z+[(V_f/R_t)^2+4\lambda D_h/R_t]^{1/2}t\}/2[D_ht/R_t]^{1/2}\})$ Where $\beta^2=(V_f R_t/2D_h)^2 + R_t \lambda/D_h$ This is the case where the column initially at tracer concentration zero is connected to a reservoir containing a tracer solution of constant concentration C_o.
$\partial C/\partial t= [D_h/R_t]\partial^2 C/\partial z^2 -$ $[V_f/R_t]\ \partial C/\partial z-\lambda C$ $t \le 0$; $z>0$ $C=0$ $t > 0$; $z=0$ $(C_0-C)Vf=-D\partial C/\partial z$ $z = \infty$ $C=0$	$C(z)/C_0= \{(1/2) +((1/4) +[D_hR_t\lambda/V_f])^{1/2}\}^{-1/2}$ $\exp((V_f z/(2D_h))\{1 - \{1+4R_t\lambda D_h/V_f^2\}^{1/2}\})$ Steady State Movement of a radiotracer in a semi-infinite column with decay, with absorption and a third type boundary condition at z=0.
$\partial C/\partial t= [D_h/R_t]\partial^2 C/\partial z^2 -$ $[V_f/R_t]\ \partial C/\partial z-\lambda C$ $C(0)=C_0$ $\partial C/\partial z=0$ $z=\infty$	$C(z)=C_0\exp\{[(V_f/R_t)-U]z/(2D_h/R_t)\}$ $U=V_f/R_t[1+4\lambda(D_h/R_t)/(V_f/R_t)^2]^{1/2}$ Steady State with decay

D-2. INTEGRAL TRANSFORM TECHNIQUES

The basic steps in applying the generalizedd integral transform technique are as follows:

- Selection of an appropriate auxiliary problem, which contains as much information as possible about the original problem, with respect to the geometry and operators in the co-ordinates to be eliminated through integral transformation. The more information is contained in the expansion basis functions, the less coupled will be the resulting ordinary differential system and smallest the number of terms required in the system truncation. A number of eigenvalue problems are readily solved in explicit analytic form in terms of well-known transcendental functions, otherwise the integral transform approach itself can be used to provide a semi-analytic error controlled solution to the original auxiliary problem.

- Development of the integral transform pair for the associated transformation and inversion operations, which is a straightforward task once the orthogonality property of the eigenfunctions has been obtained. For classical Sturm-Liouville problems these results are readily available, as well as for a number of more general situations.

- Integral transformation of the original partial differential system, by making use of the appropriate operator that recovers the transform formulae within the transformation process. The related integral operator will be responsible for eliminating all but one independent variable of the P.D.E. system, but not every each term will be fully transformable. Therefore, an infinite system of non-linear coupled ordinary differential equations will result, relating the infinitely many transformed potentials of the eigenfunction expansions. If a decoupled system is obtained, each transformed potential can be independently solved for and an exact solution would be achievable.

- Numerically solution of the coupled O.D.E. system, after truncation of the infinite system at the nth row and column. The formal aspects behind this truncation process, which warrant convergence to the infinite system solution as N increases. The numerical procedures adopted involve the use of well-established O.D.E. solvers available in scientific subroutines packages such as IMSL, with user prescribed accuracy. Note that for parabolic problems the O.D.E. system becomes an initial value problem, while for elliptic systems a boundary value problem results. In the case of eigenvalue problems, the integral transformation process produces an algebraic problem for the related matrix eigensystem analysis. Under certain circumstances, approximate solutions may be of interest in the realm of applications, readily obtainable by neglecting the nondiagonal elements in the coupled O.D.E. system, yielding a decoupled "lowest order solution", or its analytically iterated companion, the "iterated lowest order solution".

- Recallection of the inversion formula to construct the original potentials, once the transformed potentials have been numerically evaluated in the previous step. Therefore, the final solution is analytic and explicit in all but one of the independent variables, and the summations of the inversion formula are computed only at those points of interest, or analytically manipulated as needed. Thus, the truly numerical task in this approach is reduced to the error controlled solution of an O.D.E. system.

- A quite straightforward algorithm can be constructed, including the attractive feature of automatically controlling the global error in the final solution at any selected points. To achieve this goal, the semi-analytic nature of this approach is used in conjunction with well-established ODE integrators that implement thoroughly tested accuracy control schemes. The basic steps in computation are as follows.

- The auxiliary eigenvalue problem is solved for the eigenvalues and related normalized eigenfunctions, either in analytic form when applicable or through the generalizedd integral transform technique itself.

- The transformed initial or boundary conditions are computed, either analytically or, in a general purpose procedure, through adaptive numerical integration, such as in subroutine DQDAGS from the IMSL package. Similarly, those coefficients on the transformed O.D.E. system which are not dependent on the transformed potentials can be evaluated a priori, and therefore saving some computational effort during the numerical integration of the O.D.E. system. For non-linear coefficients, there are some computational savings in grouping them into a single integrand, whenever feasible.

- The truncated O.D.E. system in then numerically solved through different tools, depending on the type of problem under consideration. For an initial value problem, the numerical integration is performed, for instance, through subroutine DIVPAG of the IMSL library in Gear's method mode, since the resulting system is likely to become stiff, especially for increasing truncation orders. Boundary value problems can be handled through subroutine DBVPFD, which is a more recent implementation of the well-known PASVA3 code, an adaptive finite-difference program for first order non-linear boundary value problems. Both subroutines offer an interesting combination of accuracy control, simplicity in use and reliability, with some compromise in speed and memory requirements when compared to dedicated schemes. In either case, a pre-estimate for the truncation order N can be obtained, for instance, through the lowest order solution. Since all the intermediate numerical tasks are accomplished within user prescribed accuracy, one is left with the need of reaching convergence in the eigenfunction expansions and automatically controlling the truncation order N, for a certain number of fully converged digits requested in the final solution, at those positions of interest.

The major advantages of the presented generalizedd integral transform technique are as follows.

- The hybrid numerical-analytical nature, characteristic of this approach, collapses most of the numerical effort into one single independent variable, i.e., the numerical integration of an O.D.E. system, which is nowadays a very well-established task in numerical analysis, even for potentially stiff systems, including reliable error control schemes.

- The wide availability of O.D.E. solvers and other subroutines in scientific subroutines packages, for intermediate computational tasks, makes the standard computational implementation of the present approach quite simple, based on successive calls to such easily accessible and simple to use routines.

- The automatic global error control and estimation offers the extremely attractive feature of working within an user prescribed accuracy and with an almost optimized computational effort, not frequently found in numerical methods for P.D.E's.

- Irregularly shaped domains, with respect to the co-ordinates system adopted, are directly handled either through description of the boundary surfaces in each co-ordinate in terms of the other spatial variables, or when required, by decomposing the domain in regularly shaped regions and analytically coupling these solutions for each sub-domain.

- Due to the hybrid nature discussed above, the increase in computational effort is not too significant when the number of independent variables in the P.D.E. system is increased.

Therefore, one, two and three-dimensional applications are handled within the same order of magnitude of computer CPU time. Numerical experiments on the transient Burgers equation, for instance, confirmed this statement, with an increase of about 10% on CPU time for the two-dimensional case, and similarly for the three-dimensional situation. This is easily understood if one remembers that the numerical work in this approach is always reduced to the numerical integration of an O.D.E. system (one single independent variable), while all the remaining dependent variables are eliminated through integral transformation and recalled in analytic explicit form within the inversion formula, which is essentially a single, double or triple summation. This is indeed a major advantage over fully discrete approaches, which become in many cases prohibitive for multidimensional situations.

— The hybrid nature also makes this approach the most adequate for a mixed symbolic-numerical implementation, allowing for the automatic computer derivation of all the analytical steps in the procedure, followed by the numerical tasks required. In addition, the automatic program generation feature of the Mathematica package, permits the creation of a FORTRAN code from its own environment, which can then be executed in more powerful hardware.

REFERENCES TO APPENDIX D

[D1]BEAR, Dynamics of Fluids in Porous Media, American Elsevier Publishing Company, Inc., New York, N.Y. (1972), reprinted by Dover Publications, Inc., (1988).

APPENDIX E: FURTHER EXAMPLES OF MATHEMATICAL MODELS

This Appendix is based on the contributions of ISAM participants. The information has been transcribed from participants' contributions, however, it has not been possible to check the contributions for accuracy against the original references cited within the ISAM project. The reader should be aware of this potential limitation, and is recommended to consult the original references.

E-1. DEGRADATION OF BARRIERS

The modelling of the important degradation mechanisms has been discussed in general terms in Section 5. The more detailed modelling of these mechanisms is discussed below.

E-1.1. Sulphate attack

Sulphate ions in groundwater can migrate into concrete and react with aluminum phases to form calcium aluminum sulphates such as ettringite and at higher sulphate concentrations gypsum [E1]. Magnesium ions can migrate into concrete and react to form Brucite [E2]. The resulting reaction products displace more space in the concrete than the reactants, causing a physical disruption of the concrete's structure. Observations of magnesium sulphate attack of concrete have led to an empirical model of the form [E2]:

$$x = 0.55\, C_s\, (Mg + SO_4)\, t \tag{E1}$$

where

x is the depth of degradation (cm),
C_s is the weight percent of tri-calcium aluminate in unhydrated cements (–),
Mg is the molar concentration of Mg^{2+} in the bulk solution (mol cm^{-3}),
SO_4 is the molar concentration of Mg^{2+} and SO_4^{2-}in the bulk solution (mol cm^{-3}),
t is the elapsed time (y).

The rate of magnesium sulphate attack can be estimated for a range of sulphate concentrations and tr-calcium aluminate compositions (Table E.1). The empirical model should be used with caution. Models extrapolated beyond the range of experimental conditions on which they are based may be unreliable and non-conservative. This model ignores the effects of advective transport and the observed dependence of concrete durability on the water/cement ratio. Mechanistic models may provide more defensible results in some situations [E1]. Table E1 shows the estimated rates of sulphate and magnesium attack from an empirical model for low, mid-range and high sulphate environments (from [E2]).

TABLE E.1. ESTIMATED RATES OF SULFATE AND MAGNESIUM ATTACK FROM AN EMPIRICAL MODEL FOR LOW, MID-RANGE AND HIGH SULFATE ENVIRONMENTS (FROM [E2])

Mg^{2+} (mg l^{-1})	SO_4^{2-} (mg l^{-1})	Degradation Rate (m y^{-1})		
		5 % C_3A	8 % C_3A	15 % C_3A
3.8E-4	6.5E-3	2E-6	4E-6	7E-6
2.0E-2	4.0E-2	3E-5	5E-5	1E-5
3.7E-1	1.4E+0	8E-4	1E-3	2E-3

E-1.2. Chloride attack of steel reinforcement

The initially alkaline environment of intact concrete protects steel reinforcement from corrosion. As concrete ages, however, corrosive agents such as chloride and oxygen may penetrate the concrete and reach steel reinforcement [E2]. Steel expands as it corrodes, causing the surrounding concrete to crack. Continued corrosion of the steel may lead to structural instability. The time to the initiation of chloride attach of steel reinforcement has been estimated from an empirical model of the form:

$$t_c = \frac{129\, x_c^{\ 1.22}}{WCR\; Cl^{0.42}} \tag{E2}$$

where

t_c is the time (y),

x_c is the thickness of the concrete over the steel reinforcement in (inches), WCR is the water to cement weight ratio,

Cl isthe chloride concentration in the bulk solution (mg l^{-1}).

The estimated time to initiation of corrosion ranges from a few years to thousands of years depending on the conditions (see Table E.2).

TABLE E.2. TIME TO INITIATION OF CHLORIDE ATTACK OF STEEL REINFORCEMENT FOR VARIOUS CHLORIDE ION CONCENTRATIONS, WCRS, AND DEPTHS OF STEEL REINFORCEMENT (FROM [E2])

X_c (cm)	Time to Initiation of Chloride Attack (y)								
	Cl = 1 mg l^{-1}			Cl = 100 mg l^{-1}			Cl = 3000 mg l^{-1}		
	WCR 0.5	WCR 0.4	WCR 0.3	WCR 0.5	WCR 0.4	WCR 0.3	WCR 0.5	WCR 0.4	WCR 0.3
1	8.3E1	1.0E2	1.4E2	1.2E1	1.5E1	2.0E1	3E0	4E0	5E0
14	2.1E3	2.6E3	3.5E3	3.0E2	3.7E2	5.0E2	7.2E1	9.0E1	1.2E2

E-1.3. Concrete leaching

Water percolating into concrete will slowly leach alkali metals and calcium hydroxide from the concrete matrix [E2]. Alkali metal oxides and hydroxides are lost first, reducing the pH of the concrete. The mobility of some radionuclides may be enhanced at lower pH. Later in the leaching process, calcium hydroxide is leached from the concrete, further reducing the pH and reducing the structural strength of the concrete. Leaching is apparently a very slow process, of concern only for assessments extending thousands of years into the future. Estimates of the depth of penetration of leaching using two different models ranged from 2E-6 to 1E-4 m over 1,000 years [E2].

The shrinking core model can be given for leaching of calcium from concrete:

$$Ca(OH)_2 \Rightarrow Ca^{2+} + 2OH^- \tag{E3}$$

The simplest solution of the diffusion equation may be used for consideration calcium leaching:

$$X = \left(2D_{ef} \frac{C_l - C_{gw}}{S} t \right)^{0.5} \qquad \text{(E4)}$$

where

X is the depth of penetration of leaching (m);
C_l is the concentration of Ca^{2+} in concrete pore waters liquid (mol m^{-3});
C_{gw} is the concentration of Ca^{2+} in groundwater (mol m^{-3});
S is the concentration of calcium in concrete solid (mol m^{-3});
D_{ef} is the diffusion coefficient of Ca^{2+} in concrete (m^2 s^{-1});
t is the elapsed time (y).

E-1.4. Filtration concrete properties

Hydraulic conductivity in laboratory samples of fresh concrete has been estimated to be 1E-13 – 1E-11 m s^{-1}. In real condition conductivity may be higher. Conductivity increasing may be connected with fractures. The hydraulic conductivity of an individual crack is:

$$K = (\rho g b^2)/(12\mu) \qquad \text{(E5)}$$

where

K is the hydraulic conductivity (m s^{-1});
ρ is the density of water (kg m^{-3});
g is the acceleration of gravity (m s^{-2});
b is the fracture aperture (m);
μ water viscosity(kg (m s)$^{-1}$).

Width of concrete cracks and consequently permeability of cracked concrete can be estimated as function of the strain and crack spacing. The equations for maximum crack width are [E2]:

$$\frac{w_{\max}}{D} = a_0(\varepsilon_S - 0.0001)R \qquad \text{(E6)}$$

$$a_0 = 159(t_b/h_2)^{4.5} + 2.83(A_1/A_{sl})^{1/3} \qquad \text{(E7)}$$

$$R = h_2/h_3 \qquad \text{(E8)}$$

where

w_{max} is the maximum crack width at extreme tension face (m);
h_2 is the distance between neutral axis and lower face (m); (neutral axis is the surface into concrete roof where strain or shrinkage are absent);
h_3 is the distance between neutral axis and steel reinforcement center (m);
A_1 is the effective area of concrete surrounding one reinforcement bar (m^2);
A_{sl} is the area of one reinforcement bar (m^2);
t_b is the bottom concrete cover over reinforcement (m);
D is the reinforcement diameter (m);
ε_S is the steel strain.

To predict crack spacing, the follow equation was used:

$$\frac{s}{D} = c_0 + \frac{2.36E-7}{\varepsilon_S^2} \tag{E9}$$

$$c_0 = 25.7(t_b/h_2)^{4.5} + 1.66(A_1/A_{sl})^{1/3} \tag{E10}$$

where

s is the average spacing of cracks (m).

The average crack width (w_{avg}, m) at the surface using this formula would be:

$$w_{avg} = s\ \varepsilon_S\ R \tag{E11}$$

E-1.5. Carbonation of concrete

Carbonation is the process where carbon dioxide enters concrete and reacts with calcium hydroxide to form calcium carbonate [E2]. Carbonation's effects on concrete are complex and do not necessarily adversely affect performance. Carbonation increases the strength of concrete, except for high sulphate concrete, and in the case of Portland-cement pastes, reduces the permeability and increases the hardness [E2]. The shrinking caused by carbonation may cause cracking or joint separation and the reduced pH may enhance the mobility of some radionuclides. Carbonation can also depassivate steel reinforcement allowing corrosion. The depth of carbonation attack has been calculated to vary from 2E-5 to 3E-4 m over 1,000 years using a shrinking core model [E2]. The carbonation reaction requires carbon dioxide and moisture. The maximum reaction rate is expected for moist unsaturated conditions [E2]. Under dry unsaturated conditions there is insufficient water to drive the carbonation reaction. Under saturated conditions the reaction is slowed by the reduced rate of diffusion of carbon dioxide into the concrete.

Carbonation process described by next equation:

$$Ca(OH)_2 + H_2O + CO_2 \Rightarrow CaCO_3 + 2H_2O \tag{E12}$$

The same diffusion approach, as for leaching process, can be used for carbonation process:

$$X = \left(2D_{ef}\frac{C_{gw}}{C_s}t\right)^{0.5} \tag{E13}$$

where

X is the depth of penetration of carbonation (m);
D_{ef} is the diffusion coefficient of Ca^{2+} in concrete ($m^2\ s^{-1}$);
C_s is the bulk concentration of $Ca(OH)_2$ in concrete solid ($mol\ m^{-3}$);
C_{gw} is the concentration of total inorganic carbon in groundwater or soil moisture ($mol\ m^{-3}$);
t is the elapsed time (y).

E-2. MECHANISMS INFLUENCING RADIONUCLIDE TRANSPORT

E-2.1. Advection

The velocity needed in transport analyses is the porewater velocity given by:

$$v = \frac{v_d}{\theta\phi} \tag{E14}$$

where

- v is the pore water velocity (m s^{-1});
- θ is the total porosity of the soil (–);
- v_d is the Darcy velocity (m s^{-1});
- ϕ is an empirical modifier to account for the fact that not all the porosity is available for transport (–).

Using the assumption that the superficial area fraction of water-filled pore space equals the volumetric fraction of filled pores, the velocity is expressed by:

$$v = \frac{v_d}{\eta\phi} \tag{E15}$$

where

- η is the volumetric moisture content (–).

Owing to a lack of data, ϕ is almost universally assumed to be unity. It should be clearly understood that the effective porosity, θϕ, and the effective moisture content, ηϕ, are purely empirical constructs that cannot be predicted a priori from a knowledge of the soil structure. They can only be determined through a tracer test on the spatial scale of interest.

E-2.2. Diffusion

The most common representation for transport via diffusion is Fick's first law, which says that a diffusive flux for contaminant i is linearly proportional to concentration:

$$J_i = -D_i \nabla C_i \tag{E16}$$

where

- J_i is the diffusive flux (Bq m^{-2} s^{-1});
- D_i is the constant of proportionality, known as the diffusion coefficient (m s^{-1});
- C_i is the concentration of the contaminant (Bq m^{-3}).

E-2.3. Dispersion

The most common representation of dispersion is to treat it mathematically identically to molecular diffusion.

$$J_{disp,i} = -D_{disp} \nabla C_i \tag{E17}$$

where

$J_{disp,i}$ is the "dispersive flux" of contaminant i (Bq m^{-2} s^{-1}),
$D_{disp}$is called the dispersion coefficient (m s^{-1}).

In an additional extrapolation of the form of Taylor-Aris theory, the dispersion coefficient is suggested to be linearly proportional to velocity. In two dimensions the dispersion coefficient is represented as:

$$D_{disp,kl} = \alpha_T v_d \delta_{kl} + (\alpha_L - \alpha_T)\frac{v_k v_l}{v_d} \tag{E18}$$

where

$D_{disp,kl}$ is the dispersion coefficient for a contaminant ($m^2\, s^{-1}$);
v_d is the Darcy velocity ($m\, s^{-1}$);
v_k and v_l are the component of the velocity vector in the principal directions ($m\, s^{-1}$);
α_L is the longitudinal dispersivity (m);
α_T is the transverse dispersivity (m);
δ_{kl} is the formation factor (–).

The tensorial nature of dispersion is evident in the equation. Reducing the equation to one-dimension, (the direction of flow) leads to the following equation:

$$D_{disp} = \alpha_L v_d \tag{E19}$$

E-2.4. Decay and ingrowth of radionuclides

[E3] has derived a general form of the Bateman equations for decay and ingrowth [E4]. Their equations are solutions to the set of differential equations represented by:

$$\frac{\partial Ci}{\partial t} = -\lambda_i C_i + \lambda_{i-1} C_{i-1} \tag{E20}$$

where

C_i is the concentration (activity) of the progeny ($Bq\, m^{-3}$);
C_{i-1} is the concentration of the parent ($Bq\, m^{-3}$);
λ_i is the decay constant of the progeny (y^{-1});
λ_{i-1} is the decay constant of the parent (y^{-1}).

The main issues of concern are related to analysis of decay chains as part of the transport processes. If chain decay is calculated explicitly, an N-member chain will require solving N simultaneous equations. There are relatively few computer codes that can be used for the analysis of arbitrary decay chains with arbitrary length and branching. Rigorous treatment of the full chains is the most desirable way to treat them, but can be impractical.

This issue has led to the development of two approximate approaches for treating decay chains that can be used with any solution method for the transport.

(1) If one assumes that the parent and decay products are in radioactive equilibrium, then the transport analysis only needs to calculate the activity of the parent, and the decay product activities are established directly. This approximation is an excellent one when all decay product half-lives are much shorter than the parent half life, and if the transport time is long enough to allow equilibrium to be established. Even if this approach is not accurate in some cases, it can frequently (but not universally) be argued to be conservative.

(2) Alternatively, one can assume that the parent and decay products are transported in the same manner and at the same rate [E5]; that is, they have equal K_ds. In this case, decay product atoms behave identically in the geosphere as do parent atoms. One can therefore calculate the concentration of the parent in groundwater, and use the Bateman equations [E4] or their generalization [E3] to calculate the ingrowth of decay products as a function of time at the end of the transport analysis. This approach can often be argued to be conservative compared to explicitly analysing ingrowth of decay products, but one cannot make a general statement that the approach is conservative compared to allowing the K_ds to differ. In particular, when decay and ingrowth are combined with dispersion, it becomes very difficult to determine which combination of parameters will tend to be conservative with respect to others. Larger dispersion tends to produce higher doses from short-lived species, and lower dispersion tends to produce higher doses for long-lived species. For decay chains any generalization is difficult to make.

E-3. FLOW IN FRACTURED AQUIFERS

E-3.1. Introduction

To illustrate the flow through fractures, it was considered as an idealized situation where flow takes place between two parallel fractures. The parallel plate model considers the fracture walls to be parallel and smooth so that it resembles the space between two plates [E6]. An example of a parallel plate fracture is given in Fig. E-1.

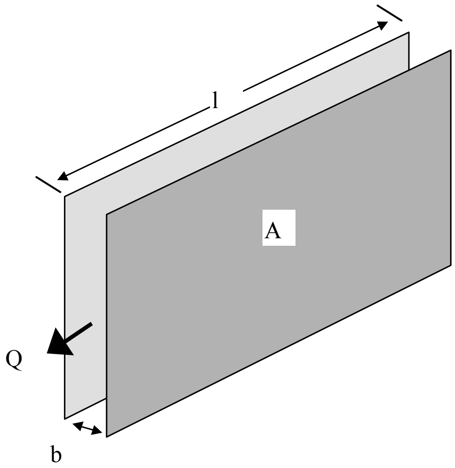

FIG. E-1. Schematic Representation of a Parallel Plate Fracture Model.

If a single horizontal fracture is considered (Fig. E-1) with aperture b (m), length l (m), and hydraulic conductivity K_f (m s^{-1}), the average fracture flow velocity is given by:

$$\overline{V}_f = -\frac{\rho g}{\mu}\frac{b^2}{12}\nabla\phi \tag{E21}$$

where:

V_f is the average flow velocity in the fracture (m s^{-1});
ρ is the fluid density (kg m^{-3});
μ is the fluid viscosity (N s m^{-2});
g is the acceleration of gravity (m s^{-2});
$\nabla\phi$ is the piezometric gradient (m s^{-1}).

Equation (E21) is known as the cubic law for fracture flow. The total flow Q_f ($m^3\ s^{-1}$) through the fracture can be obtained by:

$$Q_f = b\bar{V}_f = -\frac{\rho g}{\mu}\frac{b^3}{12}\nabla\phi \tag{E22}$$

From Equation (E22), the yield of a fracture is proportional to the cubic of its aperture. Thus, if Q_f and $\nabla\phi$ is known, the aperture of the fracture b, can be obtained by re-arranging Equation (E21).

$$b = \sqrt[3]{-\frac{12Q\mu}{\rho g}\nabla\phi} \tag{E23}$$

Equation (E20) can be written in the form of Darcy's law,

$$\bar{V}_f = -K_f\frac{d\phi}{dx} \tag{E24}$$

where K_f is the hydraulic conductivity of the fracture ($m\ s^{-1}$), defined as,

$$K_f = \frac{\rho g}{\mu}\frac{b^2}{12} \tag{E25}$$

The hydraulic conductivity is proportional to the square of the fracture aperture. Therefore, the hydraulic conductivity will increase with the second power and its yield with the third power, should the aperture of a fracture be doubled. From field tests (e.g. pumping tests), it is possible to obtain the transmissivity T of the fracture. Equation (E24) can be written in terms of transmissivity:

$$b = \sqrt[3]{-\frac{12\mu T}{\rho g}\nabla\phi} \tag{E26}$$

where T is the transmissivity ($m^2\ s^{-1}$).

Equation (E26) is known as the "hydraulic or cubic law" aperture. The reason is that the hydraulic aperture is physically different from apertures that are derived from tracer tests. According to [E7], the cubic law aperture is the most widely used in the literature. If it is assumed that the piezometric gradient is equal to unity, Equation (E26) simplifies to [E8]:

$$b = \sqrt[3]{-\frac{12\mu T}{\rho g}} \tag{E27}$$

This means that if the transmissivity of a fracture is known, the aperture can be determined. From Fig. E-2, it can be seen that the relationship between the fracture aperture and transmissivity forms a straight line on a log-log scale. From this equation, a fracture with a transmissivity of 100 $m^2\ d^{-1}$ have an aperture of approximately 1.2 mm. It is thus clear the pore volume and storativity of fractures (storativity is a function of porosity and elasticity) are very restricted if compared with the aquifer matrix. The very low storativity of fractures have an important effect on contaminant transport. Less dilution and faster movement will take place due to the fact that fractures have a low storativity.

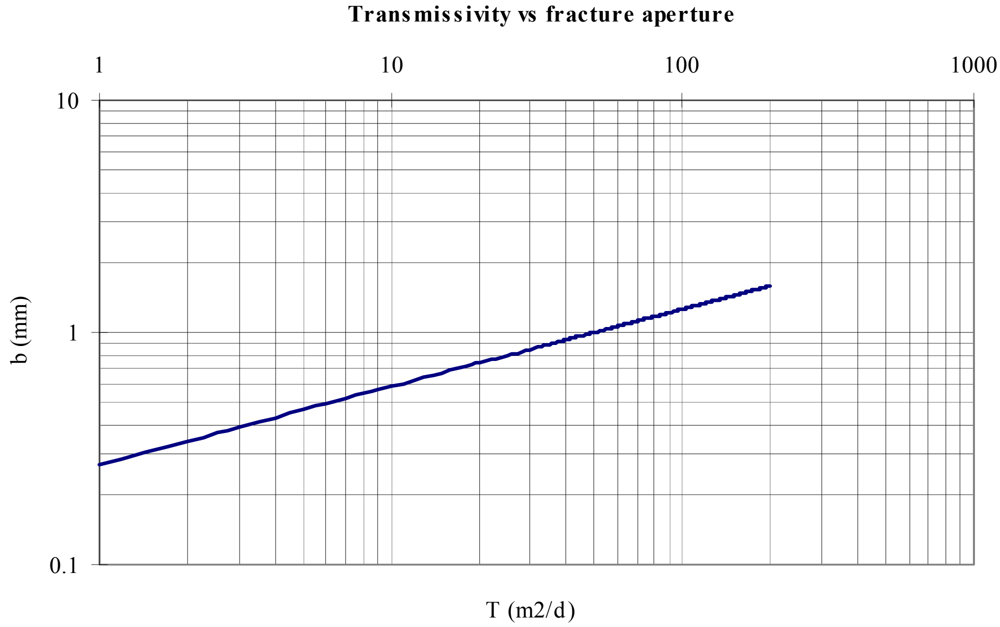

FIG. E-2. Graph of Transmissivity (T) vs. Fracture Apertures (b).

If a conceptual fracture is considered, with a transmissivity 100 m^2 d^{-1} that has an aperture of 1.2 mm and a length of 1000 m, with a saturated depth of 100 m, it can only store a volume of 120 m^3. A borehole with such a transmissivity can be pumped at 36 m^3 h^{-1} (10 l s^{-1}) but, it will take only 3.3 hours to extract the pore volume of the fracture. Fractures are thus dependent upon leakage from the matrix for a constant supply of water. The transmissivity of a 1.2 mm fracture is analogous to a 10 m thick sand unit with a transmissivity of 3.98 m^2 d^{-1}.

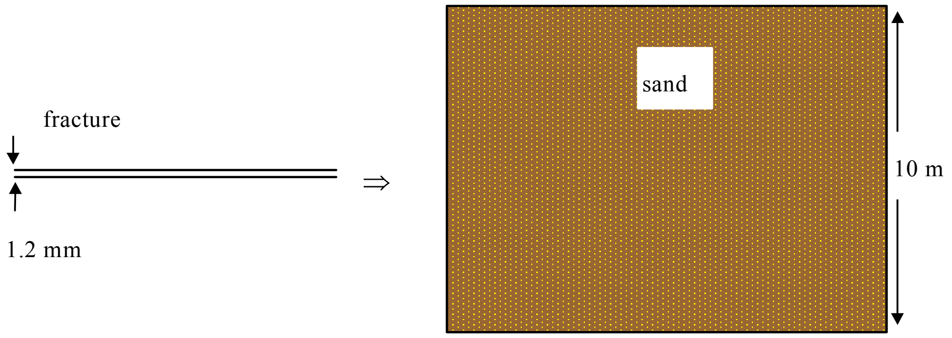

FIG. E-3. Fracture - Porous Sand Analogy in Terms of Transmissivity (after [E8]).

E-3.2. Aperture variation and channel flow

In nature, it is unlikely to find fractures that have smooth parallel walls. In stead, fracture apertures could vary with distance and fracture walls are generally rough and irregular. This cause channel flow to take place in fracture planes. The effect of channelling is that 90 % of the fluid flows through 5-20 % of the fracture plane (Fig. E-4).

Turbulent flow due to high flow velocities in rough-walled, parallel fractures cause deviations from the parallel plate model [E9].

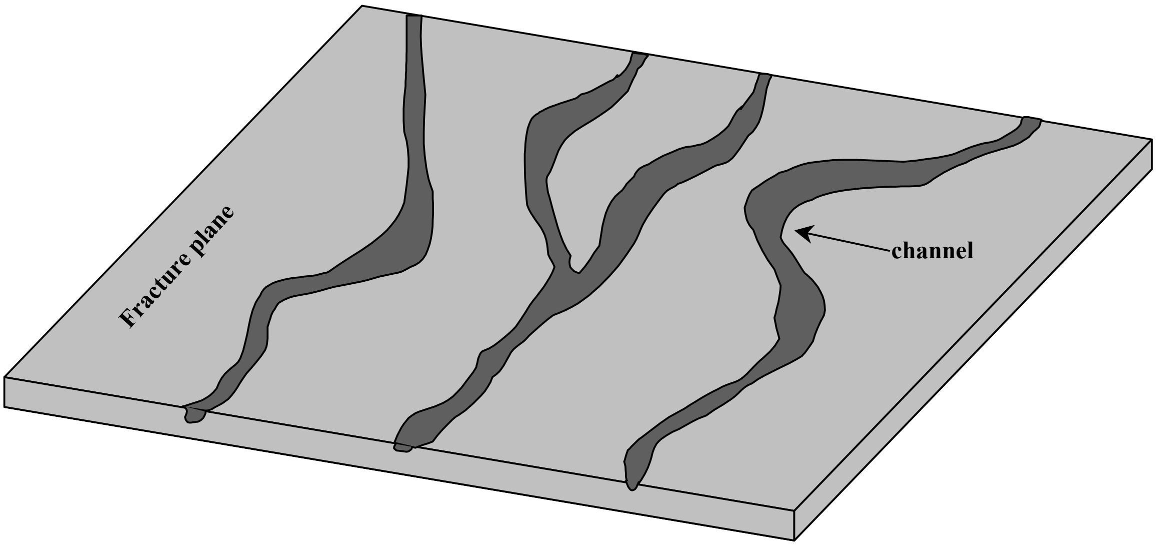

FIG. E-4. Channels in a Fracture Plane (after [E10]).

The effect of fracture channelling is that the parallel plate model resembles porous flow in the narrow zone of the fracture plane.

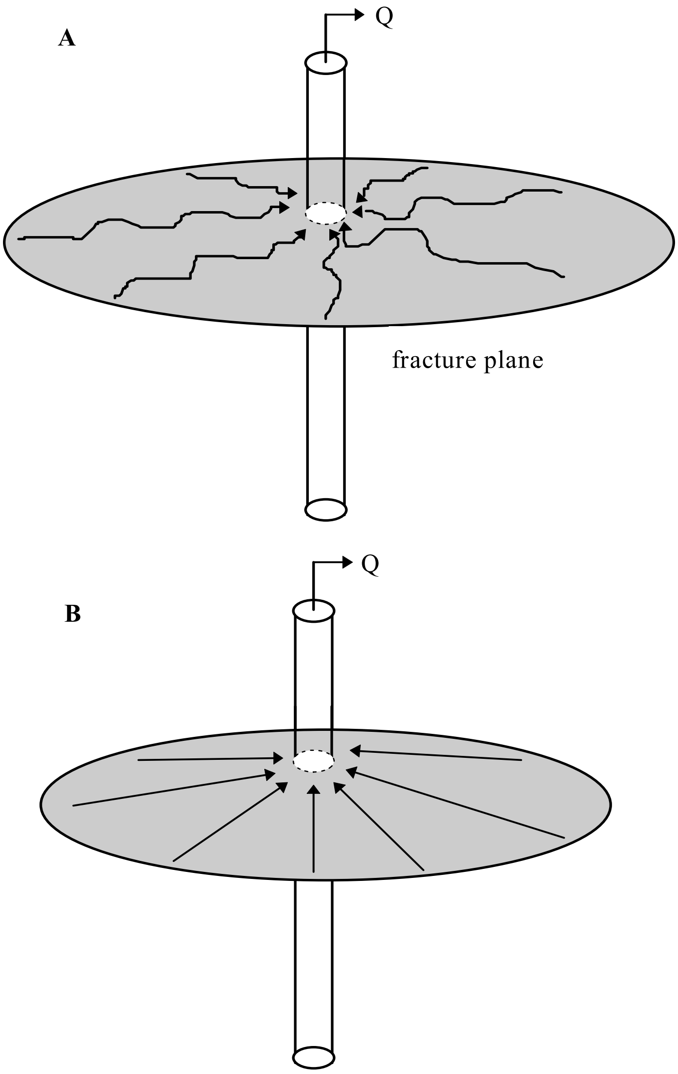

FIG. E-5. (A) Channel Flow (B) Idealized Radial Flow to a Borehole and (after [E11]).

E-3.3. Fracture Zones

Some geological forces create fractured zones where the rock ruptures in a zone rather than in a small single fracture. Fracture zones form the extreme case of channel flow and the medium (zone) is truly porous. Fracture zones are commonly caused by shear zones and faults. These zones will however have a higher storativity than an equivalent, single parallel fracture. It is also easier to incorporate fracture zones opposed to single fractures in a numerical model. This is due to the scale of fracture zones, which could be from a metre to a few metres in width.

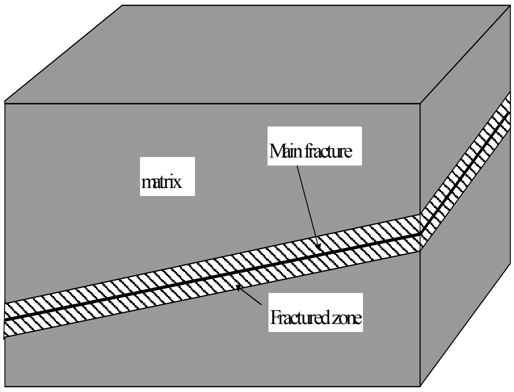

FIG. E-6. Main Fracture with Fractured Zone.

E-3.4. Fracture-matrix interaction

The general low storativity of fractures makes it important to interact with the matrix for a prolonged supply of water. Flow from the matrix to the fracture is regulated by the hydraulic conductivity of the matrix and the piezometric gradient. In terms of the double-porosity model of [E13] the interporosity flow coefficient determines flow in a uniformly fractured aquifer (ϖ). It is defined as:

$$\varpi = \alpha r^2 \frac{K_m}{K_f} \tag{E28}$$

where

α is a shape factor of the matrix block (m^{-2});
r is the distance to the pumping borehole (m);
K_m is the hydraulic conductivity of the matrix ($m\ s^{-1}$);
K_f is the hydraulic conductivity of the matrix ($m\ s^{-1}$).

Material deposited between the fracture and the matrix, at the fracture walls is known as the fracture skin, which can strongly influence the fracture-matrix interaction [E14]. The fracture skin can either restrict if it consists of a low permeability material or mineral filling or enhance flow if the skin consists of higher permeability material (e.g. a leached zone around the fracture). The low conductivity skin or matrix causes the fracture to be leaky or semi-confined.

If the hydraulic conductivity of the fracture skin is lower than the hydraulic conductivity of the matrix, a drop in pressure head takes place over the fracture skin and the flux of fluid from the matrix to the fracture is perpendicular to the skin [E13].

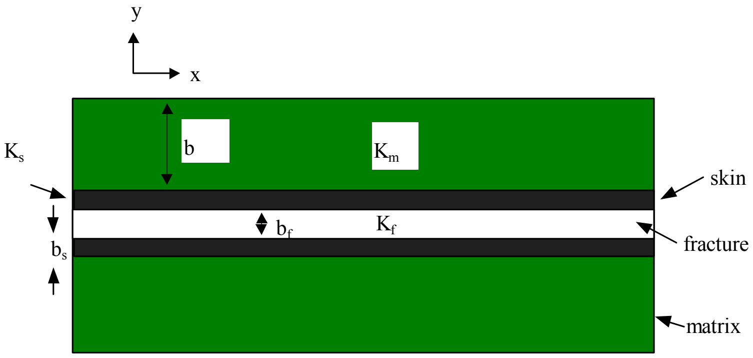

FIG. E-7. Slab-shaped Block Model with Fracture Skin (after [E13]).

E-3.5. Flow in a porous aquifer

In 1856 Henry Darcy conducted an experiment in vertical homogeneous sand filters (see Fig. E-8) to investigate the reason why the fountains of Dijon in France stopped flowing. From this famous experiment, Darcy concluded that the amount of water that will flow through a saturated column of sand (Q) ($m^3\ s^{-1}$) is proportional to the surface area (A) (m^2), the difference in water levels (h_1-h_2) (m) and inversely proportional to the length L (m).

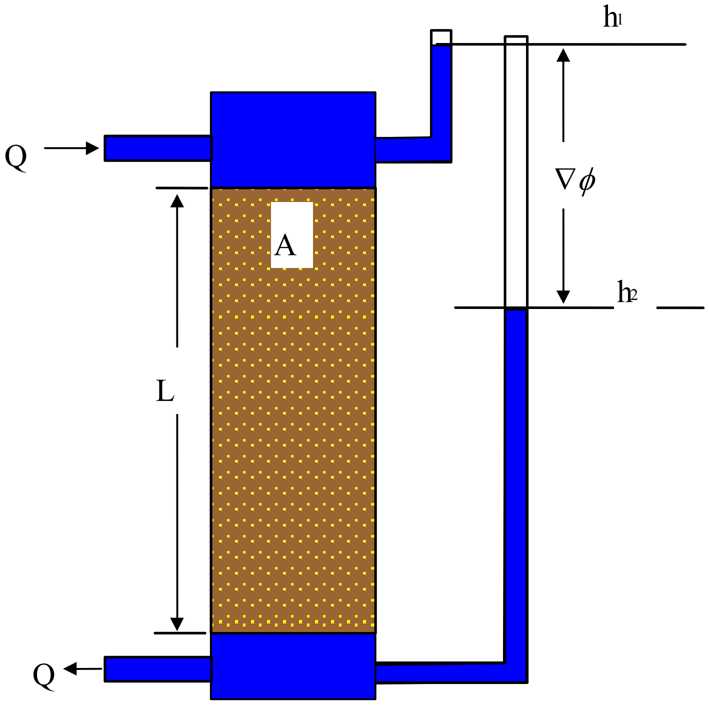

FIG. E-8. Schematical Representation of Darcy's Experiment.

This is expressed in Darcy's law:

$$Q\alpha \frac{A(h_1 - h_2)}{L} = \frac{K\ A(h_1 - h_2)}{L} \qquad \text{(E29)}$$

where the proportionality constant K is known as the hydraulic conductivity of the medium (m s^{-1}) [E14]. The values of h_1 and h_2 can also be expressed in terms of piezometric head defined as:

$$\phi = z + \frac{P}{\rho g} \tag{E30}$$

where

z is the elevation (m);
P is the fluid pressure under the influence of gravity (Pa);
ρ is the fluid density (kg m^{-3}).
g is the acceleration of gravity (m s^{-2}). Darcy's law can be expressed in terms of piezometric head as:

$$Q = -\frac{K\ A(\phi_2 - \phi_1)}{L} \tag{E31}$$

The minus sign means that the flow is opposite in direction to that of increasing piezometric pressure (i.e. extraction). The flow described by Equation (E31), is the total flow through the area A (m^2). The volume of water flowing through a unit cross-sectional area normal to the area is known as the Darcy velocity (v_d) (m s^{-1}) defined by:

$$v_d = -K\nabla\phi \tag{E32}$$

The piezometric difference (ϕ1 - ϕ2) over the distance (L) (m) is represented by the piezometric gradient (∇ϕ). The Darcy velocity defined here is actually a flux and not a velocity.

A combination of fractured and porous media exists where originally porous rock undergone fracturing, the combined system is known as a fractured-porous aquifer. The composite aquifer system (fracture and matrix) can be described by the general conceptual model [E16, E17] for groundwater flow through a non-deformable porous medium:

$$\rho C(\phi) D_t \phi(x,t) = \nabla \bullet [\rho(K\nabla\phi(x,t))] + \rho f(x,t) \tag{E33}$$

where:

ρ is the fluid density (kg m^{-3});
ϕ is the pressure head (m);
C (ϕ) is the specific moisture capacity (m^{-1});
D_t is the symbol for the derivative;
K is the hydraulic conductivity tensor (m s^{-1}).

$$f(x,t) = \frac{\textit{Volume of fluid entering a volume of porous medium per unit time}}{\textit{Volume of porous medium}}$$

(i.e. the strength of sources or sinks, s^{-1}).

If there is no significant dissolved solids in the water (constant density), Equation (E33) reduces to:

$$C(\phi)D_t\phi(x,t) = \nabla \bullet \left[\left(K\nabla\phi(x,t)\right)\right] + f(x,t) \qquad \text{(E34)}$$

which is the governing equation for flow through a porous medium.

However, the flow through fractured media is generally considered to be analogous to flow in a porous medium. This consideration is also known as the equivalent porous medium (EPM) approach. The fracture zones are considered explicitly by using effective equivalent hydraulic parameters to accommodate it [E18].

E-4. EXAMPLE ANALYTICAL APPROACH FOR GROUNDWATER FLOW AND TRANSPORT

An example of an analytical approach to perform a groundwater assessment is presented below. The approach assumes that a time-series of source-term concentrations from a facility located in the vadose zone is available. Steps of the approach are summarized:

(1) Unsaturated zone flow and transport
(2) Mixing at the water table
(3) Saturated zone transport to drinking water well.

E-4.1. Step 1: Unsaturated flow and transport

- Steady-state flow
- Recharge rate is equal to infiltration rate
- Flow is one-dimensional through a homogeneous high-permeability zone (fracture)
- No dispersion/diffusion
- Radionuclides subject to decay and sorption

The flow equation is expressed by Darcy's law:

$$v_d = I = -K(\theta)\left(\frac{\partial \psi}{\partial z} - 1\right) \qquad \text{(E35)}$$

where

v_d is the Darcy flux in "z" direction (m s^{-1});
I is the recharge, or infiltration (m s^{-1});
K(θ) is the hydraulic conductivity (m s^{-1}) at moisture content, θ (–);
Ψ is the matrix potential (m);
z is the depth coordinate (positive downward) (m);
$\partial\Psi/\partial z$ is the matrix potential gradient (–).

Assuming that the matrix potential is uniform, Equation (E35) can be expressed as:

$$v_d = K(\theta) \qquad \text{(E36)}$$

The pore water transport velocity is expressed as:

$$v = \frac{v_d}{\eta R} \qquad \text{(E37)}$$

where

v is the pore water velocity (m s^{-1}).

η is the volumetric moisture content (–), R is the retardation, expressed as:

$$R = 1 + \frac{\rho_b K_d}{\eta} \qquad \text{(E38)}$$

where

K_b is the bulk density of the medium (kg m^{-3}),

K_d distribution coefficient of the radionuclide on the medium (m^3 kg^{-1}).

The pore water velocity for a radionuclide (advective velocity) can be calculated using Equations (E37) and (E38). The relationship between the hydraulic conductivity and moisture content must be available. Using the van Genuchten relationship in Equations (E37) and (E38) below, the mositure content corresponding to the infiltration rate can be obtained.

$$K(\theta) = K_s S^{1/2} \left[1 - \left(1 - S^{1/m}\right)^m\right]^2 \qquad \text{(E39)}$$

$$S = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad \text{(E40)}$$

where

K_s is the saturated hydraulic conductivity (m s^{-1});

S is the relative saturation (–);

θ_r is the residual mositure content (–);

θ_s is the saturated moisture content (–);

m = 1-1/n, n is an empirical parameter.The time of travel of radionuclide to the water table, T (s), can then be expressed as:

$$T = \frac{d}{v} \qquad \text{(E41)}$$

where

d is the distance to the water table (m).

The radionuclide concentration at the water table can then be expressed as:

$$C_{wt} = C_s e^{-\lambda T} \qquad \text{(E42)}$$

where

C_{wt} is the concentration at the water table (Bq m^{-3});

C_s is the concentration at the source (Bq m^{-3});

λ decay coefficient (s^{-1}).

E-4.2. Step 2: Mixing at the water table

The depth of the radionuclide plume developed on the water table can be estimated as follows:

$$H = (2\alpha_v L)^{1/2} + B\left(1 - \exp\left(-\frac{I}{V_l \rho B}\right)\right) \tag{E43}$$

where

H is the mixing depth (m);
L is the length scale of source facility in the direction of flow (m);
α_v is the vertical dispersivity (m);
B is the thickness of the saturated zone (m);
I is the recharge rate (m s^{-1});
V_l is the linear pore velocity in the saturated zone porosity (m s^{-1}).

The first part of the above equation gives the mixing due to vertical dispersion, and the second, due to advection. The second part of the equation could be neglected if the saturated zone thickness is unknown. Equation (E44) below accounts for the dilution due to mixing in deriving the radionuclide concentration in the groundwater beneath the facility.

$$C_0 = C_{wt}\left(\frac{I}{I + v_{dl}}\right)\left(\frac{W}{H}\right) \tag{E44}$$

where

C_0 is the groundwater concentration, source term for saturated zone transport (Bq m^3);
v_d is the Darcy velcoity in saturated zone (m s^{-1});
W is the width of facility lateral to saturated zone flow direction (or square-root of facility area foot-print on the water table) (m).

E-4.3. Step 3: Saturated zone transport

An analytical one-dimensional transport equation is proposed to derive water concentrations in a well. Transport equation requires the linear flow velocity (pore velocity), which is computed as the potential gradient times the hydraulic conductivity divided by effective porosity. The one-dimensional solute transport equation is:

$$R\frac{\partial c}{\partial t} = \frac{D}{\theta_e}\frac{\partial^2 c}{\partial x^2} - \frac{v_d}{\theta_e}\frac{\partial c}{\partial x} - R\lambda c \tag{E45}$$

Initial and boundary conditions:

$$c(o,t) = C_j \quad \text{for} \quad t_j \le t < t_{j+1} \tag{E46}$$

$$\frac{\partial c}{\partial x}(\infty, t) = 0 \tag{E47}$$

where

c is the concentration (Bq m^{-3});

R is the retardation (–) given by: $R = 1 + \frac{\rho_b k_d}{\theta}$;

ρ_b is the bulk density (kg m^{-3});
k_d is the distribution coefficient (m^3 kg^{-1});
θ is the total porosity (–);
θ_e is the effective porosity (–);
D is the dispersion coefficient (m^2 s^{-1}) given by: $D = \theta D_e + \alpha_L v_d$;
α_L is the longitudinal dispersivity (m);
D_e is the molecular diffusion coefficient in pore water (m^2 s^{-1});
v_d is the Darcy velocity (m s^{-1});
λ is the decay constant (s^{-1});
t is the time (s);
x is the space coordinate (m);
j is the time index ($j = 1, \cdots, N$);
N is the total number of time steps.

The analytical solution of Equation (E45) subject to Equations (E46) and (E47) is derived from similar analytical solutions published by [E19].

$$c(x,t) = C_0 \left\{ \frac{1}{2} e^{(v-u)x/2D} erfc\left[\frac{Rx - ut}{2(DRt)^{1/2}} \right] + \frac{1}{2} e^{(v+u)x/2D} erfc\left[\frac{Rx + ut}{2(DRt)^{1/2}} \right] \right\} \tag{E48}$$

$$u = v\left[1 + \frac{4D\lambda}{v^2} \right]^{1/2} \tag{E49}$$

where

Equation (E48), however, is not applicable when the boundary concentration is variable in time. To account for the time variability, the principle of superposition is used. First, the boundary concentration is redefined as a series of step functions:

$$c(0,t) = \left[C_1 + \sum_{j=2}^{j=M} (C_j - C_{j-1}) \right] \text{ for } t_M < t < t_{M+1} \tag{E50}$$

The concentration at any point in space and time is then obtained by summing the contribution of individual steps *(C_j - C_{j-1})* with the time *t* in Equation (E48) set to □t_j=t-t_j:

$$\begin{aligned} c(x,t) = \sum_{j=2}^{N} \left[(C_j - C_{j-1}) \left\{ \frac{1}{2} e^{(v-u)x/2D} erfc\left[\frac{Rx - u\Delta t_j}{2(DR\Delta t_j)^{1/2}} \right] + \frac{1}{2} e^{(v+u)x/2D} erfc\left[\frac{Rx + u\Delta t_j}{2(DR\Delta t_j)^{1/2}} \right] \right\} \right] \\ + C_1 \left\{ \frac{1}{2} e^{(v-u)x/2D} erfc\left[\frac{Rx - u\Delta t_1}{2(DR\Delta t_1)^{1/2}} \right] + \frac{1}{2} e^{(v+u)x/2D} erfc\left[\frac{Rx + u\Delta t_1}{2(DR\Delta t_1)^{1/2}} \right] \right\} \\ - C_N \left\{ \frac{1}{2} e^{(v-u)x/2D} erfc\left[\frac{Rx - u\Delta t_{N+1}}{2(DR\Delta t_{N+1})^{1/2}} \right] + \frac{1}{2} e^{(v+u)x/2D} erfc\left[\frac{Rx + u\Delta t_{N+1}}{2(DR\Delta t_{N+1})^{1/2}} \right] \right\} \end{aligned} \tag{E51}$$

where

$\Delta t_j = t - t_j$ is the time since the concentration (s);
$c(o,t) = C_j$ is the concentration imposed at the boundary (Bq m^{-3}).

It is important to note here that the application of the principle of superposition to the equation at hand is valid because Equation (E48) is linear with respect to concentration *c (x,t).*

E.5. GEOCHEMICAL MODELLING

The main purpose of chemical modelling may be defined as estimation of chemical conditions inside the disposal facility and in surrounded environment. The chemical properties of wastes and barriers and their changes with time may be calculated by using of the geochemical models. The thermodynamical models are widely used for this.

Geochemical modelling is mainly used in safety assessments to calculate contaminants' solubility and speciation (i.e. their chemical form) and their potential evolution with time. These properties strongly influence the mobility and hence the release of radionuclides to the geosphere. Geochemical modelling is also used to assess the lifetime of engineered barriers such as concrete containers or backfill. Geochemical modelling can for example be used to assess the time that a concrete barrier will impose high pH (> pH 12) conditions in a disposal facility.

Concentrations of most important components of groundwater may be calculated by thermodynamic models (cations of Ca^{2+}, Mg^{2+}, $Fe^{2+(3+)}$, anions SO_4^{2-}, Cl^-, OH^-, etc.), values of pH and Eh may be assessed too. These values may be used for assessment of distribution or partition coefficients, for obtaining values of concrete degradation, metal corrosion, etc.

The clear and consequent description of contaminant transport in groundwater in equilibrium condition is presented in [E20]. To describe this process mathematically, a unit volume of porous or fractured saturated medium in considered (a similar representation can be used for unsaturated conditions). The conservation equation for the mass of a contaminant in unit volume can be written as:

$$\left(\frac{\partial}{\partial t} + \lambda_i\right)\left[\theta\left(c_i + \nu_{ij} C_j\right) + s_i + \nu_{ij} S_j + \nu_{ik} P_k\right] = \left[\nabla\left(\frac{D}{\theta_e}\nabla\right) - \frac{v_d}{\theta_e}\right]\left(c_i + \nu_{ij} C_j\right) \qquad \text{(E52)}$$

where

λ_i is the decay constant (s^{-1});
θ is the total porosity (–);
θ_e is the effective porosity (–);
D is the dispersion coefficient ($m^2\ s^{-1}$) given by: $D = \theta D_e + \alpha_L v_d$
α_L is the longitudinal dispersivity (m);
D_e is the molecular diffusion coefficient in pore water ($m^2\ s^{-1}$);
v_d is the Darcy velocity ($m\ s^{-1}$);
c_i is the concentration of components in basic form (simple ion or other) in water ($mol\ m^{-3}$) (number of these components – I_c);
s_i is the concentration of components i, in basis form, sorbed by solid phase ($mol\ m^{-3}$) (number of these components – I_s);

C_j is the concentration in water of complex component j, (complex ions, chelates, colloidal components and other) including radionuclide i (mol/.m^3) (number of these components – J_c);

S_j is the concentration of complex component j, including radionuclide sorbed by solid phase (mol m^{-3}) (number of these components – J_s);

ν_{ij} is the number of moles of basic species c_i per mole of C_j;

P_k is the concentration of precipitate component k, including radionuclide i in solid, in non exchanged form (mol m^{-3}) (number of these components or number of solid phases – K);

ν_{ik} is the number of moles of basic species c_i per mole of P_k.

There are I_c transport equations, one for each basic species, the number of unknown concentrations is $I_c+I_s+J_c+J_s+K$.

According to [E20] the next chemical processes can be considered for this model: an aqueous-phase complex, C_j, is formed by reactions among basic species:

$$\nu_{ij} c_i^{zi} + \nu_{mj} c_m^{zm} + \ldots = C_j^{vij.zi+vmj.zm+\ldots} \qquad \text{(E53)}$$

where:

z_i is the signed charges of the basic species.

The mass action relation gives the concentration of complex:

$$C_j = \frac{K_{cj}}{\gamma_j} \prod_{i=1}^{I_c} (\gamma_i c_i)^{vij}; \qquad \text{(E54)}$$

where:

K_{cj} is the thermodynamic equilibrium constant (–);

γ is the activity coefficient of components in water solution (not radioactive activity) (–).

There are I_s+J_S-1 mass action relations for sorption by cation exchange of basic species and components. One basic species is flagged and all ion exchange reactions are referred to flag species, c_f. Then, for exchange of basic species according to the chemical reactions:

$$z_f c_i^{Zi}(aq) + z_i S_f = z_f S_i + z_i c_f^{Zf}(aq); \qquad \text{(E55)}$$

the mass action relations are:

$$K_f^i = \frac{(s_i/m)^{Zf} (\gamma_f c_f)^{Zf}}{(s_f/m)^{Zi} (\gamma_i c_i)^{Zf}}; \qquad i=1\ldots\ldots I_s-1; \text{(E56)}$$

where

K_f^i is the equilibrium constant for reaction in which basic species c_i in aqueous phase replaced basic species s_f in sorbed phase (–).

The same relation may be used for complex component in the case of ion exchanged sorption:

$$K_f^j = \frac{(S_i/m)^{Zf}(\gamma_f c_f)^{Zf}}{(s_f/m)^{Zi}(\gamma_i C_i)^{Zf}}; \qquad j=1\ldots\ldots J_s\text{-}1; \quad \text{(E57)}$$

where

m is the total sorbed mass ($m = \sum_{i=1}^{Ic} s_i + \sum_{j=1}^{Js} S_j$).

There are *K* mass action relations for reversible precipitation of solid phase in equilibrium conditions:

$$P_k(c) = \nu_{kl} c_l^{Zl}(aq) + \nu_{km} c_m^{Zm}(aq) + \ldots, \qquad \text{(E58)}$$

then the corresponding mass action relation in the solubility product:

$$K_{pk} = \prod_{l=1}^{Ic} (\gamma_l c_l)^{vkl}; \qquad \text{(E59)}$$

where:

K_{pk} is the equilibrium constant for precipitation – dissolution of mineral P_k (–).

The main problem in using the Equations (E52-E59) in a safety assessment is the absence of knowledge concerning the input parameters. In addition Equation (E52) does not describe all the components in solution (non radioactive components and other). Therefore more simple approaches are used to model contaminant transport description, and geochemical models usually do not consider water flow.

Geochemical modelling may be developed by using Equations (E54-E59), but more often these equations thermodynamic approaches are used for the description of solid and liquid phases under equilibrium conditions.

E-5.1. Thermodynamic approach

In thermodynamic approaches, the Gibbs free energy, G (J), usually is used as driving force of reactions [E21]. Free energy (or Gibbs function) of any component in solution may be defined [E22]:

$$G = G^0 + nRT \ln C \qquad \text{(E60)}$$

where

C is the relative concentration, (mol of component)/(mol of solution, including H_2O);
n is the number of moles of component in system (mol);
R is the universal gas constant (J mol^{-1} K^{-1});
T is the absolute temperature (K);
G^o is the standard free energy of component (J).

Gibbs function for one mole (μ) is known as the chemical potential. The standard free energy may be defined using the standard chemical potential:

$$G^o = n\mu^o \qquad \text{(E61)}$$

where

μ^o – standard chemical potential (J mol^{-1}).

The change of free energy in reaction may be written:

$$\Delta G = \Sigma G\ products\ -\ \Sigma G\ reactants. \qquad \text{(E62)}$$

Under equilibrium conditions, the sum of the free energy of products of any reaction is equal to the sum of free energy of the reactants, in this condition:

$$\Delta G = 0 \qquad \text{(E63)}$$

If there is a reaction:

$$aA+bB \leftrightarrow cC+dD \qquad \text{(E64)}$$

The chemical potentials of products and reactants under equilibrium condition may be presented by:

$$a\mu oA + b\mu oB + RT\ ln\ ([A]a\ [B]b)= c\mu oC + d\mu oD + RT\ ln\ ([C]c\ [D]d) \qquad \text{(E65)}$$

where

a, b, c, d, are the moles quantity in system for products and reactants (mol);
[A], [B], [C], [D] are their mole concentrations (mol m^{-3}).

The next equation may be obtained:

$$c\mu^o{}_C + d\mu^o{}_D - a\mu^o{}_A - b\mu^o{}_B = -RT\ ln\ [([C]^c\ [D]^d)/([A]^a\ [B]^b)] \qquad \text{(E66)}$$

The mole standard free energy of reaction ($\Delta G^o{}_m$) may be defined as:

$$\Delta G^o{}_m = c\mu^o{}_C + d\mu^o{}_D - a\mu^o{}_A - b\mu^o{}_B \qquad \text{(E67)}$$

The value of the mole standard free energy of reaction may be used instead of thermodynamic equilibrium constant (K) in the law of mass action, [E22]:

$$\Delta G^o{}_m = -RT\ ln(K) \qquad \text{(E68)}$$

Equation (E54) may be rewritten in next form:

$$\Delta G_m^0 = -RT\ln[\prod_{i=1}^{I_c}(\gamma_i c_i)^{vij}/(C_j\gamma_j)]; \qquad \text{(E69)}$$

The equation for free energy changes (E62) may be rewritten as:

$$\Delta G = \Delta G^o + RT\ lnK \qquad \text{(E70)}$$

The free energy change may be related to the oxidation-reduction processes. These processes may be described:

$$Reduced + qH_2O \leftrightarrow Oxidised + mH^+ + n\ e^-.$$

Free energy change is: $\Delta G = -n\,F\,E$ (E71)

where:

n is the electron number participated in reaction (mol);
F is the Faraday constant (C mol^{-1});
E is the electrical potential if potential is measured relative to standard hydrogen electrode its definition is Eh (V).

Using Equation (E70), the Nernst equation may be obtained:

$$Eh = Eh^0 + \frac{RT}{nF}\ln K \qquad \text{(E72)}$$

where

Eh^o is the standard potential, $Eh^o = -\Delta G^o/(n\,F)$.

The ions H^+ take part in reactions (this is usual conditions), and Equation (E72) can be written as:

$$Eh = Eh^0 + \frac{RT}{nF}\ln\frac{[ox][H^+]^m}{[red]} = Eh^0 + \frac{2.3RT}{nF}\log\frac{[ox]}{[red]} - \frac{2.3mRT}{nF}pH; \qquad \text{(E73)}$$

E-5.2. Thermodynamic models in geochemistry

Standard energies of components of a system may be used as the basis for parameters used to describe the geochemical interaction between liquid and solid phases. The mass action law, presented by Equations (E54-E59), may be used for modelling of geochemical reaction in porous and fractures media by using the thermodynamical description with standard free energy of reactions.

But it is often more convenient to use the minimum Gibbs function to obtain concentrations of components without of consideration of the reactions in the system. Such an approach is used in many thermodynamic geochemistry models, for example [E23]. [E24] provides a useful review.

Gibbs function for multi components system may be written as:

$$G = x_j(\mu_j + RT\ln\frac{x_j}{X_J} + RT\ln\gamma_j) + \mu_p X_p \qquad \text{(E74)}$$

where

x_j is the quantity of j component of water solution in system (mol) (1=j=J);
X_J is the sum of all components in water solution, including H_2O(mol) ($X_J = \Sigma x_j$);
γ_j is the activity (–), it is assumed that $\gamma_j = 1$, (concentrations of components in water is not high), the special procedure may be used for consideration of derivation of concentrations and activity (for example by using Debye-Huckel equation [E21];
μ_p is the chemical potential of components in solid phase p (J mol^{-1}) (1=p=P);
X_p is the sum of all components in solid phase p (mol).

Obtaining the components concentrations may be solved by finding the absolute minimum of the function with many uncertain values (Gibbs function). The mathematical Lagrange method is usually used for this purpose which uses the total quantity of basic components as an additional condition. These are the most simple independent components, which may be used for construction all another components are used for this purpose. The balance equation may be written as:

$$a_{ij}\,x_j + a_{ip}\,X_p = b_i \tag{E75}$$

where:

a_{ij}	is the quality of independent component i in component j (mol mol^{-1}),
a_{ip}	is the quality of independent component i in solid phase p (mol mol^{-1}),
b_i	is the total quality of independent component i (mol) (1=i=I).

According to the Lagrange method of uncertain multipliers, it is possible to obtain a function, Φ (mol):

$$\Phi = G/RT + u_i\,(b_i - a_{ij}\,x_j - a_{ip}\,X_p); \tag{76}$$

where

u_i is the Lagrange multipliers (1=i=I).

It is possibly to see from Equation (E68), that uncertain Lagrange multipliers are the chemical potentials of basic components, divided by RT. Using this, it is possibly for simplification to use relative potentials $z_j = \mu_j /RT$, and $z_p = \mu_p /RT$. Taking the minimum of function Φ the following equations may be obtained:

$$\frac{\partial \Phi}{\partial X_p} = z_p - a_{ip} u_i = 0; \tag{E77}$$

$$\frac{\partial \Phi}{\partial x_j} = z_j + \ln\frac{x_j}{X_J} - a_{ij} u_i = 0; \tag{E78}$$

Using Equation (E78):

$$x_j = X_J \exp(-z_j + a_{ij} u_i) \text{ and } \sum_{j=1}^{J} \exp(-z_j + a_{ij} u_i) = 1 \tag{E79}$$

Using this approach, I+P+1 equations for I+P+1 unknown values may be obtained. The unknown values are: u_i (number of unknowns – I), X_j – one unknown, and X_p (number of unknown – P). There are I mass balance equations, one equation for water components, and P equations for solid phases components:

$$X_J a_{ij} \exp(-z_j + a_{ij} u_i) + a_{ip} X_p = b_i; \qquad i = 1 \ldots I, \text{(E80)}$$

$$\sum_{j=1}^{J} \exp(-z_j + a_{ij} u_i) = 1; \tag{E81}$$

$$-z_p + a_{ip} u_i = 0; \qquad p = 1 \ldots P \tag{E82}$$

The exponential function describes the dependence of concentrations in water on free energy in thermodynamic models (logarithm of equilibrium constant may be used instead of free energy). For this reason small errors in the calculation of energy give more significant errors in the calculation of concentrations.

Reliable constants for the above physical and chemical processes are not readily available. There are some attempts to obtain distribution coefficients using thermodynamic models, for example [E25]. However, such models are mainly of academic interest, and it is not possible to use them in practice since the necessary parameters are usually unknown. At present only experiments can provide a reliable basis for the calculation of radionuclides migration in groundwater.

E-5.3. Time depended interaction of solid and liquid phases

The slow processes assumed to be proceeding at a quasi-steady state for the purpose of modelling with chemical rate equations are discussed in [E26]. Such process for any component of reaction (Equation E64)) may be described by:

$$\frac{\partial [A]}{\partial t} = k_2 [C]^c [D]^d - k_1 [A]^a [B]^b \tag{E83}$$

where

k_1 and k_2 - reaction rates in forward and reserve directions (s^{-1}).

It is clear, that under equilibrium conditions:

$$K = k_2/k_1, \text{ or } \Delta G^o{}_m = -RT\,ln(K) = -RT\,ln(k_2/k_1) \tag{E84}$$

It is difficult to use equations as Equation (E52) for the description of the radionuclide migration in groundwater. The rates of sorption and desorption may be used for this purpose. Instead of Equation (E52), the the following equations for solid and liquid phases may be used:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left[\frac{D_{ij}}{\theta_e}\frac{\partial C}{\partial x_j} - \frac{v_d}{\theta_e} C\right] - \lambda (C - C_p) - K_{sb} C + \frac{K_{ds}}{\theta} S + Q_l;$$

$$\frac{\partial S}{\partial t} = -\lambda (S - S_p) + \theta K_{sb} C - K_{ds} S + Q_s; \tag{E85}$$

where

θ	is the total porosity (–);
θ_e	is the effective porosity (–);
D_{ij}	is the dispersion coefficient ($m^2\ s^{-1}$) given by: $D_{ij} = \theta D_e + \alpha_L v_d$;
α_L	is the longitudinal dispersivity (m);
D_e	is the molecular diffusion coefficient in pore water ($m^2\ s^{-1}$);
v_d	is the Darcy velocity ($m\ s^{-1}$);
C, S	are the radionuclides concentrations in liquid and solid phases ($Bq\ m^{-3}$);
Q_l, Q_s	are the activity sources in liquid and solid phases ($Bq\ m^{-3}\ s^{-1}$);
K_{sb}, K_{ds}	are the rates of sorption and desorption(s^{-1}).

Under equilibrium conditions distribution coefficient may be presented by:

$$K_d = \frac{\theta}{\rho} \frac{K_{sb}}{K_{ds}} \tag{E86}$$

where

ρ is the grain density (kg m^{-3}).

Desorption can occur as a leaching process. This process may be described by using the first term of equation of (E85) as:

$$Q_l = \frac{K_{ds} S_0}{\theta} \exp(-(\lambda + K_{ds})t) \tag{E87}$$

where

S_o is the initial concentration in solid phase (Bq m^{-3}).

Equation (E87) is the simplest analytical expression of leaching processes, more complicated analytical or numerical solutions for the source term may be used.

E-5.4. Models of energy balance

Calculation of temperature fields is very important in the safety assessment of the repositories of high level wastes, but not for near surface disposal facilities. For example, there is limit on energy source to 2 W m^{-3} for near surface disposal facilities in Russian.

However in some cases the underground temperature distribution may be considered, for example: in the assessment of disposal facilities in permafrost conditions; or if seasonal temperature and water flow oscillations need to be considered; or for the assessment of disposal facilities with spent radiation sources. The heat transport equation is used for temperature calculation:

$$(c_s + \theta c_w)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i}\left[\lambda \frac{\partial T}{\partial x_i} - \theta c_w V_i T\right] + Q \tag{E88}$$

where

c_s and c_w	are the heat capacities of solid and liquid phases (J (m^3 K) $^{-1}$);
λ	is the coefficient of heat conductivity (W (m K)$^{-1}$);
T	is the temperature (K);
V_i	is the pore water velocity (m s^{-1});
Q	is the heat sources (J (m^3 s) $^{-1}$).

The consideration of water flow, energy balance, and contamination transport under water freezing conditions is given in [E27].

E-6. EXAMPLE MODELS FROM INTEGRATED ASSESSMENTS

E-6.1. Leaching from the disposal facility

E-6.1.1. Model A

The following model is taken from [E28]. The equation governing the evolution of the residual activity, A_r (Bq), in the disposal facility is:

$$\frac{dA_r}{dt} = -(\lambda + F \times ALF)\ A_r \tag{E89}$$

where

A_r is the residual activity as a function of time (Bq);
λ is the decay constant (y^{-1});
ALFis the annual leaching fraction (y^{-1});
F is the fraction of the waste which is subject to the leaching (–).

The annual leaching fraction (ALF) is the ratio of the activity lost by leaching during the year t, A(t) (Bq y^{-1}), over the total activity remaining that year, $A_r(t)$ (Bq). It is expressed as:

$$ALF = \frac{Inf}{H_d(\theta_\omega + \rho_b \mathrm{K_d})} \tag{E90}$$

where

Inf is the annual infiltration rate (m y^{-1}) accounting for the water budget and the disposal hydraulic conductivity;
H_d is the disposal height (m);
θ_ω is the effective porosity or the moisture content (–);
ρ_b is the dry bulk density (kg m^{-3});
K_d is the distribution coefficient (m^3 kg^{-1}).

The fraction of the waste which is subject to the leaching (F) is often expressed as a Gaussian law:

$$F = \int_{-\infty}^{t} N(\tau)d\tau \qquad \text{with} \qquad N(\tau) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{(\tau-\bar{\tau})^2}{2\sigma^2}\right] \tag{E91}$$

where

$\bar{\tau}$ and σ are the average structure failure time and its standard deviation corresponding to the physical properties of the containment structure (y).

Then, the radioactivity which leaves the disposal and enters the geosphere is:

$$A(t) = A_r(t) \times F \times ALF \tag{E92}$$

— Initial Condition

Since Equation (E92) is a first order differential equation, only one initial condition is needed. In this case the initial condition can be that at time zero when all the activity (A_0) is confined into the disposal facility so:

$$A_r(0)=A_0 \tag{E93}$$

where

A_0 is the initial activity in the disposal facility (Bq).

— Solution (Analytical)

If it is assumed that F is equal to 1, which means that all radioactive materials is in contact with the water, Equation (E92) has an analytical solution given by:

$$A_r(t)= A_0\, e^{-(\lambda+ALF)t} \tag{E94}$$

The quantity of radioactivity which leaves the disposal facility and enter the geosphere is:

$$A(t)=ALF\, A_r(t) \tag{E95}$$

If F(t) is a function of time the solution can be obtained using Appendix D.

E-6.1.2. Model B

The following model is taken from [E29]. One simple and conservative model that can be used for the failure of the engineering barriers is a linear function, $F_c(t)$ (y). The beginning of the failure occurred initially at a time t_0 [$Fc(t_o)=0$] and at a time t_f all the engineering barrier collapse [$Fc(t_f)=1$] that is:

$$F_c(t)=\frac{t-t_0}{t_f-t_0} \tag{E96}$$

The contaminated water flow (leakage) through the base of the disposal facility with time can be obtained by making a mass balance of water inside the disposal facility.

The water that enters the disposal facility with time Qt(t) is given by:

$$Q_t(t)=A_t Inf F_c(t) \tag{E97}$$

$$Inf=P-E-R+I \tag{E98}$$

where

Q_t	is the flow rate that enter the disposal facility ($m^3\ y^{-1}$);
A_t	is the area of the disposal facility (m^2);
Inf	is the infiltration rate at the top of the disposal facility (cap) ($m\ y^{-1}$);
F_c	is the engineering failure function (including the top of the vault);
t	is the time (y);
E	is the evapotranspiration rate ($m\ y^{-1}$);
P	is the rainfall rate ($m\ y^{-1}$),Iis the irrigation rate ($m\ y^{-1}$);
R	is the runoff rate ($m\ y^{-1}$).

The water that flows through the base of the disposal facility can be calculated using Darcy's Law, considering that the base of the disposal facility is saturated:

$$Q_b(t) = kA_t \frac{\left(H_t(t) + \delta\right)}{\delta} \tag{E99}$$

where

Q_b is the water flow rate at the disposal facility's base ($m^3\ y^{-1}$);
k is the hydraulic conductivity of the base of the disposal facility ($m\ y^{-1}$);
H_t is the water high inside the disposal facility (m);
δ is the thickness of the base of the disposal facility (m).

The quantity of water inside the disposal facility in given by:

$$V_a(t) = H_t(t) A_t \theta \tag{E100}$$

where

V_a is the water volume inside the disposal facility (m^3);
θ is the water filled porosity inside the disposal facility (considering the waste and backfill) (–);
H_t is the water high inside the disposal facility in m.

The water balance in the disposal facility is given by:

$$\frac{dV_a}{dt} = Q_t - Q_b \tag{E101}$$

Substituting the values of V_a, Q_t and Q_b into Equation (E101) results in the following differential first order equations for the water high inside the disposal facility considering a quickly failure of the cap (t_0=1 year and t_f=30 years):

$$\frac{dH_t(t)}{dt} + \frac{k}{\delta\theta} H_t(t) + \left(\frac{-Inf(t-1)}{29\theta} + \frac{k}{\theta} \right) = 0 \quad , \quad \text{for } 1 \le t \le 30 \tag{E102}$$

— Initial Condition for t<=30

Since Equation (E102) is a first order differential equation, only one initial condition is needed. In this case, the initial condition can be that at year one the height of water inside the disposal facility is zero:

$$H_t(1) = 0 \tag{E103}$$

$$\frac{dH_t(t)}{dt} + \frac{k}{\delta\theta} H_t(t) + \frac{(Inf + k)}{\theta} = 0 \text{ , for } t > 30 \tag{E104}$$

— Initial Condition

In this case the initial condition would be:

$$H_t(30) = H_{t30} \tag{E105}$$

— Solutions

The analytical solutions for the differential equations (see Appendix D) above are:

$$\mathrm{H_t(t)} = \frac{-\mathrm{b} - \mathrm{ab} - \mathrm{ac}}{\mathrm{a}^2} + \frac{(\mathrm{b} + \mathrm{ac})\mathrm{e}^{(\mathrm{a}-\mathrm{at})}}{\mathrm{a}^2} + \frac{\mathrm{bt}}{\mathrm{a}}, \quad \text{for } 1 \leq \mathrm{t} \leq 30 \tag{E106}$$

$$H_t(t) = -\frac{d}{a} + \frac{(d + aH_{t30})e^{(30a-at)}}{a}, \quad \text{for } \mathrm{t} > 30 \tag{E107}$$

where

$$a = \frac{k}{\theta\delta} \qquad b = \frac{w}{29\theta} \qquad c = \frac{k}{\theta} \qquad d = \frac{k + w}{\theta} \tag{E108}$$

Knowing the water height H(t) inside the disposal facility with time, the contaminated water flow through the disposal facility base can be estimated. The quantity of radionuclide that flows as an overflow can be summed to the quantity that flows through the base in order to obtain, in a conservative way, the total contaminated mass leaving the disposal facility.

So in the case where: the water height inside the disposal facility is lower than the disposal facility height:

$$Q_b(t) = kA_t\frac{(H_t(t)+\delta)}{\delta} \tag{E109}$$

$$Q_o(t) = 0 \tag{E110}$$

$$v_1(t) = \frac{Q_b(t)}{A_t} \tag{E111}$$

where

Q$_o$(t) is the overflow flow rate (m^3 y^{-1});
v1(t) the Darcey velocity of water at the bottom of the disposal facility due to the total water leakage (m y^{-1}).

In the case of the occurrence of an overflow (bathtubbing):

$$Q_b(t) = kA_t\frac{(H_d+\delta)}{\delta} \tag{E112}$$

$$Q_o(t)=(H_t(t)-H_d)A_t\theta \tag{E113}$$

$$v_1(t)=\frac{Q_b(t)+Q_o(t)}{A_t} \tag{E114}$$

where

H_d is the height of the disposal facility (m).

The radionuclide mass balance can be obtained using the equations below:

$$M_R(t)=M_{R1}(t)+M_{R2}(t) \tag{E115}$$

where:

$M_R(t)$ is the total mass of radionuclide inside the disposal facility (kg);
$M_{R1}(t)$ is the mass of radionuclide in the liquid phase inside the disposal facility (kg);
$M_{R2}(t)$ is the mass of radionuclide in the solid phase inside the disposal facility (kg).

Base on the adsorption coefficient K_d of the waste/backfill we can write:

$$M_{R2}=\frac{K_d M_{R1} m_2}{V_a} \tag{E116}$$

where

V_a is the total volume of the water phase inside the disposal facility (m^3);
m_2 is the total mass of the solid phase inside the disposal facility (kg).

So making the mass balance of radionuclide inside the disposal facility:

$$\frac{dM_R(t)}{dt}=-\lambda M_R-\frac{M_{R1}}{V_a}Q_b \tag{E117}$$

And substituting the values of M_R and M_{R1} as a function of M_{R2}, the following differential equation for the mass of radionuclide inside the disposal facility with time can be obtained:

$$\frac{dM_{R2}(t)}{dt}\left(K_d m_2+V_a(t)\right)+M_{R2}(t)\left(\lambda K_d m_2+\lambda V_a(t)+\dot{V}_a(t)+Q_b(t)\right)=0 \tag{E118}$$

where

$\dot{V}_a$ is the temporal derivative of the volume of water inside the disposal facility ($m^3\ y^{-1}$);
A_e is the specific activity of the radionuclide ($Bq\ kg^{-1}$);
A_0 is the initial activity of the radionuclide (Bq).

— Initial Condition

In the beginning, there is no water inside the disposal facility and all the radionuclide is absorbed in the solid phase:

$$M_{R2}(0)=A/A \tag{E119}$$

The solution of this type of equation can be seen in Appendix D and due to the integral that appears a numerical solution is necessary.

Using the K_d relationship the quantity of radionuclide inside the disposal facility in the water phase can be calculated:

$$M_{R1}(t) = \frac{V_a(t) M_{R2}(t)}{K_d m_2} \tag{E120}$$

The concentration of radionuclide in the liquid phase inside the disposal facility as a function of time f(t) in Bq m^{-3} is given by:

$$f(t) = \frac{M_{R1}(t)\ A_e}{V_a(t)} \tag{E121}$$

E-6.2. Transport in the unsaturated zone

Usually the boundary conditions for unsaturated flow are:

- values for head, pressure, suction or moisture content (specified head or moisture content condition : Dirichlet or first kind);
- the gradient of the head, pressure, suction or moisture content (specified flux condition: Neumann or second kind); or
- a combination of both (head/water content dependent flux condition: Cauchy or third kind).

In unsaturated flow, hydraulic conductivity (in saturated zone is a function of the soils characteristics) and its associated gradient are both functions of the state of saturation of the soil. In this case Darcy's Law for the vertical component of flow takes the form:

$$V_w = -K(\theta)\ [d\varphi(\theta)/dz + 1] \tag{E122}$$

where

V_w is the Darcy velocity (m s^{-1});
θ is the moisture content (–);
$K(\theta)$ is hydraulic conductivity (a function of the moisture content) (m s^{-1});
φ is the pressure head (sometimes called negative capillary pressure head) (m).

The second term in brackets arises from a gravitational elevation gradient, and is omitted for horizontal flow. Equation (E122) has been found experimentally to be highly non-linear for most soils under practical conditions. This equation together with the conservation of mass principle form the basis for unsaturated flow model. However, dissolved solute molecules do not travel at the Darcy velocity but rather at pore water velocities which is obtained dividing the Darcy velocity by the moisture content in the case of the unsaturated zone and by the effective porosity in the saturated zone.

There are many available models for the unsaturated zone from simple ones to more complex ones. Below is a very simple one known as the retardation model.

The unsaturated zone is assumed to be homogeneous, isotropic, porous media with constant, unidirectional flow in the vertical direction. Due to the difficulties and uncertainties in the modelling of the unsaturated zone, a simple plug model can be used, neglecting dispersion. In this model non-sorbing contaminants move with the vertical velocity of the water. This velocity is calculated using a unit gradient model. For most contaminants, the plug model is conservative since the peak flux to the saturated zone exceeds the peak flux when dispersion is considered.

For radionuclides with short half lives relative to their residence time in the unsaturated zone, the plug model may not be conservative since the contaminant will arrive sooner (lower residence time in the unsaturated zone) when dispersion is considered, therefore allowing less decay [E30]. This may became a significant factor when the unsaturated transit time is greater than ten times the half live of the contaminant. For this case is recommended to use other conservative assumptions such a higher infiltration rate and/or a lower unsaturated thickness.

— Model

The unsaturated zone can be simply modelled as a delay (time buffer used by a decay function $e^{-\lambda . t}$);

— Initial Conditions

Not necessary due to the simple model used (no differential equation to solve)

— Solutions (Analytical)

The time necessary for a contaminant to travel vertically through the unsaturated zone is given by:

$$t_{unsat} = \frac{H_{unsat}}{V_{unsat}} \tag{E123}$$

where

t_{unsat} is the travel time (y);
H_{unsat} is the unsaturated zone thickness (m);
V_{unsat} is the contaminant velocity in the unsaturated zone (m y^{-1});

$$V_{unsat} = \frac{Inf}{\theta_{\omega} + \rho_b K_d} \tag{E124}$$

with

Inf is the annual infiltration rate accounting for the water budget and the disposal hydraulic conductivity (m y^{-1});
θ_w is the moisture content (smaller than or equal to the effective porosity) (–);
ρ_b is the dry bulk density (kg m^{-3});
K_d is the distribution coefficient (m^3 kg^{-1}).

This model can be coupled with leaching model A. In this case the concentration of the radionuclide G(t), in Bq m^{-3}, at the bottom of the unsaturated zone in this case can be calculated as:

$$G(t+t_{unsat})=[A(t)/(Inf\ A_t)]\ exp(-\lambda\ t_{unsat}) \text{ for time greater than } t_{unsat} \tag{E125}$$

$$G(t) = 0 \text{ for time less than } t_{unsat} \tag{E126}$$

For leaching model B the concentration of the radionuclide $G(t+t_{unsat})$, in Bq m^{-3}, at the bottom of the unsaturated zone can be calculated as:

$$G(t+t_{unsat}) = f(t)\exp(-\lambda\, t_{unsat}) \text{ for time greater than } t_{unsat} \tag{E127}$$

$$G(t)=0 \text{for time less than } t_{unsat} \tag{E128}$$

E-6.3. Transport in the saturated zone

E-6.3.1. Model A

The simplest model for the saturated zone is called plume model, which neglects dispersion and is similar to the model described for the unsaturated zone in Section E-6.2.

The maximum concentration of the contaminant in a well, C_{well} (Bq m^{-3}), located at a distance d (m) from the disposal facility can be calculated as follows. First the time of the peak, T (y), needs to be calculated. Neglecting the the engineered barriers and unsaturated zone, T can be calculated as follows:

$$T= d/V_{rad} \tag{E129}$$

$$V_{rad}= V_f/(K_d\,\rho_b/\theta_w +1) \tag{E130}$$

where

V_f is the pore water velocity (m y^{-31});
V_{rad} is the velocity of the radionuclide (m y^{-31}).

$$C_{well}(d,T) = C_w(0)\exp(-\lambda d/V_{rad}) \tag{E131}$$

$$C_w(0)=A_0/[A_t H_d\,(\theta_\omega+\rho_b K_d)] \tag{E132}$$

where

$C_w(0)$ is the initial radionuclide concentration in the disposal facility water (Bq m^{-3});
A_0 is the initial activity in the disposal facility (Bq);
A_t is the area of the disposal facility (m^2);
H_d is the disposal height (m);
θ_ω is the effective porosity or the moisture content (–);
ρ_b is the dry bulk density (kg m^{-3});
K_d is the distribution coefficient (m^3 kg^{-1}).

E-6.3.2. Model B

Taking radioactive decay in the unsaturated zone in account:

$$T= d/V_{rad} \tag{E133}$$

$$C_{well}(d,T+t_{unsat}) = C_w(t_{unsat})\exp(-\lambda d./V_{rad}) \tag{E134}$$

$$C_w(t_{unsat})=\{A_0/[A_t H_d\,(\theta_w +\rho_b K_d)]\}\exp(-\lambda t_{unsat}) \tag{E135}$$

where

t_{unsat} is calculated as described in the simplified model for the unsaturated zone (Section E-6.2).

E-6.3.3. Model C

Taking account the effect of the engineered barriers (using leaching model A – Section E-6.1.1) and decay in the unsaturated zone:

$$C_w(t)= A(t) /[Inf\, A_t] \qquad \text{(E136)}$$

$$C_w(t+t_{unsat})= \{A(t) /[Inf\, A_t]\}\, exp(-\lambda t_{unsat}) \qquad \text{(E137)}$$

$$C_{well}(d,T+t_{unsat} + t) = C_w(t_{unsat}+t)\, exp(- \lambda d/V_{rad}) \qquad \text{(E138)}$$

for time less than t_{unsat} +T ,

$$C_{well} = 0 \qquad \text{(E139)}$$

where

Inf - is the annual infiltration rate (m y^{-1}) accounting for the water budget and the disposal hydraulic conductivity;

A(t) is the activity lost by leaching during the year t, (Bq y^{-1}).

E-6.3.4. Model D

Taking account the effect of the engineered barriers (using leaching model B – Section E-6.1.2) and decay in the unsaturated zone:

$$C_{well}(t+t_{unsat}+T)= G(t+t_{unsat})\, exp(-\lambda d/V_{rad}) \qquad \text{(E140)}$$

E-6.3.5. Model E

— *Model*

This model considers a constant injection of a radionuclide (constant concentration C_0 at z=0) into an aquifer and its subsequent dispersion, retention and decay. It is equivalent to the movement of a radionuclide in a semi-infinite column. This is the case where the column (aquifer) initially with a concentration of zero is connected to a reservoir (disposal facility) containing a solution of constant concentration C_o(Bq m^{-3}).

$$R_t\, \partial C/\partial t = D/\theta_e\, \partial^2 C/\partial z^2 - v_d/\theta_e\, \partial C/\partial z - \lambda R_t\, C \qquad \text{(E141)}$$

where

R_t is the retardation (–) given by: $R = 1 + \frac{\rho_b k_d}{\theta}$;

ρ_b is the bulk density (kg m^{-3});
k_d is the distribution coefficient (m^3 kg^{-1});
θ is the total porosity (–);
θ_e is the effective porosity (–);

D is the dispersion coefficient ($m^2\ s^{-1}$) given by: $D = \theta D_e + \alpha_L v_d$;

α_L is the longitudinal dispersivity (m);

D_e is the molecular diffusion coefficient in pore water ($m^2\ s^{-1}$);

v_d is the Darcy velocity ($m\ s^{-1}$);

λ is the decay constant (s^{-1});

C is the radionuclide concentration ($Bq\ m^{-3}$).

— Boundary Conditions

$$t \leq 0\ .\ z \geq 0\ C=0 \qquad \text{(E142)}$$

$$t > 0\ \ z = 0\ C=C_0 \qquad \text{(E143)}$$

$$z = \infty\propto\ C=0 \qquad \text{(E144)}$$

— Solutions (Analytical & Semi-analytical)

The solution of the transport equation for the boundary conditions described above was given in Appendix D.

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[E26] PASHKOVSKY, I.S., Modelling of Ground Water Contamination Caused by Organic Pollutants. In. Joint Russian — American Hydrogeology Seminar, July 8–9, 1997. Berkeley, 1997, pp 117–123.
[E27] INTERNATIONAL ATOMIC ENERGY AGENCY, Derivation of Activity Limits for Disposal of Radioactive Waste to Near Surface Facilities. Draft Working Material version 0.3, International Atomic Energy Agency, Vienna (2001).
[E28] HEILBRON, P., GUERRERO, J., RUPERTI, MIGRAD N., Code Development — Brazilian Nuclear Energy Commission — Internal Report, (1998).
[E29] SEITZ, R.R., ROOD, A.S., HARIS, G.A., KOTECK, M., Sample Application of Sensitivity/Uncertainty Analysis Techniques to a Groundwater Transport Problem, DOE/LLW-108, National Low Level Waste Management Program (1991).

APPENDIX F: COMPUTER CODES

A list of computer codes relevant to the assessment of LLW disposal facilities is provided below. This list has been compiled by ISAM participants. It is not intended to be a complete list of all codes available. It is merely provided to give the reader a list of some example codes.

F-1. NEAR FIELD CODES

F-1.1. Barrier

Application:

Simulation of water flow through low-level waste disposal facilities and structural component failure

References:

[F1] SHUMAN, R., et al, Performance Assessment of Low-Level Waste Disposal Facilities, Electric Power Research Institute report NP-5745M, (1988).

[F2] BAIRD, R. D., et al, Design and Cost Methodologies for Low Level Waste Disposal Facilities, Electric Power Research Institute report NP-5745M, (1987).

User manual:

[F3] SHUMAN, R., V. C ROGERS, N. CHAU, AND G. B. MERRELL, The BARRIER Code: A Tool for Estimating the Long term Performance of Low-Level Radioactive Waste Disposal Facilities, User's Manual, Electric Power Research Institute report NP-6218-CCML (1989).

Summary:

BARRIER is designed to simulate long term performance and degradation of low-level radioactive waste facilities with concrete components. The code is applicable for a variety of vault types (surface, above and below ground, modular canister). Also, surface coverage by plants and soil properties differences between soil layers can be addressed. Unsaturated and saturated groundwater flow in one dimension through the disposal facility can be simulated. Summaries of water content, water potential, flux and plant water use as a function of depth and cumulative totals of the storage, precipitation, evaporation, transpiration, and drainage water balance components are generated. BARRIER also contains a concrete degradation model that incorporates surface and bulk attack on concrete, providing a mechanistic means of predicting structural failure. The concrete degradation and cracking results are given at specified intervals, along with consequent leach rates and projected doses due to ingestion of contaminated water and foodstuffs.

Waste form/source needs:

The waste package type (drum, box, high-integrity container, liner), dimensions, times of initial and complete failure of the package type are required. Characteristics of the solid waste are needed, along with radionuclide-specific parameters (decay constant, solubility limit, K_d, diffusion coefficient in concrete, etc.).

F-1.2. Dust

Application:

Transport of radionuclides through the disposal facility

References:

[F4] SULLIVAN T.M., DUST Data Input Guide, Brookhaven National Laboratory, Upton, New York, (1992,).

User manual:

[F5] SULLIVAN T.M., DUST-MS Instruction Guide, Brookhaven National Laboratory, Upton, New York, (1997).

Summary:

The DUST code permits the user to select from two different methods of calculating the transport of radionuclides through the facility - the Multi-Cell Mixing Cascade (MCMC) model and one-dimensional finite difference (FD) model. The MCMC is an analytical solution of the advective transport equation with radioactive decay and chemical retardation for constant flow and material properties. The model does permit a unique time to container failure and wasteform release rate for each mixing cell having a container. The MCMC model requires relatively little computer time to operate. The FD model solves the transport equation with the process of advection, dispersion, retardation and radioactive decay. It is capable of modelling a wider range of conditions than the MCMC model as it permits non-uniform flow and material properties, however, it requires substantially more input and computer time.

Waste form/source needs:

For each radionuclide in the inventory it is necessary to define its physical parameters (decay constant and atomic mass) and the solubility limit. The material property menu requires defining the bulk density and distribution coefficient for each used material in the disposal facility. The FD model needs the specification of the co-ordinates of each waste package as well.

F-1.3. Help

Application:

Landfill cover design

References:

[F6] SCHROEDER, P.R., PEYTON, R.L., MCENROE, B.M.,SJOSTROM, J.W., The Hydrologic Evaluation of Landfill Performance (HELP) Model (Draft), Volume IV, Documentation of Version 2, U.S. Army, Engineer Waterways Experiment Station, Vicksburg, (1988).

[F7] PEYTON, R.L., SCHROEDER, P.R., The Hydrologic Evaluation of Landfill Performance (HELP) Model (Draft), Volume V, Verification of Version 2 Using Field Data, US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi (1988).

User manual:

[F8] SCHROEDER, P.R., PEYTON, R.L, MCENROE, B.M., SJOSTROM, J.W., The Hydrologic Evaluation of Landfill Performance (HELP) Model (Draft), Volume II, User's Guide for Version 2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi (1988).

Summary:

HELP is a quasi two-dimensional hydrologic model of water movement across, into, through, and out of landfills. The model accepts climatologic, soil, and design data and utilizes a solution technique that accounts for the effects of surface storage, runoff, infiltration, percolation, evapotranspiration, soil moisture storage, and lateral drainage. Landfill systems, including various combinations of vegetation, cover soils, waste cells, and synthetic membrane covers and liners, may be modelled. The program was developed to facilitate rapid estimation of the amounts of runoff, drainage, and leachate that may be expected result from the operation of a wide variety of landfill designs. The model, applicable to open, partially closed, and fully closed sites, is a tool for both designers and permit writers. Default values are provided for much of the data required for operation of the HELP model. A climatologic data base is provided that includes data for over 100 cities in the United States. A list of default soil properties for a variety of soils and wastes is also provided. Thus, the user can simply select values based on the soil types to be used for a cover, as opposed to actually measuring the values. This is very useful for scoping analyses. The user also has the option of inputting site specific values for the climate and soil data.

Waste form/source needs:

No contaminant transport is considered. However, information about the hydrologic properties of the waste can be input in lieu of using the default values provided in the model.

F-1.4. Source1, source2

Application:

Evaluation of source term for low-level radioactive waste repositories

User manual:

[F9] ICENHOUR, A.S., THARP M.L., User's Guide for the SOURCE1 and SOURCE2 Computer Codes: Models for Evaluating Low-Level Radioactive Waste Disposal Facility Source Terms (Version 2.0), ORNL/TM-13035.

Summary:

The SOURCE1 and SOURCE2 computer codes calculate source terms for performance assessments of low-level radioactive waste disposal facilities. SOURCE1 is used to simulate radionuclide release from tumulus (vault) type repositories. SOURCE2 is used to simulate releases from silo-, well-, well-in-silo and trench-type disposal facilities. Both codes simulate the degradation of engineered barriers and provide an estimate of the source term. The routines of SOURCE codes have four primary functions: structural analysis, simulation of concrete and metal barrier degradation, cracking analyses and radionuclide-leaching calculations. The structural analyses routines establishes initial bending moments and shear forces. The concrete and metal barrier degradation routines calculate moments and shears required for concrete cracking and compare these values with the moments and shears evaluated in the structural analysis. Moments and shears required for cracking vary as the engineered facility degrades. The leaching routines calculate the release rate of radionuclides to the environment.

Waste form/source needs:

The SOURCE codes incorporate advection and diffusion mechanisms that are modelled in one dimension. The calculated concentration cannot exceed the defined solubility limit of the assumed chemical form of a radionuclide.

F-1.5. Unsat-H

Application:

Cover design (near surface water balance)

References:

[F10] BACA, R.G., MAGNUSON, S.O., Independent Verification and Benchmark Testing of the UNSAT-H Computer Code, Version 2.0, EGG-BEG-881 1, (1990).

User manual:

[F11] FAYER, M.J., JONES, T.L., UNSAT-H Version 2.0: Unsaturated Soil Water and Heat Flow Code, PNL-6779/UC-702, (1990).

Summary:

UNSAT-H was developed to simulate the water dynamics of arid sites used or proposed for near surface waste disposal. UNSAT-H simulates one-dimensional water and heat flow in heterogeneous, unsaturated soils and sediments. Water vapour transport, evapotranspiration, and surface energy balance are also simulated. The Crank-Nicholson numerical scheme is used to solve Richards' Equation on a finite difference grid. A limitation of UNSAT-H is the lack of consideration of run off. This is the reason why UNSAT-H is not recommended for humid sites. UNSAT-H has been primarily applied to conditions at the Hanford Site for cover design and recharge predictions.

Detailed data are required for UNSAT-H. Required site parameters can be separated into four categories: soil properties, initial conditions, plant data, and boundary conditions (meteorological data). Defaults specific to the Hanford Site are provided for some parameters. However, site specific data should be collected for other sites.

Waste form/source needs:

No transport calculations are conducted. However, hydrologic properties of the waste could be used for flow modelling.

F-2. GEOSPHERE [FAR-FIELD] CODES

F-2.1. Draf

Application:

Radionuclide transport in saturated or unsaturated porous media.

References:

[F12] RIVES, D., "Modelo de dispersión de radionucleidos en aquíferos freáticos (DRAF)", in "Memorias del II Congreso Regional de Seguridad Radiológica y Nuclear", Vol. II, 1er. Parte, Zacatecas, México, (1993).

[F13] SIRAKY, G., Safety Analysis as a Regulatory tool. A case study, in Proceedings of an International Symposium on the experience in the planning and operation of low level waste disposal facilities, IAEA, Vienna, Austria, (1996).

User manual:

[F14] RIVES, D. E., "Manual del Usuario del Modelo de Dispersión de Radionucleidos en Acuíferos Freáticos - DRAF" (User's Manual of DRAF Model) Autoridad Regulatoria Nuclear, Argentina, ARN-PI-5/99, (1998).

Summary:

The DRAF model had been developed as a mathematical tool for the safety assessment of near surface radioactive waste disposal facilities. The model solves the three-dimension advection-dispersion equation with soil-solute interaction and radioactive decay by the finite differences method. The model has two versions, one for the saturated zone, another for the unsaturated zone. In the saturated version, the velocity field may vary with X, Y and Z direction, and in the unsaturated version the velocity field only varies with the depth direction (horizontal layers). The unsaturated version's properties may vary only in the depth direction (horizontal layers), and can take into account time steps variation to consider barriers' degradation. All versions allow a three dimensional variation of the concentration.

Waste form/source needs:

The waste geometry can be defined by the number, dimension and distribution of „source nodes". The radionuclide concentrations can be defined between several pre-defined time-dependent distributions, or can be generated by a source term model as an ASCII file, that may have the activity or concentration that enters the model domain.

The data needed for the simulated region are: the velocity or velocity distribution, the retardation factor R, the longitudinal and transversal dispersivities, and the source parameters. The unsaturated version needs also the water content, the bulk density and the distribution coefficient Kd to compute the retardation factor.

F-2.2. Femwater

Application:

Simulation of saturated/unsaturated flow in porous media.

References:

[F15] REEVES, M., DUGUII, J.O., Water Movement Through Saturated-Unsaturated Porous Media: A Finite Element Galerkin Model, ORNL-4927. Yeh, G. T., 1982, Training Course No. 1: The Implementation of FEMWATER (ORNL-5567) Computer Program, TM 8327 (NUREG/CR2705), (1976).

User manual:

[F16] YEH, G T., WARD, D.S., FEMWATER A Finite Element Model of Water Flow through Saturated-Unsaturated Porous Media, ORNL-5567, (1980).

Summary:

FEMWATER is a two-dimensional finite element code that simulates unsaturated or saturated flow in porous media under either steady-state or transient conditions. The code can simulate transitions from unsaturated to saturated flow in heterogeneous and anisotropic media. Water exchange can be simulated between the surface and subsurface by seepage, ponding, infiltration; and runoff from rainfall, artificial recharge, and withdrawal; and pond, lakes, and streams. Fixed head boundary conditions or flux boundary conditions can be used. Pressure head, volumetric moisture content, and Darcy velocities are output for each node and time step. Darcian fluid flow by pressure gradients, gravity, boundary fluxes, recharge and withdrawals can be modelled.

Waste form/source needs:

FEMWATER models water flow only, not contamination migration. Therefore FEMWASTE, a two-dimensional transient model for the transport of dissolved constituents through porous media, was developed. The transport mechanisms include: convection, hydrodynamic dispersion, chemical sorption, and first-order decay. The waste transport model is compatible with the water flow model (FEMWATER) for predicting convective Darcy velocities in porous media which may be partially saturated.

F-2.3. Grdflx

Application:

Radionuclide groundwater transport and ingestion dose calculation.

References:

[F17] CODELL, R.B., KEY, KT., WHELAN, G., A Collection of Mathematical Models for Dispersion in Surface Water and Groundwater, U.S. Nuclear Regulatory Commission, NUREG-0868, (1982).

User manual:

Same as reference [F17].

Summary:

The GRDFLX code is a simple, semi-analytical computer code which calculates groundwater concentrations at selected receptor points downgradient at user specified times. This code employs the Green's function solution to the advection dispersion equation for an instantaneous release from an area source in a homogenous isotropic aquifer of infinite lateral extent and finite thickness. The groundwater flow is assumed to be constant and uniform across the porous medium. This solution is modified for a continuous, arbitrary release by use of the convolution integral. The convolution integral is solved using Simpson's rule numerical integration with a fixed number of integration steps. The concentration is vertically averaged.

In addition to groundwater concentrations, this code also calculates the contaminant flux from an aquifer intersecting a surface water body. It is assumed the entire contaminant mass enters the surface water body.

This code differs from the GROUND code in that ingestion doses are also calculated and printed in the output. The user is requested to provide dose conversion factors. The source term may include more than one radionuclide and the transport portion of the code includes routines to account for decay and ingrowth of parent/daughter relationships. The decay and ingrowth routines assume the daughter radionuclide travels at the same rate as the parent radionuclide. The reference shows that this assumption is conservative. The aquifer flow parameters needed to operate the code are pore velocity (cm/day), effective and total porosity, longitudinal and transverse dispersion factors (cm) and aquifer thickness (cm). Pore velocity may be calculated from the hydraulic conductivity, head drop (dh/dx) and effective porosity. Dispersivity values for various aquifer materials are listed in Till and Meyer (1983).

The contaminant fate and transport parameters required by the code are the contaminant half-life and the retardation factor. If decay products are considered, then the daughter half life and decay branching ratio is also required. The retardation factor may be calculated from the sorption coefficient (K_d), porosity and bulk density of the aquifer. The equation for this calculation is found in the reference. Typical K_d values for various radionuclides are listed in the reference. Ingestion dose conversion factors for total body and bone are requested. Total body dose is not widely used, however one may input any DCF into the code

Waste form/source needs:

The source term is represented as an activity release rate into the groundwater as a function of time. Each parent radionuclide must have a source input. The total time of source input along with the release rate at specific times is needed. The release rate into the aquifer is in terms of Ci/s and the time is specified in seconds. The length and width of the source is also needed.

F-2.4. Migrad

Application:

Radionuclide transport in saturated and simple unsaturated flow

References:

[F18] VIDAKOVIC ROMANI, Z., – Simulação Híbrida da Migração de Rejeitos Radioativos em Meios Porosos, M.Sc. Thesis, COPPE/UFRJ, Rio de Janeiro, 1996.

[F19] ROMANI Z. V., COTTA R.M., PÉREZ GUERRERO, J.S., HEILBRON FILHO P.F.L.; Análise da Contaminação de Solos por Rejeitos Radioativos, Parte I: Soluções por Transformação Integral, International Conference on the Radiological Accident of Goiânia – 10 Years Later, Goiânia, Oct. 26-31, (1997).

[F20] COTTA, R.M., MIKHAILOV, M.D., RUPERTI, N.J., JR., Analysis of Radioactive Waste Contamination in Soils Part IV: Solution via Symbolic Manipulation, International Conference on the Radiological Accident of Goiânia – 10 Years Later, Goiânia, Oct. 26-31, (1997).

User manual:

[F21] PÉREZ GUERRERO J. S., RUPERTI, N.J., JR.: Migrad 1.0 User Manual, CNEN, Rio de Janeiro, 1998.

Summary:

MIGRAD is designed to simulate the transport of radionuclides in unsaturated or saturated porous media. It solves the one-dimensional single contaminant transport equation with radioactive decay in one or two saturated porous media. The user has the option to choose the boundary conditions in the coupling between both media and in the last downstream boundary. The upstream boundary condition is a prescribed concentration in the aquifer as a function of time. The user can set any function for this boundary condition, either in an explicit analytical form or in a discrete form to be fit with a cubic spline interpolator. The initial concentration in the aquifer can be set as a function of the longitudinal dimension. The one-dimensional velocity field is constant and distinct in each of the porous medium. This allows to use the first medium to approximate an unsaturated zone, provided that the moisture content replaces the porosity in the first medium.

The Generalized Integral Transform Technique (GITT), a straightforward numerical-analytical method with spectral characteristics, is employed. This method has the advantageous feature of user-prescribed accuracy, thus avoiding undesirable features such as numerical dispersion.

The code has a friendly Graphical User Interface that performs the pre- and post-processing, including data input, two-dimensional plots and time animations of the concentration profiles in the groundwater. It has a structure that allows the addition of new modules to model the biosphere and perform chain and dose calculations.

Waste form/source needs:

The source term is represented as a specified concentration in the groundwater or a time-dependent contaminant flux into groundwater. For the second case, waste form release rates have to be given, since the code does not conduct such calculations. A simple calculation may also be done to determine this flux, by supposing that the total inventory of the radionuclide were dissolved in the volume of the disposal facility and using the release rate given by the water balance in the disposal facility. Then, the depletion of the disposal facility may be fit for any continuous function. For this case, the dimensions of the disposal facility are needed, as well as the water balance in the cap.

F-2.5 Modflow 96

Application:

Simulation of saturated flow in porous media

References:

[F22] HARBAUGH, A.W., MCDONALD, M.G., Programmer's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96-486 (http://water.usgs.gov/software/modflow-96.html), (1996)

User manual:

[F23] HARBAUGH, A.W., MCDONALD, M.G., User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey 96-485 (http://water.usgs.gov/software/modflow-96.html), (1996)

Summary:

MODFLOW is a three-dimensional finite-difference ground-water flow model. It has a modular structure that allows it to be easily modified to adapt the code for a particular application. Many new capabilities have been added to the original model. OFR 96-485 (complete reference below) documents a general update to MODFLOW, which is called MODFLOW-96 in order to distinguish it from earlier versions.

MODFLOW simulates steady and nonsteady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Flow from external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds, can be simulated. Hydraulic conductivities or transmissivities for any layer may differ spatially and be anisotropic (restricted to having the principal direction aligned with the grid axes and the anisotropy ratio between horizontal coordinate directions is fixed in any one layer), and the storage coefficient may be heterogeneous. The model requires input of the ratio of vertical hydraulic conductivity to distance between vertically adjacent block centres. Specified head and specified flux boundaries can be simulated as can a head dependent flux across the model's outer boundary that allows water to be supplied to a boundary block in the modelled area at a rate proportional to the current head difference between a "source" of water outside the modelled area and the boundary block. MODFLOW is currently the most used numerical model in the U.S. Geological Survey for ground-water flow problems. An efficient contouring program is available (Harbaugh, 1990) to visualise heads and drawdowns output by the model.

Waste form/source needs:

MODFLOW-96 is a stand-alone hydrogeologic flow code. The contaminant transport capabilities are included in the codes MODPATH and MT3D, which use MODFLOW data files.

MODPATH uses a semi-analytical particle tracking scheme that allows an analytical expression of the particle's flow path to be obtained within each finite-difference grid cell. Particle paths are computed by tracking particles from one cell to the next until the particle reaches a boundary, an internal sink/source, or satisfies some other termination criterion. Both steady-state and transient ground-water flow systems can be analysed with MODPATH.

MT3D is a comprehensive three-dimensional numerical model for simulating solute transport in complex hydrogeologic settings. MT3D96 is the first major upgrade since 1992 to MT3D, the leading software available for analysing contaminant migration in groundwater. MT3D is a three-dimensional transport model for simulation of advection, dispersion, and chemical reactions of dissolved constituents in groundwater systems. The model uses a modular structure similar to that implemented in MODFLOW. This modular structure makes it possible to independently simulate advection, dispersion, sink/source mixing, and chemical reactions without reserving computer memory space for unused options.

F-2.6. Porflo

Application:

Groundwater flow and contaminant transport.

References:

[F24] RUNCHAL, A.K, SAGAR, B., BACA, R.G., KLINE, N.W., PORFLO - A Continuum Model for Fluid Flow, Heat Transfer, and Mass Transport in Porous Media: Model Theory, Numerical Methods, and Computational Tests, RHO-BW-CR-150 P, Rockwell Hanford Operations, (1985).

User manual:

[F25] KLINE, N.W., K RUNCHAL, A., BACA, R.G., PORFLO Computer Code: Users Guide, RHO-BW-CR-138 P, Rockwell Hanford Operations, (1983).

Summary:

PORFLO is a deterministic, two-dimensional finite differences code applicable to an equivalent porous continuum. PORFLO is capable of simulating the coupled processes of saturated groundwater flow, contaminant transport, and heat transfer. Heat transfer is not addressed in this report. The numerical solution method used in PORFLO is the Alternating Direction Implicit technique composed with Nodal Point Integration, which is known as Integrated Finite Differences. An additional solution technique used in PORFLO is the fully implicit Cholesky decomposition method. This technique is useful for steady state solutions to the flow equation.

The conceptual modelling approach used in PORFLO allows a 2-D heterogeneous system to be defined in either the horizontal or vertical plane. Three-dimensional systems with axial symmetry (i.e., a cylinder) can also be modelled with PORFLO. PORFLO can use detailed or relatively simple data. If detailed data are available, then a relatively complex conceptual model with spatially variable gradients, specific storage, and hydraulic conductivities can be set up for PORFLO. Likewise, if only general data are available, PORFLO can be used with a constant velocity and no detailed gradients or conductivities.

Waste form/source needs:

Source term is represented as specified concentration in groundwater or time-dependent volumetric contaminant loading rate into groundwater. Waste form specific information would be required in order to determine this information. PORFLO does not conduct such calculations. Solubility, retardation factor, and inventory are required for contaminants to be modelled in the source term.

F2.7. Sutra

Application:

Simulation of water flow and radionuclide transport from the low-level waste repositories in unsaturated and saturated zone.

References:

[F26] BENEŠ, V., JANŮ, M., MARŠÁL, J., HOLUB, J., et al., Operational Safety Study for the repository (nuclear facility) Richard, NYCOM Prague 51-96-0338, (1995)

User manual:

[F27] VOSS, C.J., A finite simulation model for saturated-unsaturated, fluid-density-dependent ground-water flow with energy transport or chemically reactive single-species solute transport, U.S. Geological Survey, Water Resources Investigetions Report 84-4369, 1984 (Upgraded 1991).

Summary:

SUTRA is a computer program, which simulates fluid movement and the transport of either energy or dissolved substances in a subsurface environment. SUTRA is a two-dimensional finite element code that simulates unsaturated or saturated flow in porous media and polutant transport under either steady-state or transient conditions. The code can simulate transitions from unsaturated to saturated flow in heterogeneous and anisotropic media. Water exchange can be simulated between the surface and subsurface by seepage, ponding, infiltration; and runoff from rainfall, artificial recharge, and withdrawal; and pond, lakes, and streams. Fixed head boundary conditions or flux boundary conditions can be used. Pressure head, volumetric moisture content, and Darcy velocities are output for each node and time step. Darcian fluid flow by pressure gradients, gravity, boundary fluxes, recharge and withdrawals can be modelled. The transport mechanisms include: convention, hydrodynamic dispersion, chemical sorption, and first-order decay.

Waste form/source needs:

The source term flows from different accident scenarios in a disposal facility. The accident scenarios are based on the total inventory of the radionuclides in the disposal facility and on the solubility and mobility of radioactive substances. A time dependent contaminant flux into unsaturated zone is an output of those accident scenarios. The contaminant flux into aquiter is calculated by the unsaturated flow and transport model.

F-2.8. Tough2

Application:

Simulation of two-phase flow including heat in porous media, safety analyses for low, medium and high level waste repositories

References:

[F28] PRUESS, K., Numerical modeling of gas migration at a proposed repository for low and intermediate level nuclear wastes at Oberbayenstock, Switzerland, Report LBL-25413, Lawrence Berkeley Laboratory, Berkeley, Ca, (1990).

[F29] PRUESS, K., FINSTERLE, S., MORIDIS, G., OLDENBURG, C., WU, Y.S., General-Purpose Reservoir Simulators: The TOUGH2 Family, GRC Bulletin, pp. 53 - 57, February 1997. (also: Lawrence Berkeley National Laboratory Report LBL-40140), (1997).

User Manual:

[F30] PRUESS, K., TOUGH User’s Guide, Report LBL-20700, Lawrence Berkeley Laboratory, Berkeley, Ca, (1987).

[F31] PRUESS, K., TOUGH2, A General-Purpose Numerical Simulator for Multiphase Fluid and Heat Flow, Report LBL-29400, Lawrence Berkeley Laboratory, Berkeley, Ca, (1991).

[F32] OLDENBURG, C.M., PRUESS, K., EOS7R: Radionuclide Transport for TOUGH2, Report LBL-34868, Lawrence Berkeley Laboratory, Berkeley, Ca, (1995).

Summary:

TOUGH2 (Transport Of Unsaturated Groundwater and Heat), developed at Lawrence Berkeley Laboratory, is a multi-dimensional numerical model for simulating the coupled transport of water, vapor, non-condensible gas, and heat in porous and fractured media. TOUGH2 offers added capabilities and user features, including the flexibility to handle different fluid mixtures. Temperature and pressure dependent thermophysical properties of all fluid components and fluid mixtures (e.g. gas-vapour) are represented within experimental accuracy. Several code enhancements for considering e.g. radionuclide transport including diffusion, adsorption, hydrodynamic dispersion and radioactive decay, or solubility effects, are available. TOUGH2 uses an integral finite difference method for space discretization, and first-order fully implicit time differencing. It takes account of fluid flow in both liquid and gaseous phases occurring under pressure, viscous, and gravity forces according to Darcy's law. Several physical mechanisms can be considered optionally as e.g. heat transfer in a surrounding solid matrix or the Klinkenberg effect. The source code is available which enables self made code modifications.

Waste form/source needs:

Radionuclide release can be modelled as time dependent source terms of radionuclides and a mass fraction in the liquid phase, respectively. Specification of radionuclide specific properties (diffusion and adsorption coefficient, half-life, Henry constant, etc.) is required. Rock specific parameters (permeability, porosity and choice of relative permeability and capillary pressure function, specific heat and heat conductivity) are input terms, whereas the thermodynamic fluid properties are embedded.

F-2.9. Vam2d

Application:

Variably saturated flow and transport.

References:

[F33] HUYAKORN, P.S., JONES, B.G., PARKER, J.C., WADSWORTH, T.D., WHITE, H.O., JR, Finite Element Simulation of Moisture Movement and Solute Transport in a Large Caisson, in Modelling Study of Solute Transport in the Unsaturated Zone, Workshop Proceedings, for US. Nuclear Regulatory Commission, Washington, D.C (1987).

[F34] HUYAKORN, P.S., WHITE, H.O., JR., KOOL, J.B., BUCKLEY, J. E., VAM2DH - A Variably Saturated Flow and Transport Analysis Model in 2-Dimensions: Documentation and User's Manual Version 1.0, HydroGeoLogic, Inc., Herndon, Virginia (1988).

User manual:

[F35] HUYAKORN, P.S., KOOL, J. B., ROBERTSON, J.B., Documentation and User's Guide: VAM2D - Variably Saturated Analysis Model in Two Dimensions, NUREG/CR-5352, HGL/89-01, (1989).

Summary:

VAM2D was developed to simulate two-dimensional flow and transport in fully or variably saturated porous media. The flow and transport equations are formulated using the Galerkin finite element method. For variably saturated flow problem, non linearities due to unsaturated soil properties and atmospheric boundary conditions are treated using Picard or Newton-Raphson iterations. Saturated water table boundary conditions are treated with Picard iterations. Detailed data are required for VAM2D. Required site parameters can be separated into four categories: soil properties, initial conditions, plant data, and boundary conditions (e.g., meteorological data).

Waste form/source needs:

Source term is represented as specified concentration in groundwater or time-dependent volumetric contaminant loading rate in to groundwater. Waste form-specific information is required to determine this information. VAM2D does not conduct such calculations. Solubility, retardation factor, and inventory are required for contaminants to be modelled in the source term.

F-3. BIOSPHERE CODES

F-3.1. Genii

Application:

GENII was developed at Hanford as a second-generation environmental dosimetry computer code.

References:

See user manual.

User manual:

[F36] NAPIER, B.A., et al., GENII - The Hanford Environmental Radiation Dosimetry Software System, Volume 2: Users Manual, PNL-6584, UC-600, November, (1988).

Summary:

GENII calculates radiation doses for acute and chronic releases to air and water, from ground level and stacks, and includes doses due to initial contamination of soil and surfaces. It evaluates exposure pathways via air immersion, water immersion, ground surface (surface and buried sources), inhalation, and ingestion. The source term can be varied to include decay up to the start of the scenario, total activity or fractions, and measured concentrations in specific media (soil or water). The code includes provisions for atmospheric dispersion, geohydrology, biotic transport, and surface water transport. Receptors are individuals, populations, and intruders into contained sources and can be identified by direction and distance. GENII is a menu-driven code, directing the user through a set of steps with pull-down help menus available at every step.

F-3.2. Resrad

Application:

RESRAD is a computer code developed at Argonne National Laboratory for the U.S. Department of Energy to calculate site specific RESidual RADioactive material guidelines as well as radiation dose and excess lifetime cancer risk to a chronically exposed on-site resident.

References:

[F37] YU, C., LOUREIRO, C., CHENG, J.J., JONES, L.G., WANG, Y.Y., CHIA, Y.P., FAILLACE, E., Data collection Handbook to Support Modeling Impacts of Radioactive Material in Soil, Environmental Assessment and Information Sciences Division, Argonne National Laboratory, Argonne, Illinois, April (1993).

User manual:

[F38] YU, C., et al., Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0, ANL/EAD/LD-2, Environmental Assessment and Information Sciences Division, Argonne National Laboratory, Argonne, Illinois, September (1993).

[F39] YU, C., ZIELEN, A.J., CHENG, J.-J., LEPOIRE, D.J., GNANAPRAGASAM, E., KAMBOJ, S., ARNISH, J., WALLO III, A., WILLIAMS W.A., PETERSON, H.,: User's Manual for RESRAD Version 6, ANL/EAD-4, Environmental Assessment and Information Sciences Division, Argonne National Laboratory, Argonne, Illinois, (Latest version of RESRAD for Windows User's Guide in Adobe Acrobat PDF format is available in electronic form in http://www.ead.anl.gov/~web/resrad/avail.html), July (2001).

Summary:

RESRAD uses a pathway analysis method in which the relation between radionuclide concentrations in soil and the dose to a member of a critical population group is expressed as a pathway sum, which is the sum of products of "pathway factors". Pathway factors correspond to pathway segments connecting compartments in the environment between which radionuclides can be transported or radiation emitted. Radiation doses, health risks, soil guidelines and media concentrations are calculated over user-specified time intervals. The source is adjusted over time to account for radioactive decay and ingrowth, leaching, erosion, and mixing. RESRAD uses a one-dimensional groundwater model that accounts for differential transport of parent and daughter radionuclides with different distribution coefficients.

F-3.3. Tame

Application:

Estimation of the radiological exposure of hypothetical individuals living at locations associated with sites of near surface radioactive waste repositories.

References:

[F40] KLOS, R.A., MÜLLER-LEMANS, H., VAN DORP, F., GRIBI, P., TAME - The Terrestrial Aquatic Model of the Environment: Model definition, PSI Ber. 96-18, Paul Scherrer Institut, October (1996).

User manual:

Same as reference.

Summary:

TAME comprises two distinct sub-models - one representing the transport of radionuclides in the near surface environment and one for the calculation of doses to individual inhabitants of that biosphere. This structure is the result of a detailed review of the modelling requirements for biospheric codes. and is based on a comprehensive consideration of all features, events and processes relevant to Central-European biospheres, both in the present-day biosphere and in potential future biosphere states. Mass balance for water and solid material fluxes is used to determine the rates of contaminant transfer between components of the biosphere system. The calculation of doses is based on existing representations of exposure pathways.

F-4. SYSTEM LEVEL CODES

F-4.1. Amber

Application:

AMBER is a PC-based, flexible software tool that allows users to build their own dynamic compartmental models to represent the migration and fate of contaminants in a system, for example surface and sub-surface environments, using a Windows based graphical user interface. Radioactive and non-radioactive contaminants in solid, liquid and gaseous phases can be considered. AMBER can be used to assess routine, accidental and long term contaminant releases.

References:

[F41] AMBER 4.4, Getting Started, Enviros QuantiSci and Quintessa Ltd, April 2002.

User manual:

[F42] AMBER 4.4, Reference Guide, Enviros QuantiSci and Quintessa Ltd, April 2002.

Summary:

In AMBER the materials of interest, referred to as contaminants, are assumed to be uniformly mixed in a series of compartments between which transfers can take place. A compartment is any specific part of the system being modelled. Each transfer is 'donor controlled', depending directly on the amount of the material present in the compartment from which the material is moving, and can change with time. Limits on the transfer may also be specified, enabling non-linear transfers to be represented (e.g. leaching which is limited by elemental solubility). AMBER allows for contaminants to decay with time into other contaminants. A typical compartment model contains compartments, linear transfers between compartments and sources providing input of contaminants into compartments. The software has been fully verified against a series of tests designed for such codes and its application to a variety of cases has been documented in numerous technical reports, journal papers and conference papers.

F-4.2. Presto-epa-cpg

Application:

System-Level Pathways Code.

References:

[F43] ROGERS, V.C., HUNG, C., PRESTO-EPA-CPG: A Low Level Radioactive Waste Environmental Transport and Risk Assessment Code, EPA 520/1-87-026, (1987).

User manual:

Same as reference.

Summary:

PRESTO-EPA-CPG is a system-level code capable of modelling transport via all major non intrusive human exposure pathways. Estimates maximum annual whole-body dose to a critical population group from land disposal of LLW by shallow or deep methods (dose in maximum year is determined). Pathways and processes that can be modelled include groundwater migration with discharge to a river or a well, food grown on waste site, and inhalation of radioactive dust. PRESTO-EPA-CPG also includes the ability to model five classes of waste forms for shallow-land disposal simulations. Inventory and characteristics are input for each of the five classes of waste and modelled concurrently.

Detailed site parameters are not required for PRESTO-EPA-CPG. The level of detail for groundwater is velocity. Thus, detailed representations of the groundwater flow field are not possible. However, a large number of parameters are required for calculations related to the other pathways.

Waste form/source needs:

Inventory, waste density, container dimensions, and lifetime information are used as inputs. The inventory must be specified as absorbing, activated, trash, solidified, or incinerated/solidified wastes. The fraction of each waste class released into the groundwater each year must also be specified. The trash waste must be divided into the fraction that will be leached as absorbing material and the remainder that will be leached at a user specified rate.

The fraction of waste that is not in water tight containers must also be specified. K_d must also be specified for the different wastes and transport routes.

F4-3. RIP

Application:

System-Level Pathways Code.

References:

[F44] RIP - Integrated Probabilistic Simulator for Environmental Systems, Golder Associates, March 1998.

User manual:

Same as reference. [F44].

Summary:

RIP is PC based software program which probabilistically simulates the release, transport and fate of mass within complex engineered and/or natural environmental systems. RIP is a system level code and was specifically designed to provide systematic framework for organising and quantifying the current knowledge regarding all important aspects of an environmental system in order to provide insight as to the controlling parameters, processes and events. The software allows the user to explicitly represent the following processes:

(1) Release of mass from specified sources taking into account the failure of containers in which the contaminants are disposed, degradation of any materials in which the contaminants are bound, solubility constraints and partitioning of contaminants between various media.

(2) Physical transport of contaminants through multiple transport pathways within an environmental system.

(3) Biological transfer of contaminants within or between organisms.

Waste form/source needs:

Within RIP there are two ways to introduce contaminant mass into the system:

(1) An initial mass of contaminant(s) or a rate of addition of mass can be directly specified at one or more locations within the system.

(2) The user can define the properties of one or more sources and based on these properties the code will compute rates of mass release from source for each contaminant species.

The properties and characteristics, which must be specified for each source are the inventory, containment, waste matrix, mass transfer properties and connections to the environmental systems.

F-4.4. GTM 1

Application:

System-Level Pathways Code.

References:

[F45] NEA PSAC User Group, PSACOIN Level E Intercomparison, NEA/OECD, (1989).

[F46] NIES A., PSACOIN Level 1a, Case Specification, Questionnaire and Example Results.“ GSF Braunschweig, Germany (1990).

User manual:

[F47] PRADO, P., User’s Manual for the GTM-1 Computer code , CIEMAT, ITN, EUR 13925 EN, February (1991).

Summary:

The GTM-1 Code was developed for the assessment of radionuclide transport by the groundwater through geologic formations whose properties can change along the pathway. This code solves the transport equations by finite differences Method (Crack-Nicolson Scheme). It was developed for specific use within Probabilistic System Assessment (PSA) Monte Carlos code. The first application of GTM-1 was within the LISA (Long term Isolation System Assessment) code.

The GTM-1 is available as an independent model, which includes various submodels simulating a generic multibarrier disposal system. This code has been tested with the PSACOIN benchmark exercises from PSAC User Group (OECD/NEA). The code is available in the NEA data bank, NEA number 1400/01.

GTM-1 is coded in Fortran 77, following a structured program approach, quality assurance criteria have been followed on its development.

The code includes two near field submodels, a geosphere submodel (main model) and a simple biosphere submodel. The user can easily replace the near field and biosphere models allowing different approaches to be included.

Waste form/source needs:

Inventory, decay constant, leach rate and containment time information are used as inputs. Two simple sources models are included in this code, the first one only consider the chain decay trough the bateman decay equation (Classical) and the second one includes an exponential leaching term once the containment fails. This model follows the Level E test case exercise (PSAC, 1987) specifications.

APPENDIX G: OVERVIEW OF DATA ACQUISITION TECHNIQUES

This appendix contains information about different data acquisition techniques, which can provide the site, disposal facility design or waste form specific data needed for the computer codes used in the safety assessment procedure. The list is not intended to be complete because of the wide variety of data required by different codes. However, the appendix does aim to cover a range of the acquisition techniques that can be used to derive frequently used data.

G-1. PRECIPITATION DATA

Measurement of the precipitation rate at a site specific location can be performed with a precipitation gauge, which basically consists of a receptacle with vertical walls and an opening at the top with a specified area. The ratio of the volume collected in the receptacle during a specified period of time to the area of the opening at the top of the receptacle gives the estimate of the precipitation rate at a specific location and time. In principle, any receptacle with an open collector area of known dimensions, plus a volume measuring device can be used as a precipitation gauge. However, because of some operational features of these devices, unless they are of the same shape and dimensions and similarly exposed, precipitation rate measurements are usually not comparable [G1]. The standard precipitation gauge adopted by the U.S. National Weather Service has a collector (receiver) with a 20.3 cm diameter and can measure the precipitation to the nearest 0.25 mm. Two types of precipitation gages can be used, recording and non-recording. The recording gauge, the most commonly used, records on a strip of paper, paper punch, or data logger every 0.0254 cm of precipitation along the time scale. The recorded data are then reported as an:

- Average annual precipitation sum;
- Highest annual precipitation sum;
- Lowest annual precipitation sum;
- Highest precipitation sum in 24 hours;
- Monthly precipitation sum (average, maximum, minimum).

According to [G2] a network of five to ten gages per 260 km^2 is usually required in urban areas to define precipitation variability. The maintenance costs of such networks are high and, therefore, for a particular application, it is usually more convenient to rely on data collected locally from existing networks with gages already installed near the site of interest. Local rain gauge networks could serve as a first source of information on the precipitation rate at the site. On a larger scale, information on the precipitation rate could be obtained from national networks. Data on the point estimates of precipitation rates obtained from either local or national networks can be used to estimate the average areal precipitation rate over a specific area. The areally averaged values of the precipitation rate can be derived by three methods [G2]: arithmetic mean, the Thiessen polygon method, and the isohyetal method.

The arithmetic mean of the point precipitation rates provides the simplest and most straightforward way to obtain an estimate of the area precipitation rate at a particular site. For cases in which the gages are uniformly distributed and the point values have minimal variations, this method provides satisfactory results.

The Thiessen polygon method consists of areally weighting the point precipitation from each gauge. This is the most commonly used method, although not the most accurate. The isohyetal method consists of drawing contour lines of equal precipitation (isohyets) and areally weighting the average precipitation between pairs of contour lines crossing over the area of the site being considered. It is the most accurate among the methods for determining areally averaged values of the precipitation rate but requires an extensive gauge network to draw the isohyets accurately.

G-2. EVAPOTRANSPIRATION

Evapotranspiration is another that affects the water balance. Evaporation is the net transfer of water from the liquid phase to the vapour one. Transpiration is the process by means of which plants remove moisture from the soil and release it to the atmosphere as vapour. Evapotranspiration, a combination of the above two processes, is the term used to describe the total water removal from an area partly covered by transpiration, evaporation from soil (actually from the water present in the void space of unsaturated soil), from snow, and from open water surfaces (lakes, streams, and reservoirs).

The evapotranspiration process is fundamentally governed by the meteorological conditions at the site, as well as by the properties of the soil/plant system.

Meteorological parameters such as air temperature, wind speed, atmospheric pressure, air humidity, and exposure to the sun, all have an important role in determining the evapotranspirational demand at a specific location and time of year. However, it is the amount of water available in the root zone of the soil that limits the occurrence of the evapotranspiration process. Thus, the power of the atmosphere to extract water from the ground surface because of evaporation decreases as the moisture content of the soil decreases. The smaller the moisture content is, the more strongly the water is bound to the porous matrix of the soil because of capillarity, and thus more energy is needed to extract it.

Transpiration is also limited by the availability of water at the root zone, the ability of the soil to supply and transmit water toward the root zone, and the ability of the root system to absorb water from the soil in its vicinity. Below a certain value of soil moisture called the wilting point, the roots of the plants are not able to extract water from the soil, and the transpiration process is broken, resulting in dehydration and wilting. Therefore, as a combination of evaporation and transpiration, the actual evapotranspiration at a specific site depends on external climatic conditions and on the type and density of vegetation covering the ground surface as well as on soil moisture, root distribution, and other soil properties.

The concept of the "potential evapotranspiration rate," ET_{pr}, has been introduced into the hydrology literature to represent the so-called "climatic demand" for water, independently of the transient properties of the soil [G3]. As such, the potential evapotranspiration rate, ET_{pr} (or the evaporating power of the atmosphere), is defined as the evapotranspiration rate that occurs on the ground of a land area totally covered with vegetation and where sufficient water is continuously available for the needs of plants. The actual evapotranspiration rate, ET_r, is then a function of the potential evapotranspiration rate, ET_{pr}, and the quantity of water available in the root zone of the soil. Where there is an excess of water in the root zone, the value of ET_r is at its maximum, equal to ET_{pr}, and the excess water percolates through the soil toward the groundwater system. During a water shortage period, however, the value of ET_r becomes lower than ET_{pr}, with no resulting percolation.

There are many methods of measuring or estimating the actual (ET_r) and the potential (ET_{pr}) evapotranspiration rate. However, no one method can be used for all purposes [G-4]. Most of the methods used for estimating ET_r can also be used for estimating ET_{pr}, provided that the available water supply is sufficient for the area under observation during the duration of the test. These methods can be classified into three broad categories: (1) the theoretical approach, based on physical principles governing the process; (2) the analytical approach, based on conservation principles, either as a mass or as an energy balance; and (3) the empirical approach, based on experimental results expressing the correlation between measured evapotranspiration and local climatic conditions.

A generic description of various methods used for measuring evapotranspiration can be found in [G4]. For example, the lysimeter method consists of using a large barrel (also called a tank or evapotranspirometer) with about a 1-m diameter and a 2-m depth that is filled with soil and buried in the ground so that its top is flush with the ground surface. Individual crops and/or natural vegetation are grown on and around the lysimeter. The evapotranspiration rate can then be determined on the basis of the mass balance by measuring the infiltration flux seeping out of the bottom of the lysimeter and the rainfall rate. The loss of water necessary to maintain satisfactory plant growth represents the evapotranspiration. When operated properly, the lysimeter can provide reasonably reliable values of potential evapotranspiration. However, reliable measurements of actual evapotranspiration (particularly when it is much lower than the potential) are rarely attainable because of the difficulty in maintaining comparable soil moisture and vegetation cover conditions on and around the lysimeter.

Because of the inherent difficulties of field methods for measuring evapotranspiration, several empirical formulae have been developed to relate the potential evapotranspiration to some readily available climatic data, such as temperature, sunshine, wind velocity, and so forth.

The data are acquired from the meteorological station close to the waste disposal facility site.

G-3. HYDRAULIC CONDUCTIVITY

G-3.1. Unsaturated Zone

Hydraulic conductivity is one of the hydraulic properties of the soil; the other involves the soil's fluid retention characteristics. These properties determine the behavior of the soil fluid within the soil system under specified conditions. More specifically, the hydraulic conductivity determines the ability of the soil fluid to flow through the soil matrix system under a specified hydraulic head (gradient); the soil fluid retention characteristics determine the ability of the soil system to retain the soil fluid under a specified pressure condition. The hydraulic conductivity depends on the soil grain size, the structure of the soil matrix, the type of soil fluid, and the relative amount of soil fluid (saturation) present in the soil matrix. The important properties relevant to the solid matrix of the soil include pore size distribution, pore shape, tortuosity, specific surface, and porosity. In relation to the soil fluid, the important properties include fluid density, and fluid viscosity.

G-3.2. Saturated zone

The hydraulic head at a point in the saturated zone can be measured in the field by installing a piezometer at the site. A piezometer is basically a tube or pipe long enough to be introduced through the unsaturated zone down into the saturated zone. Its walls must be completely sealed along all its length, but it must be open to the atmosphere at the top and to the water flow at the bottom. The water level measured inside the piezometer, as compared with a defined reference level (such as mean sea level), gives the hydraulic head of the aquifer at the point of measurement. The distribution of the hydraulic head in a groundwater system is actually three-dimensional. Thus with the installation of three or more piezometers spatially distributed in an aquifer, it is possible to determine the spatial distribution of the hydraulic head at the site. By knowing the distances between the piezometers, the hydraulic gradient of the dominant aquifer flow at the site can be evaluated [G5]. Because of the spatial variability usually found in the geological formations, saturated hydraulic conductivity values also show variations throughout the space domain

G-4.Effective porosity

In natural porous systems, such as subsurface soil, where the flow of water is caused by capillary, molecular, and gravitational forces, effective porosity can be approximated by the specific yield, which is defined as the ratio of the volume of water drained by gravity from a saturated sample of soil to the total volume of soil. The most accurate means of obtaining effective porosity data is by conducting site specific field tracer tests. These tests, however, are time consuming and may not significantly reduce the uncertainty associated with the effective porosity. Since the greatest source of uncertainty relative to transport is typically the distribution coefficient. It is generally necessary to estimate effective porosities from the literature.

G-5 Molecular diffusion coefficients

The laboratory determination of diffusion coefficients is generally based on Fick's second law of diffusion. The measured diffusion coefficient is not a pure molecular diffusion coefficient in solution but is generally referred to as the apparent diffusion coefficient. There are three fundamentally different methods to determine the apparent diffusion coefficient [G6]: two transient and one steady state.

Method I - air-dried soil is compacted in a steel ring prior to placing in a cylindrical diffusion cell. The soil is then de-aired using a vacuum and subsequently subjected to a hydraulic gradient to achieve saturation. Following saturation, development of a soil with homogeneous microstructure is achieved by contacting both end of the soil with the selected solution via porous plates. After some time the tracer is added to the solution at the one end of the specimen and circulated through the porous plate in contact with the soil. The tracer concentration and water content in the soil profile are determined after the pre-defined diffusion period, when the soil is removed from the diffusion cell and sliced and the tracer concentration determined.

Method II - with this technique the tracer-free soil is contacted with either an impulse tracer source or a planar tracer source of limited extent in the soil. Two methods of specimen preparation are used:

- Method II.A (planar source) - the water-saturated, tracer-free soil is prepared in the same manner as that described in Method I. The planar source is obtained by first making a clay slurry: drops of this slurry are then dried on a glass plate. The dry clay residue forms a thin clay layer. The solution containing the tracer is dropped on this layer and evaporated to dryness. The clay layer is removed from the glass plate and then placed in the middle of the diffusion cell separating the two identical tracer-free soil specimens. The entire diffusion cell is then submerged in the solution for diffusion. After a predetermined diffusion time, the soil specimens are sectioned into thin slices and the tracer concentration determined.

- Method II.B (impulse source) - in this method for a selected soil density, a predetermined amount of air-dried soil is mixed with an appropriate amount of the solution, with and without tracer. The two soils are then compacted to the same density. The compacted soil specimens are then allowed to equilibrate in a water-tight cell. Using this preparation technique, the soils will be less saturated than that in Method I. After the equilibration period. the tracer-free and tracer-containing soil specimens are brought in contact inside the diffusion cell for diffusion. Good contact is assured by placing a thin bentonite paste between the specimens. At the end of the experiment, the specimens are sectioned into slices and the tracer concentration and water content are analysed.

Method III - the preparation of the tracer-free soil specimen and diffusion experiment is similar to Method I. In addition to the analysis of the tracer concentration within the soil specimen, the temporal change in tracer concentration in the initially tracer-free solution is measured. This provides an estimate of the cumulative amounts of tracer diffused through the soil specimen.

G-6. DISTRIBUTION COEFFICIENTS

G-6.1. Batch method

Distribution coefficients can be measured in laboratory by the batch method with any radionuclide on any soil material or rock, independent of the porosity, brittleness, or other properties of the soil or rock. In most instances, the soil material or rock is continually agitated to facilitate mixing and contact. At specified times, to approach equilibrium conditions, the solid and solution are separated and the resultant distribution of the radionuclide is determined. In the batch system, radionuclide desorption and adsorption are affected by the following: agitation effects [G7]; solid-liquid separation techniques; and limitation of analytical determination, that is, multiple species of soil or rock cannot be differentiated if present [G8].

Because the distribution coefficient varies with the solution-medium ratio, it is also recommended that determination of the isotherm by making several runs with different ratios of solution to geomedium may be necessary. To demonstrate that a steady state is attained in this short term test, each set of samples should be run in triplicate at a minimum. The soil solution mixtures in each contact tube should be gently agitated on a laboratory shaker/rotator for a minimum of 6 hours for every three-day portion of the contact period. The contact periods should be for a minimum of 3 days, and the longest should extend to 14 days or longer. The contact periods should differ by at least a three-day period. During the final one or two days of the contact period, all mixtures should be allowed to stand and settle. The soil solution mixture should be separated by centrifugation at a minimum setting of 1,400 g for 20 minutes.

G-6.2. Column experiments

Column experiments can be used to simulate the migration of radionuclides through soils under saturated and/or unsaturated conditions. They allow observation of radionuclide migration rates without significant soil particle alteration caused by grinding, as in batch experiments, and produce more representative site specific results. However, even removing a core sample to the laboratory results in alteration of the soil from its field condition. Typical equipment used in column experiments include a reservoir to the column, a cylindrical holder to contain the crushed or intact soil being tested, and a sample collector for the column effluent. For experimentation on intact and fissured soil with low permeability, high-pressure apparatus has to be used. The associated equipment costs, time constraints, experimental complications, and uncertainty in data reduction usually discourage potential users of the column system. Several operational problems of column experiments have been observed by numerous investigators: (1) homogeneity of column packing [G9, G10]; (2) potential short-circuit effects [G11, G12] and (3) residence time required for experimentation.

The K_d values are dependent on the soil's physical and chemical characteristics, which in themselves, do not necessarily remain constant over the long term because soils are dynamic systems. Soil properties affecting the distribution coefficient include the texture of soils (sand, loam, clay, or organic soils) [G13], the organic matter content of the soils, pH values [G14], the soil solution ratio [G15], the solution or pore water concentration [G16, G17, G18, G19], and the presence of competing cations and complexing agents [G16, G17, G20, G21, G22, G23].

G-7. LEACHING

Leaching occurs when water contacts a solidified waste. Leach testing has been recognized as a primary technique for the evaluation and comparison of solidified waste forms. Even so, the situation remains complex for several reasons [G24].

— Leaching can proceed by several concurrent mechanisms such as diffusion, dissolution, corrosion, etc., the relative importance of which may change with time, temperature, substances dissolved in the water, matrix material, the radionuclides of interest, and other variables.

— The actual leaching conditions which a solidified waste form will encounter during its sound life (i.e., the time during which the waste form meets the specifications for all applicable parameters) are not precisely known, with postulated conditions varying widely.

— Investigators of waste forms have tended to use leach testing procedures unique to their own studies, making comparison difficult.

The test set forth in [G24] is short term and simple. It does not attempt to simulate exactly the actual conditions for contact of the waste forms with aqueous leachants; the variables are too many. It does not utilize accelerating conditions such as elevated temperatures, nor does it reproduce a specific natural environment. The test consists of a procedure in which the leachant is sampled and replaced at designated intervals. The procedure permits the accumulation of sufficient data in a reasonably short time for quality assessment purposes. The data obtained by the procedure of this standard are expressed as a material parameter of the leachability of each leached species. This parameter is called "Leachability Index" (L). It has a specific meaning for each tested solid. It expresses the leaching data in terms of mass-transport theory, but without implying that the long term leaching mechanisms are known. The latter can only be determined by independent, long term leach testing, performed as part of generic studies for the type of solid under consideration.

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APPENDIX H: EXAMPLES OF APPROACHES USED FOR UNCERTAINTY AND SENSITIVITY ANALYSIS

H-1. AECL

The Preliminary Safety Analysis report (PSAR) for the Intrusion Resistant Underground Structure (IRUS) [H1] provides a comprehensive analysis of safety issues concerning a low-level radioactive waste disposal facility.

The sources of uncertainties that are considered are:

(1) Future evolution of the IRUS facility established through a Features, Events and Processes (FEPs) analysis and relevant human activities;
(2) Model conceptualization where site specific information and expert opinion were used to build the NSURE model;
(3) Numerical and coding errors; and
(4) Parameters values. The code SYVAC3 was used in the deterministic mode and for each simulation used a parameter value chosen by the assessor. The parameter values were selected according to the following principles:

— Radiological and chemical consequences would not be underestimated;
— The values were consistent with assumptions made in modelling IRUS; and
— The values were consistent with the assumptions defining the scenarios being assessed.

Sensitivity analysis was used to quantify the effects of changes in single parameter values on the results of interest, in particular the annual dose to a representative member of the receptor group.

Also pseudo-random sampling methods were used to investigate the impact of changing parameter values on the dose estimates.

H-2. EUROPEAN COMMISSION

The MUNVAR (Review on Development of Methodologies for Modelling with Uncertainty and Variability Project [H2], a study sponsored by the European Commission, extensively investigated the types of uncertainties encountered in modelling the possible future behaviour of radioactive waste disposal facilities and techniques for handling them, including fuzzy logic as an alternative to probabilistic calculations.

The objective of the project was to review and investigate the types of uncertainties encountered when modelling the possible future behaviour of prospective radioactive waste repositories and to consider techniques for handling them.

According to MUNVAR report [H2], uncertainty analysis is well developed for Type A parameter uncertainty with the use of probabilistic safety assessment (PSA) techniques. Uncertainties in the future conditions are generally handled by scenario approach or by simulations; however, the assignment of probabilities to scenarios has proved difficult , and expert judgment is the only way to resolve them. The Fuzzy set approach has been used to combine expert opinions of all types, and it was demonstrated that this approach can also be used for parameter uncertainty.

H-3. BNFL

The approach is being applied to the Post-Closure Safety Case (PCSC) for the Drigg near surface low level radioactive waste disposal facility is summarizedd below. More information is provided in [H3].

The overall approach to uncertainty is presented in the Safety Case Context and is strongly driven by regulatory requirements set out in the UK published guidance [H4]. It is recognized that uncertainties must be systematically identified, assessed and reduced where possible. The approach is also based on a combination of quantitative and qualitative aspects.

The qualitative approach seeks to make explicit all decisions made and assumptions adopted in the course of the assessment. These are identified as an on-going activity in the work leading up to, and whilst implementing, the PCSC. An audit trail for the assessment is maintained and justifications provided for decisions and choices made.

The quantitative approach to uncertainty encompasses a range of methods. These may include simple scoping calculations, a number of deterministic modelling approaches or probabilistic simulation studies. The choice of approach is influenced by the Safety Case Context and also reflects the stage of development of models, the quality and availability of data and the resources available.

Key aspects of the approach are as follows.

- Identification of uncertainties is driven by the application of a systematic, auditable approach to the safety assessment which utilizes the ISAM FEP database. FEP interactions are identified at a more detailed level using tools such as interaction matrices; and
- Classification of uncertainties into scenario, conceptual model and parameter uncertainty.

A number of different scenarios representing classes of possible futures are assessed. The scenarios selected must be sufficiently representative and adequately justified by using a well-defined screening methodology. Systematic scenario derivation is based on identification of relevant external FEPs (EFEPs), EFEP screening and EFEP modelling at different spatial scales.

Conceptual model uncertainty (CMU) is addressed through systematic disaggregation of the process system to identify detailed FEPs using interaction matrices. Each identified FEP is associated with a CMU form which records how the FEP is dealt with in current assessment models, justifies the approach taken, considers alternative assumptions and provides other supporting information.

Parameter input forms derived from the ISAM example are used to provide a record of data sources and the recommended parameter value with justification. The forms also record the range of uncertainty for the parameter and its estimated significance with respect to the safety assessment endpoints. This information aids prioritization of assessment calculations.

The safety assessment is undertaken through the deterministic modelling of a suite of calculation cases, some of which are specifically designed to address parameter uncertainty by considering the effect of parameter value variations on assessment endpoints. With a large number of parameters included in the assessment models, the potential number of different combinations is considerable. Therefore, developing a representative programme of calculation cases is a challenging task and prioritization on the basis of significance and range of uncertainty is crucial.

Reduction of uncertainties, which have a significant impact on the safety assessment, is addressed by inclusion of a forward programme of work as an integral part of the safety case.

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APPENDIX I: PROPOSED CONTENT OF A SAFETY ANALYSIS REPORT

As part of the work of the Confidence Building Working Group, a review of the contents' lists of Safety Assessment Reports for a range of near surface disposal facilities was undertaken. The review showed that there was much commonality in the contents' lists. In light of the review, the following generic contents' list was developed.

1. **Introduction**
2. **Background**
    - *2.1. Waste Management Practices*
        - 2.1.1. Current Practice
        - 2.1.2. Strategy for Future Practice
        - 2.1.3. Waste to be Emplaced
    - *2.2. Safety Assessment*
        - 2.2.1. Safety Assessment Philosophy
        - 2.2.2. Safety Assessment Goals
        - 2.2.3. Safety Assessment Process
            - 2.2.3.1. Systematic Review
            - 2.2.3.2. Dose and Risk Assessment
            - 2.2.3.3. Environmental Impact
3. **Facility Description**
    - *3.1. Site Characteristics (Description)*
        - 3.1.1. Location (Geography)
            - 3.1.1.1. Introduction
            - 3.1.1.2. Requirements
        - 3.1.2. Functional Objectives
        - 3.1.3. Geology
            - 3.1.3.1. Regional Geology
            - 3.1.3.2. Geology of the Site
                - 3.1.3.2.1. Structural Features
                - 3.1.3.2.2. Potential for Seismic Activity
                - 3.1.3.2.3. Evidence for Volcanism
                - 3.1.3.2.4. Local Stratigraphy
                - 3.1.3.2.5. Flooding
        - 3.1.4. Hydrology
            - 3.1.4.1. Regional Hydrology
                - 3.1.4.1.1. Surface
                - 3.1.4.1.2. Subsurface

3.1.4.2. Hydrology of the Site
3.1.4.2.1. Surface
3.1.4.2.2. Subsurface
3.1.4.2.3. Water Quality of the Uppermost Aquifer
- Aquifer Geochemistry
- Aquifer Contamination
3.1.5. Meteorology
3.1.5.1. Climate
3.1.5.2. Precipitation
3.1.5.3. Temperature
3.1.5.4. Evaporation
3.1.5.5. Wind
3.1.6. Demography
3.1.7. Land Use
3.1.7.1. Geological Resources
3.1.7.2. Natural Resources (Mineral Resources)
3.1.7.3. Water Supply
3.1.7.4. Agriculture
3.1.7.5. Soil Characteristics
3.1.8. Ecology
3.1.8.1. Flora
3.1.8.2. Fauna
3.1.9. Radiological Environment
3.1.10. Nearby Facilities
3.1.11. External Man-made Threats

3.2. Facility Description (Design and Construction)

3.2.1. Introduction
3.2.2. Requirements (Functional)
3.2.2.1. Design Objectives
3.2.2.2. Minimize Contact between RAW and Water
3.2.2.3. Maintain Long term Integrity
3.2.2.4. Resist Inadvertent Intrusion
3.2.2.5. Restrict Loss of Radionuclides
3.2.2.6. Minimize Long term Maintenance
3.2.3. Facility Overview
3.2.4. Facility Structure
3.2.5. Design Documentation
3.2.6. Geotechnical Considerations

- 3.2.6.1. General
- 3.2.6.2. Stability of the Soil Slope
- 3.2.6.3. Measures to Reduce Liquefaction Potential
- 3.2.6.4. Preparation of Foundation
- 3.2.6.5. Seismic Stability of the Soil Slopes

3.2.7. Description of the Facility Structure

- 3.2.7.1. Foundations
- 3.2.7.2. Walls
- 3.2.7.3. Roof (Cap)
- 3.2.7.4. Buffer Layer
- 3.2.7.5. Backfill Layer
- 3.2.7.6. Monitoring Shaft
- 3.2.7.7. Seismic Design of the Facility Structure
  - 3.2.7.7.1. Requirements
  - 3.2.7.7.2. Seismic Design Parameters
  - 3.2.7.7.3. Seismic Criteria
  - 3.2.7.7.4. Seismic Analysis
  - 3.2.7.7.5. Consequences of Exceedance
- 3.2.7.8. Design Features for Long term Integrity
  - 3.2.7.8.1. Concrete Cover
  - 3.2.7.8.2. Concrete Durability
  - 3.2.7.8.3. Cover Design
- 3.2.7.9. Process Description
- 3.2.7.10. Confinement Systems
- 3.2.7.11. Safety Support Systems
  - 3.2.7.11.1. Monitoring Programmes
  - 3.2.7.11.2. Fire Protection
  - 3.2.7.11.3. Maintenance Systems
  - 3.2.7.11.4. Safety Communication
  - 3.2.7.11.5. Alarm Systems
  - 3.2.7.11.6. Safety Structures, Systems and Components
- 3.2.7.12. Utility Distribution Systems -
  - 3.2.7.12.1. Electrical Power
  - 3.2.7.12.2. Emergency Power
  - 3.2.7.12.3. Water System
  - 3.2.7.12.4. Storm Damage System

3.3. Waste Characteristics

3.3.1. Waste Characterization

3.3.2. Waste Certification

3.3.3. Preliminary Inventory

3.3.4. Inventory Revisions

3.3.5. Waste Streams

3.3.5.1. Biological

3.3.5.2. Solid

3.3.5.3. Spent Sealed Sources

3.3.5.4. Mixed RAW

3.3.5.5. Other

3.3.6. Waste Treatment

3.3.7. Waste Storage

3.3.8. Waste Inventory Record Keeping

3.3.9. Comparison with the Requirements

4. Analysis of the Performance

4.1. Performance Assessment Methodology

4.1.1. Overview of the Analysis

4.1.2. Site Hydrology

4.1.3. Facility Performance

4.1.4. Shallow Subsurface Transport

4.1.5. Transport in Groundwater

4.1.6. Transport in Surface Water

4.1.7. Verification and Validation of the Methodology

4.2. Source Term

4.1.1. Radionuclide Screening Calculations

4.3. Pathways and Scenarios

4.3.1. Releases Pathways

4.3.2. Groundwater Pathways and Scenarios

4.3.2.1. Source Term Model

4.3.2.1.1. Mass Transfer

4.3.2.1.2. Boundary Conditions

4.3.2.1.3. Performance of the engineering Barriers

4.3.2.2. Radionuclide Migration in the Unsaturated Layers and Aquifer

4.3.2.2.1. Layers

4.3.2.2.2. Aquifer

4.3.2.3. Waste Form Performance

4.3.2.4. Effects of Ion and Radionuclide Complexants

- 4.3.2.5. H-3 Migration
- 4.3.2.6. C-14 Migration
- 4.3.2.7. Major Sources Contributing to the Dose
- 4.3.2.8. Groundwater Pathway Results and Conclusions

4.3.3. Human Exposure
- 4.3.3.1. Critical Groups
    - 4.3.3.1.1. Location
    - 4.3.3.1.2. Lifestyle
- 4.3.3.2. Receptors
- 4.3.3.3. Well Location and Characteristics
- 4.3.3.4. Exposure Scenarios for the Off-site Individuals
- 4.3.3.5. Exposure Scenarios and Pathways for the Inadvertent Intruders

4.3.4. Atmospheric Pathways
- 4.3.4.1. Degradation of Organic Compounds
    - 4.2.4.1.1. Gas Generation Rates
    - 4.2.4.1.2. Factors Controlling Gas Generation Rates
    - 4.2.4.1.3. Gas Generation Potential
    - 4.2.4.1.4. Archaeological Analogues
- 4.3.4.2. Post-closure Release of H-3 and C-14
- 4.3.4.3. Annual Dose and Risk
- 4.3.4.4. Results and Conclusions

4.3.5. Non-radiological Contaminants
- 4.3.5.1. Non-radiological Organic Contaminants
- 4.3.5.2. Non-radiological Inorganic Contaminants
- 4.3.5.3. Assessment Criteria for Non-Radiological Contaminants
- 4.3.5.4. Impacts on Human Health
- 4.3.5.5. Results and Conclusions

4.3.6. Non-human Biota
- 4.3.6.1. Dose to a Sensitive Indicator Species - Humans
- 4.3.6.2. Dose to a Generic Target Organism
- 4.3.6.3. Dose to a Specific Biota
- 4.3.6.4. Increase of Environmental Concentrations
    - 4.3.6.4.1. Variations in Background Concentrations
    - 4.3.6.4.2. Increase in Environmental Concentrations

- 4.3.6.5. Results and Conclusions

- *4.4. Assumptions*
  - 4.4.1. Source Term
  - 4.4.2. Site
  - 4.4.3. Waste
- *4.5. Conceptual Models*
  - 4.5.1. Conceptual Models of the Radioactive Waste Unit
  - 4.5.2. Conceptual Models of the Cap Performance
  - 4.5.3. Base Case Conceptual Model
  - 4.5.4. Subsided Case Conceptual Models – volatile radionuclides
  - 4.5.5. Subsided Case Conceptual Models – non-volatile radionuclides
- *4.6. Software*
  - 4.6.1. Performance Assessment Codes
  - 4.6.2. Description of the Codes (overview)
  - 4.6.3. Capabilities and Features of the Codes
  - 4.6.4. Quality Assurance, Verification and Validation
  - 4.6.5. Input Data Quality
  - 4.6.6. Master Input Database and Control
- *4.7. Dose Analyses*
  - 4.7.1. Requirements
  - 4.7.2. Analysis of the Human Exposure Scenarios and Pathways
  - 4.7.3. Discussion of Uncertainties in the Exposure Pathways Analyses
  - 4.7.4. Dose Analyses
    - 4.7.4.1. Water Pathways
    - 4.7.4.2. Direct Intrusion
    - 4.7.4.5. Comparison of the Results with the Regulatory Body's Requirements
- *4.8. Verification and Validation of the Methodology*
- *4.9. Sensitivity Analysis and Uncertainty Analysis*
  - 4.9.1. Analysis of the Disposal System Description
    - 4.9.1.1. Sensitivity and Uncertainty Analysis of Leaching from the Disposal Units
    - 4.9.1.2. Uncertainty of Shallow Subsurface Chemical Transport
    - 4.9.1.3. Uncertainty of Groundwater Transport
    - 4.9.1.4. Subjective Uncertainty
  - 4.9.2. Analysis of the Human Exposure Scenarios
    - 4.9.2.1. Scenarios for Transport of Radionuclides in Water
    - 4.9.2.2. Scenarios for Direct Intrusion in the Disposal Facility

5. Quality Assurance
  5.1. Programme Document Structure
  5.2. Project Organization
  5.3. Project Schedule
  5.4. Quality Assurance of Nuclear Safety Related Activities
  5.5. Quality Assurance of the Safety Assessment Project
    5.5.1. General
    5.5.2. Responsibilities
    5.5.3. Working Planning and Control
    5.5.4. Documentation and Record
    5.5.5. Independent Assessment
      5.5.5.1. Corrective Action
      5.5.5.2. Quality Assurance Records
  5.6. References
6. Results
  6.1. Interpretation of the Results
    6.1.1. Input Data
    6.1.2. Analysis of the Results for the Members of the General Public
      6.1.2.1. All Pathways Analysis – base case release scenario
      6.1.2.2. All Pathways Analysis – subsides case release scenarios
      6.1.2.3. Atmospheric Pathway – base case release scenario
    6.1.3. Analysis of the Results for the Intruders
      6.1.3.1. Agriculture Scenario
      6.1.3.2. Drilling Scenario
    6.1.4. Discussion
  6.2. Design Changes Required to Meet Performance Objectives
7. Licensing Approach
8. Public Communication
  8.1. Public Communication Programme
  8.2. Public Communication Methodology
    8.2.1. Briefings
      8.2.1.1. To the Local People
      8.2.1.2. To the Media
  8.3. Media Coverage
  8.4. Open Houses
  8.5. Information Dissemination
  8.6. Newsletters
  8.7. Public Information Centres

8.8. Public Presentations

8.9. General Observations

9. Conclusions

Summary

Comparison of the Performance Assessment Results with the Performance Objectives

10. Authors

10.1. Principle Investigators

10.2. Contributors

11. References

APPENDIX J: ISAM DOCUMENT REVIEW FORM AND PROCEDURE

1. Purpose

This instruction describes how to fill in the Document Review Form and apply it in safety assessment

2. Scope

This form is to be completed and apply for each document produced in the framework of Safety Assessment where QA is applied. The form is to be used when a complete draft has been completed and is circulated for external review.

3. Definitions

Author: The person (or persons) who produces the document. If there is more than one
Author: one should be selected as the contact person.

Authority: The person who has the ultimate responsibility for the project (project manager – working group leader).

Document Review: The set of documents made up by the document review record

Form (DRF) and reviewing procedure

Document Review: The document containing information about all the changes

Record (DRR) brought to the document being revised.

Review: Competent person who reviews the document.

4. References

This procedure was prepared by the ISAM Working Group on Confidence Building. It is based on procedures provided by AECL, Canada [1a] and Environment Agency, UK [2a].

5. Responsibilities

After the Author issues a new version of a document, it is the responsibility of the Authority to determine the list of Reviewers. It is the responsibility of the author to distribute the new version of the document and the DRF to the Reviewer(s). The Reviewer(s) have the responsibility to complete the DRR and return it to the Author. The Author proposes a new resolution and the Authority adopts the final resolution. It is also the responsibility of the Author to produce a new version of the document according to the adopted remarks by the Authority.

6. Procedure

.1. The Author prepares a document.

.2. The Authority determines the list of Reviewer(s).

.3. The Author distributes the new version of the document and the document review form (DRF) to the reviewers.

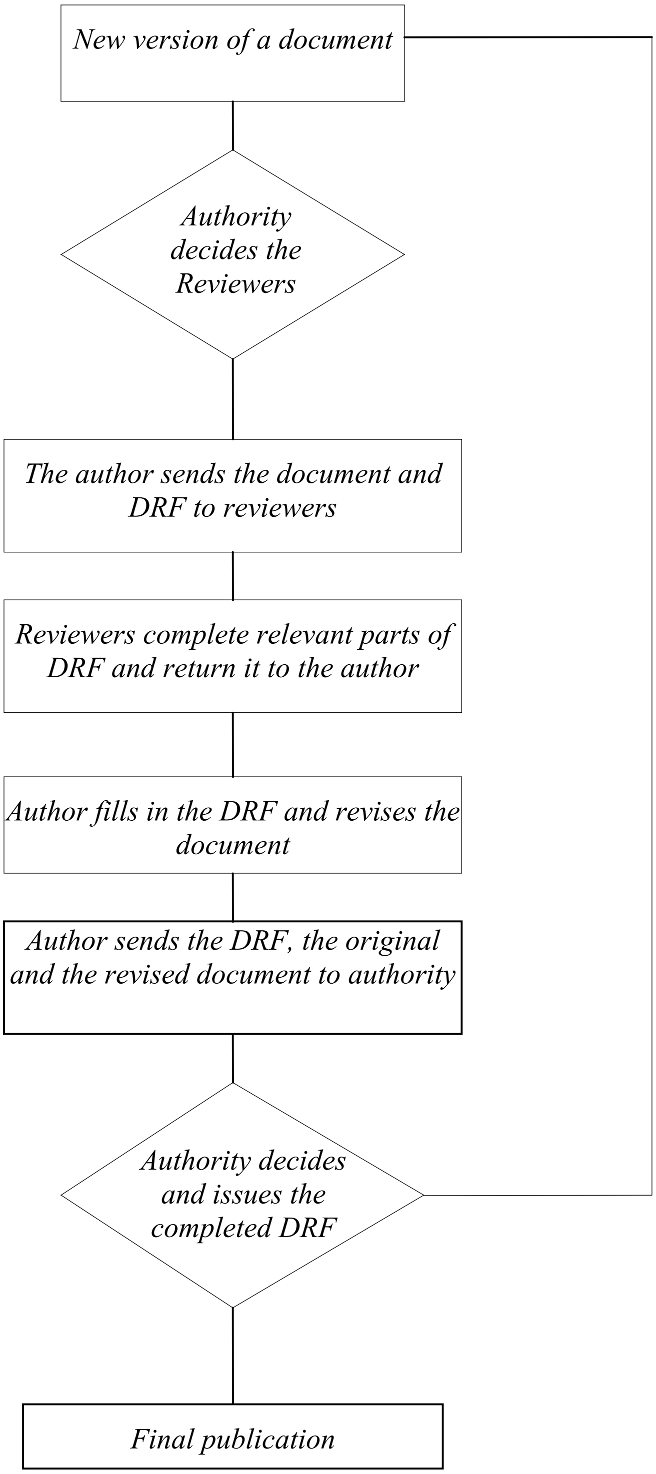
.4. The relevant portions of the DRR are completed by the Reviewer(s). The Reviewer(s) returns the filled DRR to the Author.

.5. The Author comments and fills the column "proposed resolution by the Author". At the stage, the Author is encouraged to communicate with the Reviewer(s). The Author presents both the original (version) and the revised document to the Authority, together with the DRF.

.6. The Authority adopts a resolution on the contentious issues in consultation with the Author(s) and the Reviewer(s), when possible and fills in the column "adopted resolution by the Authority" of the DRR. In more extraordinary circumstances the Authority may need to impose a resolution if no terms can be found acceptable to the Reviewers(s) and Author(s).

.7. A new version is written according to the adopted resolution.

Procedure Flowchart



Prepared by:	**Endorsed by:**	**Approved by:**
Name:	**Name:**	**Name:**
Date:	**Date:**	**Date:**
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Instructions for Filling in Document Review Record

Numbering corresponds to box numbering on the attached form.

1. ***Document Title and Version Number :*** *Each document will be assigned an ISAM identification number and revisions will be noted by sequential numbering starting with revision 0 – Rev. 0 for the first version to be reviewed.*
2. ***Reviewer :*** *include Name and Affiliation (company or organization they work for).*
3. ***Author :*** *Document author - if there is more than one author one should be selected as the contact person.*
4. ***Authority :*** *This is the person will ultimate responsibility for the project (project manager - working group leader).*
5. ***Date :*** *Date issued and date completed form must be returned.*
6. ***Comment number :*** *Sequential number of comments (1,2,3…).*
7. ***Section or chapter :*** *If applicable.*
8. ***Page, paragraph, line/sentence :*** *Reference to the exact location of the comment on the page - it is recommended that each line should be numbered.*
9. ***Comment/Issue :*** *Enough detail should be provided by the Reviewer so the comment is easily understood. In some cases this may be several sentences or up to a few paragraphs. Possible references with relevant information could also be given.*
10. ***Proposed resolution by Reviewer :*** *The Reviewer should propose possible routes to resolution, if possible specific items should be listed.*
11. ***Proposed resolution by Author :*** *The Author resolution should reflect an understanding of the comment and provide the specific details on how the comment is to be addressed.*
12. ***Adopted resolution by Authority :*** *In the normal case this will simply acknowledge the Author resolution. In more extraordinary circumstances the Authority may need to impose a resolution if no terms can be found acceptable to the Reviewer and Author.*

7. Remarks

.1. Timescale

The time for the review to be completed should be established based on the project schedule as well as the schedules of the Reviewer(s) and should reflect the length and content of the *document. Typically, one month for review should be adequate for most documents. The time an Author requires for addressing comments should also be scheduled because of the required interaction with the Reviewer and project Authority. The addressing of comments should be completed soon after receipt of comments while issues are still fresh in the minds of Reviewer(s).*

.2. Form Retention/Archiving

Completed forms should be retained by each the Authority, Author and Reviewer (for their comments) and official project files should be used for all the comments received. Filing should be in electronic and physical paper form.

8. References

[J1] DOLINAR, G. et al, "The preliminary safety analysis report of the IRUS Facility", AECL-MISC-295 (Rev. 4), October 1996.

[J2] DUERDEN, S.L. et al., "Regulatory assessment of an applicant's long term safety case in the UK", UK Environment Agency, January 1999.

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Comment Number	*Section or Chapter*	*Page Paragraph Line/sentence*	*Comment/Issue*	*Proposed Resolution by Reviewer*	*Proposed Resolution by Author*	*Adopted Resolution by Authority*
(6)	*(7)*	*(8)*	*(9)*	*(10)*	*(11)*	*(12)*

Prepared by:	**Endorsed by:**	**Approved by:**
Name:	**Name:**	**Name:**
Date:	**Date:**	**Date:**
Position:	**Position:**	**Position:**

APPENDIX K: ISAM PARAMETER INPUT FORM AND PROCEDURE

1. Purpose

This instruction describes how to use the ISAM Data Input Form in safety assessment.

2. Scope

This form is to be completed for each model parameter used in calculations that are included in a report where QA is applied. Data collection will typically begin at a very early stage in the assessment and those individuals responsible for collecting data should be aware of the requirements for parameter acceptance based on the input form. The actual use of the form may not be necessary or required until the assessment has progressed to a near final stage when external review of the results will take place. Prior to this stage this form may still be useful and could therefore be used at the discretion of the project manager.

3. Definitions

Assessor:	*The safety assessor who requires the parameter for the use in safety assessment*
Expert:	*The competent person who collects data and provides best estimate of parameter appropriate to for the purpose*
Reviewer:	*Competent person who reviews information provided through on form and confirms best estimate.*

4. References

This procedure was prepared by the ISAM Working Group on Confidence Building. It is based on procedures provided by AECL Canada and SCK-CEN Belgium.

5. Responsibilities

It is the responsibility of the project leader and assessor to initiate the process of data collection. They also determine the list of parameters and select appropriate experts and reviewers. The expert should respond to the request as defined on the parameter input form and consult with the assessor as required. The project leader should ensure that records of the completed forms are retained on file.

6. Procedure

6.1. The Assessor defines a parameter required for modelling. This might be a single parameter, a functional relationship (e.g. distribution coefficient as a function of pH) or a table of data. It may be useful for the assessor to prepare a list of required parameters organized according to model or submodel.

6.2. The Expert collects documentation (reports, publications, references etc) on the desired parameter in order to:

- *interpret the available information;*
- *determine the values for best estimates;*

- *determine the uncertainty and/or probability distribution function (PDF) taking into account measurement errors, difference in available data and possible variations in time and space; and*
- *provide references to essential data on the form.*

6.3. The Reviewer reviews the collected data, and confirms that:

- *the data is complete enough for the required parameter estimation;*
- *the best estimate is based on the data;*
- *the uncertainty and/or probability distribution function defined and*
- *the results are fit for purpose.*

6.4. If the Reviewer disagrees with the conclusions of the Expert, the Reviewer and the Expert should try to resolve their differences by discussion. If they cannot resolve their differences by discussion, the Assessor will make a decision on how to resolve the issue.

7. Instructions for Filling in Parameter Data Input Form

Numbering corresponds to box numbering on the attached form.

7. ***Study:*** *Provides the name for the safety assessment (e.g. study, test case) for which the data is requested.*

8. ***Data Request Description****: describes the general scope of the request e.g.,* ^{90}*Sr distribution coefficient (solid water) for shallow aquifers in sand.*

9. ***Parameter name and definition****: gives the symbol, name and if needed the definition of the parameter as it will be applied in the safety assessment. If appropriate identify radionuclide for which is applied.*

10. ***Units:*** *use of SI units if possible and other units if specified in the request.*

11. ***Model****: name of the model in the safety assessment in which parameter is applied, e.g., source term, human intrusion.*

12. ***Available data and references****: provide a listing of the relevant collected or measured parameter values and add the remarks concerning their applicability in the safety assessment.*

13. ***Best estimate value and justification****: The recommended best estimate value should be justified on a technical basis relating it's applicability to the data request. The assessor and expert should agree that a level of conservatism has been maintained in the selection the best estimate parameter value.*

14. ***Assigned uncertainty or probability distribution function****: Provide the type (normal, log-normal etc.) and parameters which are used to define the distribution. Information on how the distribution was derived (expert opinion, empirical evidence etc.) should also be included.*

15. ***Dependence on other parameters (correlation):*** *List other dependent parameters if applicable, should be specified.*

16. **Remarks:** *If possible/applicable information on the limitations of the use of the parameter should be provided.*

17. **Attachments:** *If the source for the parameter value is an internal report, memo these should be attached to the form. If the reference is a journal, or a report there is an option on whether to attach the form.*

8. Records

Originals of the form should be kept on file in the project records.

ISAM Parameter Input Form **No.**

1. Study:
2. Data request description:
3. Parameter name and definition (identify radionuclide if appropriate)
4. Units:
5. Model:
6. Available data and references:
7. Best estimate value and justification:
8. Assigned uncertainty or probability distribution function: *Type (e.g. uniform, normal) and attributes (e.g. mean, standard deviation, limits)*
9. Dependencies on other parameters (correlation):
10. Remarks:
11. Attachments

	Name	***Date***	***Signature***
Research			
Reviewed			
Approved			

ANNEX I: ISAM PROJECT ORGANIZATION

I.I. ISAM COORDINATED RESEARCH PROJECT

The ISAM project was aimed at improving safety assessment methodologies with primary focus on development of scenarios, models and confidence in safety assessment. It therefore organized in accordance with its main objectives.

I.II. SCENARIO GENERATION AND JUSTIFICATION WORKING GROUP

The group aimed to compare and review existing and currently developing methodologies on *scenarios generation and justification* for near surface disposal facilities, to improve approaches for systematic development of scenarios and to focus on their application to near surface disposal facilities. Any methods, which had been developed, were taken in full account. Since development of a FEPs list has been a common activity in many scenario generation methodologies, the development of a keyword *FEPs list* for near surface disposal facilities was one of the objectives of the working group. The ISAM aimed to ensure that its work complimented rather than duplicated that of other projects.

I.III. MODELLING AND DATA WORKING GROUP

The ISAM project focused on approaches, which could be used to formalize the process of conceptual model development and justification. Approaches were evaluated for their robustness in treating alternative *conceptual models* and on their ability to produce a defensible, traceable safety assessment. The ISAM project aimed to provide review and summary of the *mathematical models* and computer tools used in different test cases, noting the associated assumptions and limitations. The group focused on the main parameters and *data* related to the description of a disposal system, scenario development and justification; model formulation and implementation; and interpretation of results of safety assessment.

I.IV. CONFIDENCE BUILDING GROUP

The Confidence Building Group had the objective to review the main existing regulatory requirements and internationally agreed safety standards and criteria relevant to safety. Approaches to *sensitivity analysis* as a method for building confidence in results was another area of investigation. One of the tasks of the working group was to catalogue methods and tools that had been found useful in performing of sensitivity analyses. The group also reviewed different methods used for the *presentation and communication of results*. In addition to these areas explicitly mentioned above other measures providing confidence were the aim of the group, such as *quality assurance*. The ISAM project investigated the usefulness of these measures.

I.V. TEST CASES

The ISAM project was primarily focused on the methodological aspects of safety assessment with emphasis on the practical application of these methodologies. Two kinds of practical problems were addressed in the project. First, safety assessments associated with proposed facilities for future waste disposal were considered (Borehole Test Case) and second — safety assessments of existing facilities (Vault and RADON Test Cases). Each of these situations has common safety assessment problems, and each has its own sources of difficulties. In addressing these two kinds of problems, the ISAM project brought diverse experience and approaches together and has compared and improved them. As already noted, this was done by individual participants developing their own safety cases, and by all participants developing three "group" test cases. The group test cases provided a reference for participants when developing their own safety cases. They also provided the basis for open discussion of the many practical issues, which were encountered when undertaking an assessment with the aim of reaching consensus, in as many areas as possible.

The project was attended by specialists from the Member States, who had experience for technical activities related to safety assessments for near surface radioactive waste disposal facilities. The ISAM participants were experts from regulatory bodies, facility operators or developers, or from research organizations. In general they were actively involved in developing the methodology and test cases.

The ISAM project was overall managed by the Coordinating Group (see Fig. 2) that included the Chairperson, the Scientific Secretary, the Working Groups Leaders and a Co-ordinator for the group test cases. During the ISAM project, a number of persons fulfilled the role of Chairperson:

- Ms. A. Pinner of British Nuclear Fuels Plc (BNFL), United Kingdom (from 1997 to 1999);
- Ms. S. Voinis of Agence Nationale pour la gestion des Déchets Radioactifs (ANDRA), France (from 1999 to 2000); and
- Mr. D. Graham of United Kingdom Atomic Energy Authority (UKAEA), United Kingdom (from 2000 to 2001).

The Working Group and Test Case Leaders were:

- Scenario Working Group: Mr. J. J. van Blerk, NECSA and currently with AquiSim Consulting (Pty) Limited, South Africa;
- Modelling Working Group: Mr. P. Heilbron, Comissao Nacional de Energia Nuclear (CNEN), Brazil;
- Confidence Building Working Group: Mr. G. Dolinar, Atomic Energy of Canada Limited (AECL), Canada;
- Overall Test Cases: Mr. M. Kozak, Monitor Scientific LLC, United States of America;
- Vault Test Case: Mr. E. Kelly, British Nuclear Fuels Plc (BNFL), United Kingdom;
- RADON Test Case: Mr. A. Gouskov, MosNPO "RADON", Russian Federation, supported by Ms. B. Batandjieva (whilst with the Committee on the Use of Atomic Energy for Peaceful Purposes, Bulgaria); and
- Borehole Test Case: Mr. K. Vivier, Geoconsultants (PTY Limited) (GeoCon) and Mr. J. J. van Blerk, NECSA and currently with AquiSim Consulting (Pty) Limited, South Africa.

The IAEA officers responsible for the ISAM project were Mr. C. Torres-Vidal and Ms. B. Batandjieva.

ANNEX II: COMPILATION OF REGULATORY REQUIREMENTS

The information in Tables II.1 to II.9 was obtained from the responses received to the ISAM questionnaires. The information was transcribed directly from the responses in the period from 1998 to 2000, although there was no attempt to check the responses for accuracy. Multiple responses from the same country, but from different individuals, were sometimes conflicting (or contradictory).

TABLE II.1. ACTS AND REGULATIONS

COUNTRY	**ACTS**	**YEAR**	**REGULATIONS**	**YEAR**
Argentina	National Law of Nuclear Activity, Act No 24804 Radioactive Waste Management Regime (Act N° 25018)	April 1997 October 1998	Standard AR 10.1.1 - Basic Standard of Radiological Safety	1994
Australia			Code of practice for the near surface disposal of radioactive waste in Australia issued by the Australian National Health and Medical Research Council (NHMRC)	1992
Belgium	Law of 11.01.1991 (Belgian Official Journal of 12.02.1991) Law of 12.12.1997 (Belgian Official Journal of 18.12.1997).	1991 1997	The Royal Decree of 16.10.1991 (Belgian Official Journal of 22.11.1991). The Royal Decree of 28.02.1963, as amended	1991
Brazil	Law 7781 of June 27	1989	NORM CNEN-NE-6.05 - Radioactive Waste Management in radioactive Installations, November; NORM CNEN-NE-6.06 - Site Selection for Radioactive Waste Repositories, December; Technical Instruction IT-01/91 - Radiological Protection and safety for Final Disposal of Radioactive Wastes Stored in Abadia de Goiás, December DRAFT REGULATION FOR APPROVAL - Radiological Protection and Safety for Final Disposal of Low Level and Intermediate Level Radioactive Wastes,	1985 1989 1991 1992
Bulgaria	Act on the Use of Atomic Energy for Peaceful Purposes (AUAEPP), last amended in	1995	- Regulation No. 2 on the Cases and the Procedure of Notification of the CUAEPP on operational changes, events and emergency situations related to the nuclear and radiation protection (CUAEPP);	1988

COUNTRY	ACTS	YEAR	REGULATIONS	YEAR
			- Regulation No. 3 on Ensuring the Safety of Nuclear Power Plants during Design, Construction and Operation (CUAEPP); - Regulation No. 4 on Accounting for, Storage and Transport of Nuclear Material (CUAEPP, Ministry of Internal Affairs); - Regulation No. 5 on the Issuance of License on the Use of Atomic Energy (CUAEPP, 1993); - Regulation No. 7 on Collection, Handling, Treatment, Storage, Transport and Disposal of Radioactive Waste on the Territory of the Republic of Bulgaria (CUAEPP); - Regulation No. 8 on Physical Protection of the Nuclear facilities and Nuclear Material (CUAEPP, Ministry of Internal Affairs); - Basic Standards on Radiation Protection – 92 (CUAEPP), etc.	1988 1993 1993 1992 1993 1992
Canada	Atomic Energy Control Act, which established the Atomic Energy Control Board (AECB) Nuclear Safety and Control Act, 20th March 1997	1946 1997	Atomic Energy Control Regulations, August 1992	1992
Cuba	Nuclear Act (draft)	1999	Resolution No 168/95 (Ministry of Science, Technology and Environment. CITMA) Reglamento para la realizacion de las evaluaciones de impacto ambiental y el otorgamiento de las licencias ambientales Internal Regulation (CPHR ver donde aparece algo de evacuacion)	1995
Czech Republic	Law No. 18/1997 Coll. on Peaceful Use of Nuclear Energy and Ionising Radiation (Atomic Act). New Atomic Act (Law No. 13/2002 Coll.) will be valid from summer 2002 Law No. 17/1992 Coll. on Environmental Protection Law No. 244/1992 Coll. on Environmental Impact Assessment Law No. 28/1987 Coll. on State Supervision of Nuclear Safety and Nuclear Facilities	1997 (2002) 1992 1992	Decree of State Office of Nuclear Safety (SUJB) No. 142/1997 Coll. on Type Approval of Package Systems for Transportation, Storage or Disposal of Radionuclide Sources and Nuclear Material ... Decree of SUJB No. 143/1997 Coll. on Transport of Declared Nuclear Material and Radionuclide Sources Decree of SUJB No. 144/1997 Coll. on Physical Protection of Nuclear Material and Nuclear Facilities and on their Categorization Decree of SUJB No. 145/1997 Coll. on Evidence and Control of Nuclear Material Decree of SUJB No. 146/1997 Coll. on Definition of Activities Directly Influencing Nuclear Safety	1997 1997 1997 1997 1997

COUNTRY	ACTS	YEAR	REGULATIONS	YEAR
	Law No. 50/1976 Coll. on Areal Planning and Construction Regulations	1987	Decree of SUJB No. 147/1997 Coll. on Definition of List of Items and Items of Double Use for Nuclear Field	1997
		1976	Decree of SUJB No. 184/1997 Coll. on Requirements on Radiation Protection Assurance	1997
			Decree of SUJB No. 214/1997 Coll. on Quality Assurance by Activities Related to the Use of Nuclear Energy and Ionising Radiation	1997
			Decree of SUJB No. 215/1997 Coll. on Criteria for Sitting of Nuclear Facilities and Important Sources of Ionising Radiation	1997
			Decree of SUJB No. 106/1998 Sb.on Nuclear Safety and Radiation Protection Assurance during Commissioning and Operation of Nuclear Facilities	1998
			Decree of SUJB No. 195/1999 Coll. on Requirements on Nuclear Installations for Assurance of Nuclear Safety, Radiation Protection and Emergency Preparedness	1999
			Decree of SUJB No. 196/1999 Coll. on the Decommissioning Nuclear Installations or Workplaces with Significant and Very Significant Ionising Radiation Sources	1999
			Decree of the SUJB No. 324/1999 Coll., on Limits of Concentration and Amount of Nuclear Material for which Nuclear Liability Requirements does not Apply	1999
Italy			Decree N°230 (march 1995),	1995
			The Technical Guide N°26 on the Management of the Radioactive Waste	1987
Japan	"Law concerning regulation of nuclear material substances, nuclear fuel substances and nuclear reactors"		NSC established the upper bound concentration limits for low-level radioactive waste which is permitted to be disposed of into a near surface disposal facility	1987
	"Law concerning the prevention from radiation hazards due to radio-isotopes, etc."		NSC established the fundamental guidelines of licensing review of land disposal facility of LLW	1988
			NSC revised the upper bound concentration limits for low-level radioactive waste which is permitted to be disposed of into a near surface disposal facility (Second Interim Report)	1992
Korea	Atomic Energy Act		Enforcement Decree of the Atomic Energy Act	
			Enforcement Regulation of the Atomic Energy Act	

COUNTRY	ACTS	YEAR	REGULATIONS	YEAR
			Ministry of Science and Technology Notice - Criteria of the performance objective for the disposal of LILW - Siting Criteria on disposal site for LILW - Criteria for the design of LILW disposal facilities - Acceptance criteria for radioactive waste - Criteria for Quality Assurance on LILW disposal facility	
Lithuania	Law on nuclear energy Environmental protection law Law on management of radioactive waste (draft) Radiation protection law (draft)		Basic standards of radiation protection HN73-1997 Radiological safety rules for operation of NPP (It includes requirements for collection, transportation and disposal of RAW) (PRB AS-89, former USSR document) Sanitary regulations on management of radioactive waste (SPORO-85, former USSR document)	1997
Mexico			Nom-004-nucl-1994 “clasificacion de los desechos radiactivos” Nom-018-nucl-1995 “metodos para determinar la concentracion de actividad y actividad total en bultos de desechos radiactivos” Nom-019-nucl-1995 “requerimientos para bultos de desechos radiactivos de nivel bajo para su almacenamiento cerca de la superficie” Nom-020-nucl-1995 “Requerimientos para instalaciones de incineracion de desechos radiactivos” Nom-021-nucl-1996 “Pruebas de lixiviacion para especimenes de desechos radiactivos solidificados” Nom-022/1-nucl-1996 “Requerimientos para una instalacion para el almacenamiento definitivo de desechos radiactivos de nivel bajo cerca de la superficie parte 1. Sitio” G) nom-022/2-nucl-1996 “Requerimientos para una instalacion para el almacenamiento definitivo de desechos radiactivos de nivel bajo cerca de la superficie parte 2. Diseño” Nom-022/3-nucl-1996	1994 1995 1995 1995 1996 1996 1996

COUNTRY	ACTS	YEAR	REGULATIONS	YEAR
			“Requerimientos para una instalacion para el almacenamiento definitivo de desechos radiactivos de nivel bajo cerca de la superficie parte 3. Operacion y clausura”	1996
Romania	Law No. 111/ 1996 on Safe Performance of Nuclear Activities Law No. 137/1995 on Environmental Protection Law regarding the agreement of the Convention on Nuclear Safety/1995	1996 1995 1995	Decree for Romanian agreement of Convention regarding the fast notification of an nuclear accident and the Convention regarding the assistance in situation of an nuclear accident or radiological emergency. National Nuclear Safety Regulations. Nuclear Reactors and Nuclear Power Plants National Nuclear Safety Regulations. Radiation Protection National Standards National Nuclear Safety Regulations. Work Conditions with Nuclear Radiation Sources National Nuclear Safety Regulations. Radioactive Material Transport National Nuclear Safety Regulations. Physical Protection of Nuclear Materials National Nuclear Safety Regulations. Recording and Preservation of Nuclear materials and Facilities and Nuclear Related Materials National Nuclear Safety Standards regarding planning, preparation and intervention in case of the nuclear accidents and radiological emergency P 118-83- Fire Protection Technical Standards for Building Design & Construction.	1975 1976 1976 1976 1976 1975 1993
Slovenia	Act on Liability for Nuclear Damage (ZOJŠ - Zakon o odgovornosti za jedrsko škodo, Ur.l.- Off.Gazette SFRJ 22/78, 34/79), Act on Radiation Protection and the Safe Use of Nuclear Energy (ZVISJE - Zakon o varstvu pred ionizirajoèimi sevanji in o posebnih varnostnih ukrepih pri uporabi jedrske energije, Ur.l. - Off.Gazette SFRJ 62/84), The Environmental Protection Act, (Zakon o varstvu okolja, Ur.l.RS - Off.Gazette 32/93).	1978-79 1984 1993	on sites, method and time limits for examinations of contamination by radioactive materials (Z1), on the mode, the extent and the limits of the systematic examinations of radioactive material contamination in the surroundings of nuclear facilities (Z2), on the mode of collecting, accounting, processing, storing, final disposal and release of radioactive waste into the environment (Z3), on limits that must not be exceeded by radiation to which the population and those that work with sources of ionising radiation are exposed, on the measurement of the degree of exposure to ionising radiation of persons that work with the sources of these radiation and on the testing of the contamination of the working environment (Z6), on the maximum limits of radioactive contamination of the environment and the decontamination (Z9)	

COUNTRY	ACTS	YEAR	REGULATIONS	YEAR
			on the conditions for siting, constructions, commissioning, commencement of operation and operation of nuclear facilities (E1), on the compilation and contents of the safety report and other documentation necessary for the assessment of the safety of nuclear facilities (E2).	
Spain	Nuclear Energy Act (Law 25/1964) Nuclear Safety Council Creation Act (Law 15/1980)	1964 1980	Regulation of Nuclear and Radiation facilities (Dec 2869/1972) Health Protection Standard against Ionising Radiation (Royal Dec. 2519/1982, 53/1992)	1972 1982, 1992
United Kingdom	Environment Act 1995 Act 1974 (H&SaW-74),	1995 1974	Guidance on Requirements for Authorization of Disposal Facilities On Land For Low And Intermediate Level Radioactive Wastes, issued under the RSA Act 93, 'Disposal facilities on Land for Low and Intermediate Level Radioactive Wastes: Principles for the Protection of the Human Environment'. Sustainable development - The UK strategy. Cm 2426 HMSO London 1989. Department of the Environment. Review of radioactive waste management policy - final conclusions. Cm 2919, HMSO London July 1995 'NRPB (Vol. 4, No 1 1993) Board Statement on the Recommendations of ICRP 60', 'NRPB (Vol. 3, No. 3 1992) Board Statement on the radiological protection objectives for the land based disposal of solid radioactive wastes'. 'Tolerability of risk from Nuclear Power Stations' (1992) published by Her Majesty's Stationary Office. 'The Radioactive Material (Road Transport) (Great Britain) Regulations 1996. SI 1996 No 1350. ISBN 0-11-054742-X'. and 'The packaging, Labelling and Carriage of Radioactive Material by Rail Regulations 1996, SI 0-11-062921-3.' 'Environmental Assessment: A guide to the procedures. Department of the Environment and Welsh Office. HMSO, London 1989' (general principles are applicable to Scotland and Northern Ireland).	1997 1989 1995 1993 1992 1992 1996 1996 1989
United States of America	Nuclear Waste Policy Act of 1982 [Public Law 97-425], as amended in 1987 [Public Law 100-203], Low-Level Radioactive Waste Policy Amendments Act of 1985 [Public Law 99-240].	1982, 1987 1985	Regulations by the Environmental Protection Agency, 40 CFR 193 for low-level waste. 10 CFR, 60	

TABLE II.2. CLASSIFICATION OF RADIOACTIVE WASTE

Country	**Comments**	**Category**			
Argentina		low	intermediate	high level	
Australia	No data provided				
Belgium		A (near surface disposal)	B (deep geological disposal)	C (deep geological disposal)	
Brasil					
solid	surface exposure rate (μG/kg.h)	< 50	50-500	> 500	
liquid	concentration (Ci m^{-3}))	< 1	$1\text{-}10^{3}$	$> 10^{3}$	
Bulgaria		I category	II category	III category	
	equivalent dose rate (mSv h^{-1})	$3.10^{-3} – 3.10^{-1}$	3.10^{-1} - 10	> 10	
solid waste	specific alpha (Bq kg^{-1})	$7.10^{3} – 3.7.10^{5}$	$3.7.10^{5} – 3.7.10^{8}$	$>3.7.10^{8}$	
	specific beta (Bq kg^{-1})	$7.10^{-4} – 3.6.\ 10^{6}$	$3.6.10^{6} – 3.7.\ 10^{9}$	$> 3.7.\ 10^{9}$	
		LLW	ILW	HLW	
liquid	specific activity (Bq l^{-1})	$<3.7.10^{5}$	$3.7.10^{5} – 3.7.10^{10}$	$>3.7.10^{10}$	
Canada		low	intermediate	high level	
Italy		I category	II category	III category	
	decay (y)	Half life < 1year	Half life < few centuries to activity level 370 Bq g^{-1}	those not in I and II category	
Japan		LLW and gamma-ray emitting waste	HLW	TRU waste	Uranium waste
		Very Low Level Waste LLW Waste Exempted from regulation			
Lithuania		1	2	3	
	Dose rate (0.1 m) (mSv h^{-1})	$10^{-3} – 0.3$	0.3-10	> 10	
	Specific activity (Bq kg^{-1}) • alpha • beta	$7.4.10^{3} – 3.7.10^{5}$ $7.4.\ 10^{4} – 3.7.10^{6}$	$3.7.10^{5}$ - $3.7.10^{8}$ $3.7.10^{6} – 3.7.10^{9}$	$> 3.7.10^{8}$ $> 3.7.10^{9}$	
	Specific contamination (Bq/cm^{2}. min) • alpha • beta	$5 – 10^{3}$ $5.10^{2} – 10^{4}$	10^{3} - 10^{6} $10^{4} – 10^{7}$	$> 10^{6}$ $> 10^{7}$	

Country	Comments	Category			
Mexico		LLW	ILW	HLW	
		A B C			
Romania		not specified			
Slovenia		LLW (III category)	ILW (II category)	HLW (I category)	
	Specific activity (Bq m^{-3})				
	alpha	< 5.10^{9} (Ai/Iki ≥ 1)	5.10^{9} – 5.10^{14}	> 5.10^{14}	
	beta/gamma	< 5.10^{7} (Ai/Iki ≥ 1)	5.10^{7} – 5.10^{14}		
United Kingdom		Very Low Level Waste	Low Level Waste	Intermediate Level Waste	High Level Waste
	alpha		< 4 GBq/t	> 4GBq/t (without heating)	waste with significant rise of temperature, so this factor has to be taken into account
	beta/gamma	< 400 kBq/ 0.1 m^{3} < 40 kBq (single item)	< 12 GBq/t	> 12 GBq/t (without heating)	
United States of America		LLW	HLW	Transuranic waste	Uranium and Thorium Waste Spent Fuel
		RAW not HLW, spent fuel, transuranic, or uranium or thorium mill tailings	primary waste, either liquid or solid from chemical reprocessing of SNF	> 4 kBq/g long lived alpha THU RNs (solid or solidified waste)	residues resulting from extraction of uranium or thorium from any ore processed primarily for its sources material fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing

TABLE II.3. REQUIREMENTS ON THE TYPE OF WASTE

Country	**Waste**	**Matrix**	**Emplacement**
Argentina	site specific and established in the operating license - total activity disposes of - waste form - radionuclide limits	site specific and established in the operating procedures	
Belgium	- 400 l carbon steel container - heavy metal content to be studied	generally consists of: - cement - bitumen, or - polymer resin	concrete blocks (monolyth)- 2 to 4 containers
Bulgaria	- only solid or solidified waste are to be disposed of the disposed radioactive waste are to contain mainly beta or gamma emitting radionuclides with $T_{1/2}$<30 years (including Cs-137) and insignificant content of alpha radionuclides; - the specific alpha activity of the radioactive waste in average for the facility should be less than 370 MBq t^{-1}; - the max. specific activity of a solidified waste package should be 3.7 GBq t^{-1}; - the max. specific activity of Ra-226 and Th-232 in a solidified waste package should be 3.7 MBq t^{-1} and respectively 1.1 MBq t^{-1}; - the specific alpha activity of the waste in a package should be max. 0.19 MBq kg^{-1} and the specific activity of Ra-226 or Th-232 - 0.037 MBq kg^{-1}. In some cases is allowed solidified radioactive waste with specific activity 3.7-18.5 GBq t^{-1}. Additional requiremets:		

Country	Waste	Matrix	Emplacement
Cuba	have not been defined yet		
Czech Republic Richard facility	***Activity:*** - alpha (long lived) (Am-241, Pu-238, Pu-239) $< 10^9$ Bq m^{-3} - C-14 $< 10^{10}$ Bq/drum - other beta/gamma radionuclides to be derived - natural radionuclides - excluded ***Non-radioactive compounds:*** toxic, strongly corrosive, explosive and pyrophoric materials excluded	- concrete in 200 l drums - Effective dose rate (0.5m) for a drum-1mSv/h - drum surface contamination – 3kBq m^{-2} (alpha radionuclides) - drum surface contamination – 30kBq m^{-2} (beta/gamma radionuclides)	
Bratrstvi facility	- only natural radionuclides (e.g. Ra-226, Ra-228, Th-228, Po-210) - technogene radionuclides are excluded ***Non-radioactive compounds:*** toxic, strongly corrosive, explosive and pyrophoric materials excluded	- concrete in 200 l drums - Effective dose rate (0.5m) for a drum-1mSv/h - drum surface contamination – 3kBq/m^2 (alpha RNs) - drum surface contamination – 30kBq/m^2 (beta/gamma RNs	
Dukovany facility	mobile activity in a vault: - 2.4E12 Bq (for beta and gamma radionuclides) - max 2.3E8 Bq for Sr-90 - 7.8E11 Bq for Sr-90 - 2.2E11 Bq for Cs-137 - 3.9E6 Bq for Pu-239 - 2.3E6 Bq for Am-241	- dose rate on the surface of a barrel-0.9 Gy/h - leachability of a waste form-0.4% for activities above 200 MBq/l - 4% for activities from 0.02 to 200 MBq/l - not estimated for activities below 0,02 MBq/l	- activity in a vault-1300 times more than in a barrel - activity in a double row of vaults-112 times more than in a vault
	non-solidified waste form	max. 4 MBq in one barrel or double barrel with surface dose rate below 0,9 Gy/h	
Italy	- Radionuclide concentrations- not exceeding values of the Tab.3	- Compressive strength at least 5 MPa (UNI - Destructive tests for concrete) - Thermal cycling-after 30 thermal cycles (-40°C/+40°C) compressive strength must be at least 5 MPa - Radiation resistance-after an absorbed	

Country	Waste	Matrix	Emplacement
		dose of 108 rads compressive strength must be at least 5 MPa	
		- Fire resistance incombustible or self extinguishing according to the ASTM D 635-81 test method - Leaching rate- measurement according to long term leaching test ANSI 16.1 - Free liquids measurement according to ANSI/ANS 55-1 - Biodegradation compressive strength >5 MPa after biodegradation test resistance ASTM G21 and G22 - Immersion resistance compressive strength >5 MPa after 90 days of water immersion	
Japan	Activity limits (Bq t^{-1}):	Cement, polymers and bitumen	packages in 200 l drums
	Solidified waste (except for Waste (3)) **Large equipment (pumps, pipes, etc.)** C-14- $3.7.10^{10}$ Co-60-$1.11.10^{13}$ Ni-63-$1.11.10^{12}$ Sr-90-$7.4.10^{10}$ Cs-137-$1.11.10^{12}$ alpha emitters-$1.11.10^{9}$		
	Solidified concrete waste: C-14-$3.7.10^{10}$ Ca-241- $3.1.10^{9}$ Co-60-$1.11.10^{13}$ Ni-63-$1.11.10^{12}$ Sr-90-$7.4.10^{10}$ Cs-137-$1.11.10^{12}$ alpha emitters-$1.11.10^{9}$		

Country	Waste	Matrix	Emplacement
	Not solidified concrete waste: H-3-3.10^9 C-14- $1.1.10^8$ Ca-241-$1.5.10^5$ Co-60- 8.10^9 Ni-63-$7.2.10^9$ Sr-90-$4.7.10^6$ Cs-137-10^8 Eu-152- $3.6.10^8$ alpha emitters-$1.7.10^7$		
Mexico	no data provided		
Romania	no specific requirements		
Slovenia	no data provided		
United Kingdom	no data provided		
United States of America	CFR 10 Part 61.55 - < 1% liquid - stabilized (Band C category) - non-radioactive compounds content - leach test	- cement, polythiene, bitumen, etc. - high integrity container (HIC) - structural stability for 300 years	

TABLE II.4. DISCHARGE, EXEMPT, CLEARANCE LIMITS

Country	**Exemption**	**Clearance**
Argentina	10 μSv/y dose	
Australia	no data provided	
Belgium		
Installations • RA materials	5 kBq – Pu-239, Ra-226, Am-241 50kBq – Co-60, I-125, Sr-90 500 kBq – Fe-55, Sr-89, Cs-137 5000 kBq – H-3, I-129, U-238	
• devices	1 μSv h^{-1} (0.1 m)	
• materials	100 Bq g^{-1}	
• natural substances	500 Bq g^{-1}	
solid	radiation background	
liquid	sewage system-1/100 surface water-1/1000 groundwater-1/10 000 of the annual limit for ingestion by members of the pubic	
gaseous	1/50 of derived air concentration limits for professionally exposed individuals	
Bulgaria	10 μSv y^{-1}	
Canada	0.05 mSv y^{-1} (case by case)	
Cuba	not defined	
Czech Republic	10 μSv y^{-1} sum of weight factors<1	
critical group	250 μSv y^{-1}	
release in surface water	sum of volume fractions.DCF (ingestion)< 10^{-4} Sv m^{-3}	
release into atmosphere	sum of volume fractions.DCF (inhalation)< 10^{-3} Sv m^{-3}	
disposal at dump sites	sum of volume fractions.DCF (ingestion)< 10^{-4} Sv kg^{-1}	
release into sewage system	sum of volume fractions.DCF (ingestion)< 10^{-2} Sv m^{-3}	
Italy		case by case basis (Gagliano NPP) -beta emmiters – 1 Bq g^{-1}, 1Bq cm^{-2}. -alpha emmiters- 0.1 Bq g^{-1}, 0.1 Bq cm^{-2}
Japan	under investigation	under investigation
Lithuania	not specified	not specified
Mexico	not specified	not specified
Romania	no data provided	
United Kingdom		
solid substances	<0.4 Bq g^{-1}	
United States of America	case by case	case by case

TABLE II.5. DOSE TARGETS

Country	**Dose** **Equiv. dose limit**		**Risk**
	Normal conditions	**Accident conditions**	
Argentina - public	1 mSv		10^{-5} 10^{-6}
eyes	15 mSv		
skin	50 mSv		
- occupational	20 mSv*		10^{-5} 10^{-6}
eyes	150 mSv		
skin	500 mSv		
- critical group			
Belgium	No specific regulatory requirements		
Bulgaria	1 mSv		
Canada	0.05 mSv		10^{-6}
Cuba	not applicable		
Czech Republic	Decree of SUJB No. 184/1997		
Italy dose constraint	0.1 mSv y^{-1}		
Lithuania	not specified		
Mexico public - whole body - thyroid - other organ-	0.25 mSv 0.75 mSv 0.25 mSv		
Romania	dose		
Slovenia	Regulation Z6		
United Kingdom	dose constraint- - 0.5 mSv y^{-1} source related dose constraint-- 0.3 mSv y^{-1}		10^{-5} y^{-1} (during operation) 10^{-6} y^{-1} (after withdrawal of control)

TABLE II.6. PERIOD OF INSTITUTIONAL CONTROL

Country	**Active**	**Passive**
Argentina	not specified, depends on the facility	
Australia	no data provided	
Belgium		
near surface facility	200-300 years (operational and control period)	
deep geological	tens of years (operational and control period)	
Brasil	300 years <	depends on the safety assessment results
Bulgaria	not specified	
Canada	100 years	
Cuba	not specified	
Czech Republic	300 years	
Italy	not specified	
Japan	300 years	
Lithuania	not specified	
Mexico	5 years	not determined
Romania	not specified	
Slovenia	5 years	not determined
United Kingdom	a few hundred years	
United States of America	100 years	

TABLE II.7. IMPORTANT INTERNATIONAL DOCUMENTS APPLIED

COUNTRY	**INTENATIONAL ATOMIC ENERGY AGENCY** **(IAEA)**	**INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION** **(ICRP)**	**EUROPEAN COMMISSION (EC)**	**OTHER**
Argentina	RADWASS Series			
Australia	IAEA Codes of Practice RADWASS Recommendations			
Belgium	SS No. 111-F SS No. 115 SS No. 111-G.3	ICRP No. 64	Directive 96/29/Euratom	
Bulgaria	IAEA Codes of Practice RADWASS Recommendations	ICRP No. 60	Directive 96/29/Euraom	
Cuba	SS No. 63 SS No. 69 SS No. 62 SS No. 54 TRS No. 216 TRS No. 523 TRS No. 349			
Czech Republic	Safety Series TECDOCs	ICRP documents		
Italy	Safety Guides		CEC recommendations	
Japan	IAEA publications		ICRP recommendations	
Lithuania	not specified			
Mexico	SS No. 111G-1.1 SS No. 111-G.1.3 SS No. 111-F SS No. 111-P.1.1 SS No. 111-S-1			
Romania	SS No.53 SS No.9	ICRP No. 60	Council Directive 96/29/Euratom	US NRC-10CFR

COUNTRY	**INTENATIONAL ATOMIC ENERGY AGENCY (IAEA)**	**INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION (ICRP)**	**EUROPEAN COMMISSION (EC)**	**OTHER**
	SS No.37 SS No.71 SS No.63 SS No.111-F SS No.111-G-1.1 SS No. G-3.1 SS No. 64 Joint Convention *			
Slovenia	IAEA recommendations Treaty on Non-Proliferation of Nuclear Weapons: Convention on Physical Protection of Nuclear Material		EU legislation	
	Agreement with the IAEA on Application of Safeguards in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons			
United Kingdom		ICRP No. 60 ICRP No. 64	Euradwaste series No.1 Euradwaste series No.4 Euradwaste series No.6	
United States of America	IAEA Guidelines			

* Joint Convention – Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management

** SS-IAEA Safety Series

TABLE II.8. REQUIREMENTS ON MONITORING

Country	Requirements	Specific Requirements
Argentina	Monitoring plan Submission of results every 3 months Environmental measures taken after closure	
Belgium	operational period – as for all class I installations post-closure period - not specified	
Bulgaria	on-site: - equivalent dose rate of gamma-emission; - density of the beta flux; - equivalent dose rate of the neutron emission or neutron flux density; - specific activity of the aerosols activity in the air; - specific activity of the discharged water; - radionuclide content in the air, soil, subsurface layer, plants, etc. controlled area: - gamma equivalent dose rate; - beta and gamma equivalent dose; - specific activity of the aerosols in the air; undergroundwater and the open water sources; - surface density of the radioactive contamination; - radionuclide content of the aerosols in the air; water from the water sources; undergroundwater, atmospheric depositions; soil; plants, foodstuffs, etc.	
Canada	Monitoring plan required	
Cuba	not specified	
Czech Republic	Monitoring of the site is required according to the Law No. 18/1997	should cover both operational and 300 years institutional control
Italy	to be determined	

Country	Requirements	Specific Requirements
Japan	The storage stage (under monitoring) (a) It is confirmed that in this stage that the engineered barrier prevents the leakage of radioactive material to the barrier outside by the artificial barrier, and that there is no leakage by observation and measurement (patrol inspection and monitoring of facilities, etc.) of the requirement. The disposal stage (under monitoring or under management) (b) The migration of the radioactive material is prevented by engineered barrier and natural barrier, and it is confirmed to be safe by observation and measurement (monitoring of surroundings, etc.) of the requirement. (c) Specific action of human is controlled (stage of the slight management). The uncontrolled stage (non-management) (d) In this stage, the site is released for free use, as the exposure dose which the general public receives by buried radioactive waste does not need the management of disposal site from the viewpoint of the exposure management (the stage without institutional control).	monitoring is carried out mainly at stages a and b
Lithuania	not specified	
Mexico	pre-operational environment stage - determination of parameters related to meteorolgy, hudrology, geology, ecology, demography. etc. operational and post-closure environmental programme periodical evaluation of physical parameters determination of groundwater velocity and direction (every 5 years) evaluation of airborne, ground and superficial water and soil radiological contaminants, etc. environmental surveillance during institutional control Groundwater sampling bioindicators (vegetation, deep root plants, digger animals, etc.)	data to be collected every 1 year

Country	Requirements	Specific Requirements
Romania	general requirements	
Slovenia	defined requirements for a nuclear installation but no specific for a disposal site	
United Kingdom	investigation and pre-construction phase - measures of pre-existing radioactivity in media, geological, physical and chemical parameters (e.g. groundwater properties-pressure, flows, chemical composition) construction and operational phase radiological monitoring of the types undertaken at other nuclear sites are required non-radiological parameters monitored withdrawal of control	safety of facility must not depend on monitoring or surveillance after control has been withdrawn
United States of America	pre-operation pre-operational programme providing environmental data (ecology, meteorology, climate, geology, hydrogeology, seismology, etc.) plans for corrective measures operation maintaining a monitoring programme recorded data evaluation of long term effects institutional control maintaining a monitoring system on operational history	monitoring system must be capable of providing early warning of releases

TABLE II.9. REQUIREMENTS ON THE FACILITY DESIGN AND LOCATION

Country	**Natural barriers**	**Engineered barriers**	**Location**	**Other**
Argentina	No data provided			
Belgium		fully engineered barriers draining system complement with the natural geological barriers		the proposed solution to be: flexible reversible controllable
Bulgaria	Radioactive waste is disposed in near surface engineered facilities or in natural cavities; design of the engineered facilities for disposal of radioactive waste, the operational period, institutional control period and the period for recovering of the site have to be taken into account		Interaction between the radioactive waste and the aquifer should be excluded Rock or mineral formations that prevent the radionuclide migration into the environment should be used Chemical correspondence between the natural minerals (materials) and the materials of the facility, including the radioactive waste There should not be precious mineral resources on the site Hydrogeological, geological and other factors related to the protection of the human health, the environment, natural and cultural resources	Technical and economical criteria Socials assumptions Transport factors, etc.
Canada	Natural barriers are considered in the safety assessment	Engineered barriers are considered in the safety assessment and their requirement can be found in	Site is accepted at an early stage of facility licensing	

Country	Natural barriers	Engineered barriers	Location	Other
		the need for redundant and multiple barriers		
Cuba		IAEA recommendations	IAEA recommendations	
Czech Republic	Decree SUJB No. 215/1997 Law No. 50/1976			
Italy	technical guide in preparation			
Japan	Consideration of earthquake, typhoon, high tide, flood, heavy snowfall, ground, fault, wind direction and velocity, precipitation, river and groundwater	Consideration of : Resistance to natural phenomena, e.g. earthquake resistance, etc. fire and explosion blackout conformity with standards		Social environment : (fire and explosion of approach factories, etc., situation of utilization of river and groundwater, land usage pattern on fishery and livestock industry and agriculture, artificiality distribution, distribution of underground resources such as coal and ore)
Lithuania	not specified			
Mexico		stability for minimum of 500 years		
Romania	not specified			
Slovenia	Regulation Z3	The disposal units are: monoliths or shafts for wastes of category II with alpha emitters or lower categories,		

Country	Natural barriers	Engineered barriers	Location	Other
		mounds for radioactive wastes of categories III and II with beta and gamma emitters. With monoliths waste materials are packed, poured with concrete and covered by reinforced concrete slab. With mounts the packed waste materials are covered with earth or clay.		
United Kingdom	the geological conditions in each particular section of the facility, as distributed by construction, are appropriate to the types and quantities of waste that is proposed to dispose of in that section	avoidance of undue disturbance of the geological environment and the containment properties of the host rock	proposed location is of sufficient extent to accommodate the categories and quantities of waste to be disposed of whilst maintaining adequate separation from geological media of less suitable characteristics	the design takes full account on the requirements of the safety case and that suitable techniques are available corrective measures in case of geological and geotechnical problems to be taken
United States of America	NRC 10CFR 61.50, 61.51, 61.52			

ABBREVIATIONS AND ACRONYMS

ALARA	As Low As Reasonably Achievable
APE	Asphalt Propylene Concrete
BIOMASS	BIOsphere Modelling and ASSessment project
BIOMOVS	Biosphere Model Validation Study
CFR	Code of Federal Regulations (USA)
DSIN	Direction de la Sûreté des Installations Nucléaires (France)
EFEPs	External FEPs
EGE	Engineering and Geological Elements
FEPs	Features, Events and Processes
FSAR	Final Safety Analysis Report
GIS	Geographical Information System
HLW	High Level Waste
ICRP	International Commission on Radiological Protection
IFEPS	International FEPs
IHI	Inadvertent Human Intrusion
IM	Interaction Matrix
IRUS	Intrusion Resistant Underground Structure
ISAM	Improvement of Long term Safety Assessment Methodologies for Near Surface Waste Disposal Facilities
LDE	Leading Diagonal Elements
LHS	Latin Hypercube Sampling
LILW	Low and Intermediate Level Waste
LLW	Low Level Waste
NSARS	Near Surface radioactive Waste Disposal Safety Assessment Reliability Study
ODE	Off-Diagonal Elements
OECD	Organisation for Economic Co-operation and Development
PA	Performance Assessment
PAGIS	Performance Assessment of Geological Isolation Systems
PCRSA	Post Closure Radiological Safety Assessment
PDF	Probabilistic Distribution Functions
PID	Process Influence Diagram
PSAR	Preliminary Safety Analysis Report
RAW	Radioactive Waste

SITE-94	Deep Repository Performance Assessment Project, SKI (Sweden)
SRS	Simple Radon Sampling
WIPP	Waste Isolation Pilot Plant

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RELATED MEETINGS

Consultancy to assist in developing the ISAM CRP,
Vienna, Austria:
20–24 May 1996

Consultancy to assist in developing the ISAM CRP
Vienna, Austria
18–22 November 1996

Consultancy to assist in launching the ISAM CRP
Vienna, Austria
16–18 April 1997

Consultancy to prepare for the 1st ISAM Research Co-ordination Meeting
Vienna, Austria
19–21 November 1997

1st ISAM Research Co-ordination Meeting (RCM)
Vienna, Austria
24–28 November 1997

Consultancy to assist in implementing the ISAM Work Programme
Risley, United Kingdom
23–27 February 1998

1st ISAM Working Groups Meeting
Rio de Janeiro, Brazil
27–31 July 1998

Consultancy to assist in implementing the ISAM Work Programme,
Risley, United Kingdom
16–20 November 1998

2nd ISAM RCM, Plenary and Working Group Meetings
Vienna, Austria
1–5 February 1999

2nd ISAM Working Groups Meeting
Madrid, Spain
28 June – 2 July 1999

Consultancy to assist in implementing the ISAM Work Programme
Risley, United Kingdom
15–19 November 1999

3rd ISAM RCM, Plenary and Working Group Meetings
Vienna, Austria
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Final Meeting of the ISAM Co-ordinating Group
Vienna, Austria
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