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Performance Assessment for Underground Radioactive Waste Disposal Systems

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PERFORMANCE ASSESSMENT FOR UNDERGROUND RADIOACTIVE WASTE DISPOSAL SYSTEMS

INTERNATIONAL ATOMIC ENERGY AGENCY
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FOREWORD

This document is addressed to authorities and specialists responsible for or involved in planning, making and reviewing performance assessments of underground disposal systems for radioactive wastes. Considerations for making total safety assessments are given in Safety Assessment for the Underground Disposal of Radioactive Wastes, IAEA Safety Series No. 56, 1981. The present document is intended to complement the earlier report, placing emphasis on the performance assessment of subsystems within the overall waste disposal system. It is hoped that this document will stimulate discussion and contribute to the foundation of a common understanding among authorities and practitioners of performance assessment.

Because of the rapid growth of ideas and experiences in this area, much additional material is likely to become available in the next few years, and it will eventually be possible to produce a comprehensive guidebook on performance assessment. The present document represents one step towards the preparation of such a guidebook.

Since 1977, the IAEA has been pursuing a programme on the underground disposal of radioactive wastes with the intention of publishing a set of guidelines to cover the needs and interests of both developed and developing countries. These guidelines will deal with the following subjects:

(a) Generic and regulatory activities and safety and performance assessments;
(b) Investigation and selection of repository sites;
(c) Waste acceptance criteria;
(d) Design and construction of repositories;
(e) Operation, shutdown and surveillance of repositories.

The present publication is part of this IAEA programme.

At its fourth meeting in 1981, the Technical Review Committee on Underground Disposal of Radioactive Waste (TRCUD) recommended the preparation of a report on The Analysis of the Performance Requirements of the Waste Isolation System, which was the first version of the present document. A consultants meeting was held in Vienna from 15 to 19 March 1982 to review the recommendations of the TRCUD and to make proposals regarding the scope, content and limitations of the analysis. The consultants prepared a preliminary reference waste isolation system definition and guidelines for further development of a general definition. An ad hoc Technical Group met in Columbus, Ohio, from 3 to 5 August 1982 and agreed upon a definition which could be adopted for analysing the performance requirements of waste isolation systems. More improvements were advised at the fifth meeting of the TRCUD in October 1982, and a Technical Committee which met in Washington, D.C., from 19 to 23 September 1983 drafted another version of the report. Referring to further comments made by the TRCUD in its 1983 meeting, a group of consultants met in Baden, Switzerland, from 13 to 16 March 1984 and revised the report.

A number of publications produced by the IAEA in its programme on the underground disposal of radioactive wastes examine possible options for the disposal of high-, intermediate- and low-level radioactive wastes in deep, continental geological formations, in rock cavities at various depths and in shallow ground. The most recent of these publications are:

Shallow Ground Disposal of Radioactive Wastes: A Guidebook, IAEA Safety Series No.53 (1981)
Underground Disposal of Radioactive Wastes: Basic Guidance, IAEA Safety Series No.54 (1981)
Safety Assessment for the Underground Disposal of Radioactive Wastes, IAEA Safety Series No.56 (1981)
Concepts and Examples of Safety Analyses for Radioactive Waste Repositories in Continental Geological Formations, IAEA Safety Series No.58 (1983)
Disposal of Low- and Intermediate-Level Solid Radioactive Wastes in Rock Cavities: A Guidebook, IAEA Safety Series No.59 (1983)
Criteria for Underground Disposal of Solid Radioactive Wastes, IAEA Safety Series No.60 (1983)
Site Investigations, Design, Construction, Operation, Shutdown and Surveillance of Repositories for Low- and Intermediate-Level Radioactive Wastes in Rock Cavities, IAEA Safety Series No.62 (1984)
Design, Construction, Operation, Shutdown and Surveillance of Repositories for Solid Radioactive Wastes in Shallow Ground, IAEA Safety Series No.63 (1984)
Safety Analysis Methodologies for Radioactive Waste Repositories in Shallow Ground, IAEA Safety Series No.64 (1984)

Other IAEA publications prepared in the Radiological Safety Standards programme and the Nuclear Safety Standards (NUSS) programme might also be consulted. In relation to the present document the most important are:

Basic Safety Standards for Radiation Protection: 1982 Edition, IAEA Safety Series No.9 (1982)
Principles for Establishing Limits for the Release of Radioactive Materials into the Environment, IAEA Safety Series No.45 (1978)

The IAEA gratefully acknowledges all those who took part in the preparation of this document. The responsible officer at the IAEA was K.T. Thomas from the Waste Management Section of the Division of Nuclear Fuel Cycle.

CONTENTS

1. INTRODUCTION

In the development and utilization of nuclear energy, work is proceeding on concepts and strategies for disposal of radioactive wastes. Most efforts are currently focused on emplacement of solid wastes in (a) deep geological repositories, (b) repositories in man-made or natural rock cavities, and (c) shallow ground repositories, these being suitable for different categories of waste.

A waste disposal system comprises a number of subsystems and components. For example, in the case of a mined geological repository, the whole system consists of the waste package, the engineered features within the repository, the host rock, the entire geological environment and the biosphere.

Approaches for achieving the required isolation of the waste vary considerably with the concepts used and with the type of host rock, and depend on the desired performance of the waste disposal system as a whole. The performance of most systems can be demonstrated only indirectly because of the long period that would be required to test them. The general problem of performance demonstration is discussed in Refs [1, 2].

The present report gives special attention to performance assessment of subsystems within the total waste disposal system, and is an extension of an IAEA report on Safety Assessment for the Underground Disposal of Radioactive Wastes [3].

The objectives of the present document are:

(a) To assist in understanding the role and objectives of performance assessment in the development of waste disposal systems;
(b) To provide insights into the methods currently employed in performance assessment work;
(c) To give practical guidance in specific technical areas of importance.

The ideas presented have been developed primarily for assessment of underground disposal options, and examples given are almost exclusively for these options. However, much of the material has wider application.

2. ASSESSMENT OF SYSTEMS AND SUBSYSTEMS

2.1. DEFINITIONS

A number of special terms will be used in the following sections. For the assistance of the reader, these are defined here.

A waste disposal *system* consists of a number of subsystems and components which together provide the required degree of protection of humans and the environment. An example is a mined geological repository containing packaged wastes.

A *subsystem* of a waste disposal system is a portion of a system which has been divided in a particular way, such as according to its functional or physical properties. For instance, an engineered barriers subsystem for high-level waste might consist of a waste form, a canister, an overpack and a backfill. A set of seals for a geological repository also constitutes a subsystem.

In dealing with systems or subsystems, it will be necessary to define one or more *performance measures*. Examples are the lifetime of a canister and the risk to individuals caused by a geological repository.

Once performance measures have been chosen, it is possible to set *performance targets,* i.e. specified levels of performance, usually as numerical values. For instance, a performance target for a canister might be a lifetime of 500 years.

Performance analysis is the development, testing and application of quantitative models that are used to calculate or predict the performance of a waste system or subsystem in terms of a particular performance measure or measures. Performance analysis should take proper account of uncertainties in models and data.

Performance assessment consists of analysis to predict the performance of the system or subsystem, followed by comparison of the results of such analysis with appropriate standards or criteria. When the system under consideration is the overall waste disposal system and the performance measure is radiological impact or some other global measure of impact on safety, performance assessment becomes the same as safety assessment.

The general reference waste disposal system described in the next section illustrates these definitions for a mined geological repository. The definitions can also be used for other waste disposal concepts, such as repositories at shallow depths on land, rock cavities and emplacement in geological formations below the seabed.

2.2. A GENERAL REFERENCE WASTE DISPOSAL SYSTEM

For the purpose of this document, a definition of a general reference waste disposal system has been developed. It is shown in Table I. To ensure that the definition is general, it was decided that it should be:

(a) Applicable to waste disposal in various types of geological media;
(b) Compatible with other definitions in current use;

(c) Flexible enough to accommodate different approaches to performance analysis.

The system definition, as developed by the IAEA, covers only those components of the waste disposal system which would determine the effects on man of releases from the waste which occur after permanent closure of the repository. Thus, no attempt was made to include components specific to the operational phase of a waste disposal system.

The total waste disposal system is divided into functional levels and physically distinct subsystems with distinct interfaces, as shown in Table I.

2.2.1. System components and their functions

The subsystems in Table I are functional combinations of components defined in terms of the concept or process being analysed. The following components and their functions may be identified in the waste disposal system:

Waste form: limits release and mobility of radionuclides from the waste matrix.

Container: physically isolates the waste form for a limited time.

Vault or repository: provides a conditioned environment for the waste form and container and limits the migration rate of radionuclides within the vault.

Sealed penetrations: limit direct hydraulic connections between the rock and the accessible environment.

Geological setting: separates the vault and its contents from the accessible environment and external influences; limits water access; limits and/or delays migration of radionuclides from the vault or repository to the accessible environment.

Accessible environment: determines the distribution of radionuclides and their possible pathways to humans.

Institutional measures: reduce the probability of human intrusion.

2.2.2. Subsystems

Analysis and modelling of specific scenarios, of interactions between components and of concept structures will require the combination of the components into subsystems. Subsystems tend to be defined within the framework of particular analyses. One example is the combination of waste form, container and vault as a 'near-field' subsystem.

TABLE I. GENERAL REFERENCE WASTE DISPOSAL SYSTEM

Example of systems and subsystems	Waste disposal system			
	Waste		Vault/Repository	
Components	Waste form	Container	Vault/ Repository	Sealed penetrations
Elements	Glass Ceramic Concrete Bitumen Spent fuel Resins Synroc	Container and internal components other than waste forms	Structures Buffers Backfill Disturbed rock seals	Seals Disturbed zone Surrounding penetrations
Major functions	To limit release and mobility of radionuclides from waste	To physically isolate waste form	To provide conditioned environment for waste form and container To limit migration of radionuclides to vault/rock boundary	To limit direct hydraulic connections between rock and accessible environment
Examples of key performance measures	Radionuclide release rates Form of release	Distribution of canister lifetimes	Isolation time Attenuation of radionuclide migration within vault	Isolation time Attenuation of radionuclide migration across sealed penetrations Hydraulic resistance

Waste disposal system			Humans
Natural system			
Geological setting	Accessible environment	Institutional measures	Populations
Undisturbed host medium and surrounding geological formations surrounded by accessible environment	Local environment Regional environment Global environment	Controlled buffer zone Markers Fences Records Monitoring system	Critical group Regional population Global populations
To separate vault and contents from man and external influences To prevent, delay or limit water access To limit migration of radionuclides from vault to accessible environment	To reconcentrate, hold up, dilute or disperse radionuclides	To reduce probability of human intrusion	
Isolation time Attenuation of radionuclide migration across geological setting	Attenuation of radionuclide migration along pathways to man	Duration of institutional control	Risk or dose

2.3. SUBSYSTEM PERFORMANCE ASSESSMENT

2.3.1. Rationale for subsystem assessments

Approaches for assessing the safety of an overall system of waste disposal are introduced and described in detail in IAEA Safety Series Nos 56 and 58, respectively [3, 4]. Subsystem performance analyses can be carried out for the following reasons:

(a) To reduce the analytical effort: if a limited performance assessment is required, only a limited analysis is performed.
(b) To focus the performance analysis on areas or processes peculiar to a specific technical field or discipline.
(c) To satisfy regulatory requirements on subsystems as part of a licensing or other formal approval procedure.

In site selection and engineering design activities, intensive use is commonly made of performance analyses at the subsystem level.

2.3.2. Role of subsystem analyses

The role of subsystem performance analyses is indicated in Fig. 1, which emphasizes the overriding importance of the total system evaluation. Subsystem analysis is a subordinate activity which can be used to aid conceptual design and detailed analyses of component and process performance. The upper loop in Fig. 1 represents the preliminary, generic type of analysis which is normally done when first formulating a waste disposal concept. When it has been decided which is the most important overall performance measure – in this application normally radiological impact – and once an overall target has been set, a system is built from subsystems. A preliminary assessment of the functioning of the subsystems is made and a first overall analysis indicates whether the total system could be acceptable.

Interpretation of the first analyses can also provide sufficient insight into the functioning of the subsystems to allow useful and compatible subsystem performance targets to be formulated (centre of Fig. 1). One can then proceed to more detailed analyses of specific designs and sites. Here the models used may be more complex and the relevant scenarios must be identified for the particular site and repository design. Working at the subsystem level can have practical advantages in the organization of this work. Subsequently, however, one must check again that the total system requirements are indeed fulfilled.

By this stage a total system has been developed which satisfies the overall target(s) and also a range of subsystem targets. Normally there is next an 'engineering optimization' step. In this one examines whether the subsystem targets can be relaxed to allow less costly designs which, nevertheless, will still

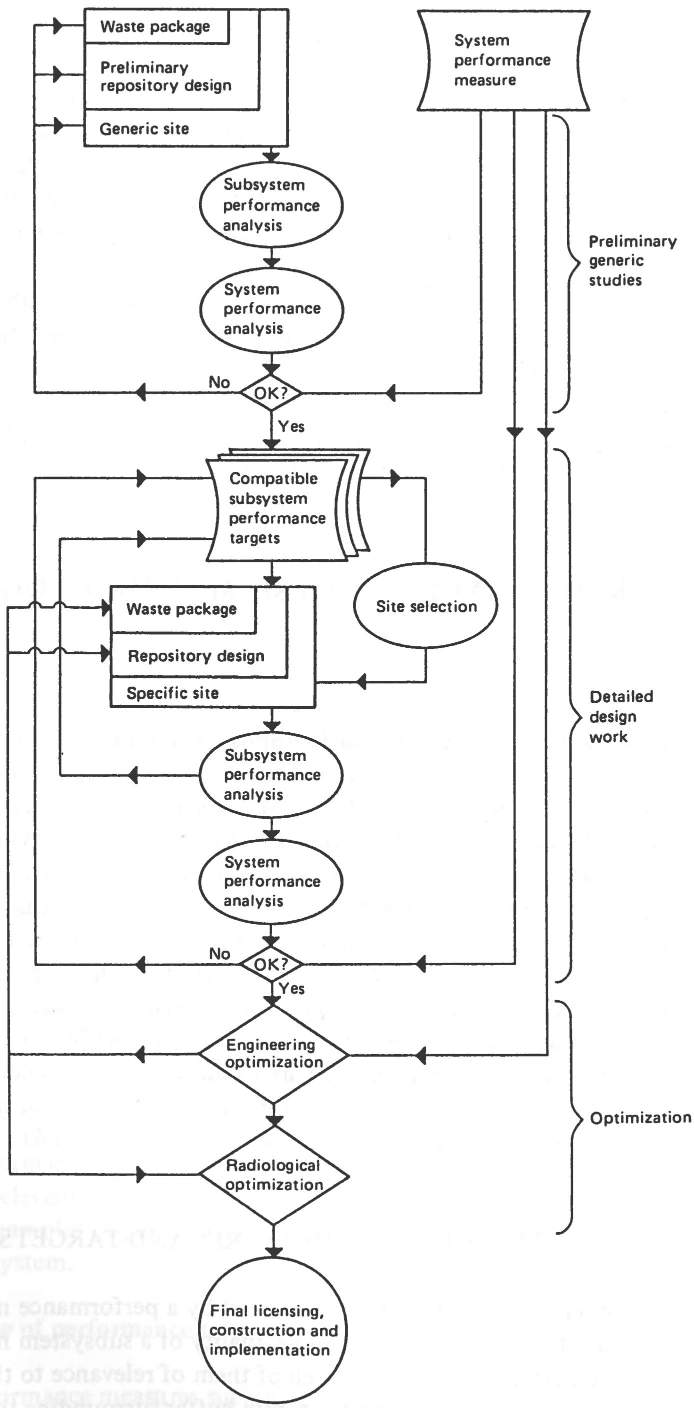

FIG.1. The role of performance assessment in the development of an underground waste disposal system and subsystems.

enable the total system target to be met. A typical question is, for example, whether containers with thinner walls or of simpler materials will still allow a given performance target to be met. Distinct from engineering optimization, with its aim of meeting a given target at minimum cost, there is also an activity called 'radiological optimization'. This reflects current radiological principles which require that, for *any* level of predicted radiological impact, one must quantify the costs, financial and other, of further impact reduction [5] in order to determine whether any reduction is worth while.

The Swedish KBS-3 report illustrates the use of a sequence of subsystem performance analyses prior to final site selection and system optimization [6]. It contains an assessment of the feasibility – with the technology of today – of constructing a repository in crystalline rock that is able to meet very stringent safety requirements. In the Swedish legislation such an assessment of feasibility is required before the fuelling of a reactor is permitted.

3. PERFORMANCE ANALYSIS METHODOLOGY

3.1. GENERAL

To analyse the performance of a waste disposal system or any part of it, the system and site have to be defined (data) and the phenomena that can occur in the site and engineered components of the system and their interactions have to be identified (models). Theoretically the influence of every possible environmental state should be analysed if complete knowledge is to be achieved. In practice, however, the analysis must be limited to a number of scenarios that involve the crucial factors characterizing the performance of the system. The performance assessment process has been broadly described in Section 2; in the present section more detailed comments are made on the procedures used in performance analysis.

Both the selection of appropriate performance measures (Section 3.2) and the selection of relevant scenarios (Section 3.3) are influenced by the objectives of the performance analysis. The objectives can also influence the choice of models (Section 3.4) and of the techniques applied in an analysis (Section 4).

3.2. SELECTION OF PERFORMANCE MEASURES AND TARGETS

The performance of a system is characterized by a performance measure selected with a specific function in mind. The quality of a subsystem may be indicated by many performance measures, all of them of relevance to the total system performance. For instance, the bentonite buffer surrounding the canister in the KBS-3 concept constitutes:

(a) A barrier to water movement to limit canister corrosion and fuel dissolution; the performance measure could be hydraulic conductivity.
(b) A heat transfer medium to limit the maximum canister temperatures; the performance measure could be temperature at the canister surface.
(c) A sorbing and ion exchange medium limiting nuclide transport to the geosphere; the performance measure could be nuclide flux at the borehole wall.
(d) A protection of the canister against rock movements; the performance measure could be plasticity of the buffer.

3.2.1. Suitable performance measures

Performance measures should be selected to evaluate the extent to which a component or subsystem carries out its assigned function(s). Some criteria for the selection of performance measures are given here:

(a) The performance measure for the subsystem should be related directly to the overall system performance measure – usually one involving radiological impact. One example is groundwater travel time as a performance measure in geosphere performance assessment.
(b) If possible, a performance measure should be chosen to allow a comparison with some observable relevant quantity. For example, the thermal behaviour of the near-field subsystem can be evaluated by using as a measure the temperature distribution at short time intervals; this can be checked against results of in situ experiments.
(c) Sometimes performance measures are chosen because they provide specific information for further detailed study of effects whose impacts on the total system are to be investigated. For example, the behaviour of different waste packages can be analysed to predict the quantities of gases which could be released within the repository.
(d) As analyses become more advanced, more specific (objective-oriented) performance measures can become useful. For example, in an optimization phase it may be appropriate to use as a performance measure the cost of achieving a particular container lifetime.

Performance measures can vary according to the waste disposal concept and must be relevant to the intended use of the results of the performance evaluations. Several examples of performance measures are given in Table I for a general waste disposal system.

3.2.2. Use of performance targets

Performance measures such as those described above allow one to quantify the performance of the total system or of subsystems. The most important measures are those expressing radiological impact. In designing or assessing the waste disposal system, it is useful to have reference values of performance measures for comparison. In radiation protection one set of reference values are dose limits, i.e. the maximum allowable doses for workers or the public. All reference values of performance measures can be specified as performance targets. Other targets for design of a total system might be the minimum volume of wastes to be disposed of or the maximum costs judged acceptable.

Often performance targets are not rigid but can be amended during design. Interim targets may be set during development and then relaxed or made more stringent as work proceeds on the disposal concept. In the design of radiation protection systems, the fixed dose limits are used as constraints on the optimization process, and acceptable levels of dose are judged not against performance targets but against costs incurred in further reductions. Often, however, it is practical to develop an appropriate target for judging acceptable performance, particularly at the subsystem level. In all cases it is imperative that any subsystem performance target be chosen only within the framework of a total system analysis.

This is indicated in Fig.1, which shows that initial subsystem evaluations at the conceptual stages can be done with reference to particular performance measures but with no fixed target. Before selecting even preliminary subsystem performance targets, one should establish, by means of an overall system assessment, the appropriate ranges within which these targets can be sensibly chosen. Among the best-known examples of subsystem performance targets are the numerical limits set by the United States Nuclear Regulatory Commission (USNRC) for the waste canister in terms of container lifetime, for the site in terms of minimum groundwater travel time to the biosphere and for allowable rates of nuclide release from the engineered barriers [7]. Specification of targets for subsystems can be useful if appropriately implemented, but can also raise problems, as noted below.

Subsystem performance targets have potential advantages in licensing procedures. If only subsystem targets are specified, application for a licence can be made simpler because the task of total system assessment is partly transferred to the regulatory body. A more auditable process, which is more understandable to decision-makers, can result. Subsystem targets can also help to guide specialist discussion. Internal targets within disposal system development are often set for this purpose. Finally, subsystem targets can help to specify engineering design tasks or to identify R&D needs at the subsystem level.

Most of the potential advantages of subsystem performance targets apply only in particular cases, and improperly chosen targets can lead to problems. They may preclude optimization of the total system, resulting in a costly yet less effective system, or they can lead to excessive conservatism in system design. Badly chosen subsystem targets can also result in misleading indications of R&D requirements if consistency with total system targets is not assured.

The problems of using subsystem targets were illustrated in a recent study by the Waste Isolation Systems Panel (WISP) of the US National Academy of Sciences regarding the USNRC criteria [8]. The study showed that there may be circumstances in which all three criteria (i.e. for container lifetime, groundwater travel time and allowable nuclide release rates) may be fulfilled, even though predicted doses to man were above the selected targets. Also, cases were discussed where very low doses were predicted even when some of the subsystem criteria were not fulfilled. Such disadvantages can be avoided by ensuring that final subsystem targets are not set until the disposal concept is fully developed and has been assessed as a whole.

3.3. SELECTION OF SCENARIOS FOR SAFETY AND PERFORMANCE ANALYSES

In this document a scenario is defined as a quantified description of a waste disposal system, including its environment and how this will change with time. It is also possible to define scenarios for subsystems; these should be consistent with scenarios for the overall system. Scenarios depend on the system characteristics and on events and processes which could either initiate release of radionuclides from waste, and cause their transport through the geosphere and the biosphere to humans, or influence release and transport rates. The choice of appropriate scenarios is very important and strongly influences subsequent analysis of the waste disposal system. The first step in identifying which of the many phenomena are relevant to a safety or performance analysis is to establish a check-list. For this purpose it is usual to divide phenomena into the following categories: (a) natural processes and events, (b) human activities, and (c) effects of the waste and the repository.

Table II shows a typical check-list arranged in this way. While this classification of phenomena by their cause is helpful in explaining all the factors taken into account in an analysis, it is not sufficient for defining radionuclide release and transport scenarios because it does not include any information about the effects of phenomena or about their probabilities of occurrence. Thus, the second step in scenario selection is to recategorize events and processes so as to indicate how they are to be handled in calculations.

For any given type of waste and geological formation, particular events and processes are certain to occur. For example, in crystalline and argillaceous rock formations below the water table it is certain that groundwater will be present and that, even in the absence of external perturbations, this will eventually cause corrosion of waste canisters and radionuclide transport via diffusion and/or advection. Similarly, in any high-level waste repository there will be temperature changes due to the heat output of the waste and its variation in time. Biosphere changes will also take place after repository closure (e.g. climatic changes).

TABLE II. PHENOMENA POTENTIALLY RELEVANT TO RELEASE SCENARIOS FOR WASTE REPOSITORIES [3]

Natural processes and events

- Climatic change
- Hydrological change
- Sea level change
- Denudation
- Stream erosion
- Glacial erosion
- Flooding
- Sedimentation
- Diagenesis
- Diapirism
- Faulting/Seismicity
- Geochemical change
- Fluid interactions
  - Groundwater flow
  - Dissolution
  - Brine pockets
- Uplift/Subsidence
  - Orogenic
  - Epeirogenic
  - Isostatic
- Undetected features
  - Faults, shear zones
  - Breccia pipes
  - Lava tubes
  - Intrusive dykes
  - Gas or brine pockets
- Magmatic activity
  - Intrusive
  - Extrusive
- Meteorite impact

Human activities

- Undetected past intrusion
  - Boreholes
  - Mine shafts
- Inadequate design
  - Shaft seal failure
  - Exploration borehole seal failure
- Improper operation
  - Improper waste emplacement
- Transport agent introduction
  - Irrigation
  - Reservoirs
  - Intentional artificial groundwater recharge or withdrawal
  - Chemical liquid waste disposal
- Climatic change (including climate control)
- Large-scale hydrological change
- Intentional intrusion
  - War
  - Sabotage
  - Waste recovery
- Inadvertent future intrusion
  - Exploratory drilling
  - Archaeological exhumation
  - Resource mining (mineral, water, hydrocarbon, geothermal, salt, etc.)

Waste and repository effects

- Thermal effects
  - Differential elastic response
  - Non-elastic response
  - Fluid pressure, density, viscosity changes
  - Fluid migration
- Chemical effects
  - Corrosion
  - Interactions of waste package and rock
  - Gas generation
  - Geochemical change
- Mechanical effects
  - Canister movement
  - Local fracturing
- Radiological effects
  - Material property changes
  - Radiolysis
  - Decay product gas generation
  - Nuclear criticality

This observation that some phenomena are certain to occur leads to the concept of a 'normal' scenario, which consists of the most probable sequence of events following repository closure [9]. The parameters and assumptions used in analysing the consequences of this scenario are based on extrapolations into the future of past and present geological and climatic trends, and on models for waste form, engineered barriers and site interactions. The normal scenario does not depend on the assumption of constant geosphere and biosphere conditions, but on the assumption of unperturbed evolution. For some disposal systems, e.g. in salt formations, the normal scenario leads to no release or transport of radionuclides.

There are also 'non-normal' events and processes which perturb the normal situation but which do not change conditions so substantially as to create an entirely new scenario which is qualitatively different from the normal case. One example is erosion, which may decrease the depth of cover of an underground repository, thus altering the length of groundwater flowpaths, but which would not cause a direct release of radionuclides into the biosphere from a deep repository. Another example is a seismic event which may change fracture patterns, but again does not cause direct releases. The important feature of non-normal phenomena in this category is that their effects can be predicted using the same models as for the normal scenario, but with different parameter values.

A second type of non-normal phenomenon is that which does create a new scenario but does not have catastrophic effects. Major examples are phenomena which lead to a small, direct release into the biosphere (e.g. inadvertent human intrusion), or which involve changes to biosphere conditions but do not affect the repository or the geosphere (e.g. farming of land which was previously used for another purpose). Such scenarios must be analysed using models which differ from those used for the normal scenarios.

The fourth category of events which can be easily identified from a check-list are those which have the potential to cause abrupt and direct release of radionuclides into the biosphere. Examples of these are extrusive magmatic activity and the impact of large meteorites. Such events are characterized by their low probabilities of occurrence and their significant radiological or non-radiological consequences. For modelling purposes, they can be classed as 'catastrophic scenarios'. These scenarios may often be discarded at an early stage of an assessment if a simplified analysis shows that their probability of occurrence is negligible, or if the consequences of the scenario are dominated by other consequences that are not related to the presence of the repository.

Table III gives an example of a classification of phenomena relevant to analyses of a deep geological repository. Such a classification scheme has practical advantages in terms of selecting models for use in predictive calculations (Section 3.4). It also has advantages in developing methodologies (or calculational frameworks) of analysis and in ensuring consistency in scenario selection. For methodology development, its advantages are that it distinguishes between

TABLE III. EXAMPLE OF CLASSIFICATION OF PHENOMENA FOR ANALYSIS PURPOSES

Normal phenomena	Less probable phenomena		
	Perturbations to normal scenario	New scenarios	
		Non-catastrophic	Catastrophic
Thermal effects	Seismic activity	Inadvertent human intrusion	Meteorite impact
Radiation effects	Uplift	Land use change	Magmatic explosion
Mechanical stress	Subsidence		Severe glacial erosion
Sea level change	Erosion		
Erosion	Flooding		
Aggradation	Tectonic displacement		
Climatic change	Aggradation		

Note: Some phenomena are mentioned twice because, while they are virtually certain to occur to some extent, there is also a lower probability that they will occur to a significantly greater extent than allowed for in the normal case.

phenomena which are certain to occur and those which have lower probabilities of occurrence and thus may need to be dealt with using probabilistic analysis techniques. It promotes consistency in the selection of scenarios because it allows superposition of perturbations and 'non-normal' phenomena on an existing set of conditions.

The final steps in scenario selection consist of identifying the parameters needed for a quantitative definition of each scenario and of assigning values to them. When a scenario list is used in this way, the changes in parameter values needed to quantify some scenarios will be within variations already specified to cover scenarios earlier in the list. Thus, it should be possible to eliminate some phenomena from explicit consideration in the analysis and to provide a smaller number of scenarios for use in performance analysis. In particular, by examining the changes which each of the perturbing phenomena causes in the parameter values and parameter value distributions for the normal scenario, it should be possible to decide whether the effects of some or all of these probabilistic phenomena will be covered by the uncertainty analysis for the normal scenario. For example, if the changes in groundwater flow patterns and rates which could be produced by seismic events are small compared with the uncertainties in predicted normal patterns and rates, then seismic events are implicitly covered in the uncertainty analysis and do not need to be considered in a separate scenario.

These final steps in scenario selection are necessarily site specific and can be carried out only when the appropriate data have been assembled. For this reason, none of the published examples of performance analyses have yet included this step; most have bypassed it by selecting scenarios which appear reasonable on the basis of the limited data available.

3.4. MODEL SELECTION

The choice of models to be used in a particular performance analysis is influenced by several factors. The most important of these are: (a) the aims of the analysis, (b) the availability of data, and (c) the scenario under consideration.

The effects of each of these factors on model selection are discussed in the following sections. However, before this discussion it is worth making two general points. Firstly, in performance analyses there are usually a number of models available for any particular type of analysis, all involving different levels of complexity and using different mathematical techniques. In choosing a model, a sensible rule to follow is that the preferred model should be the simplest one which suits the purpose.

Secondly, in general it will be necessary to use several different models for each subsystem during a performance assessment of a complete system. One normally begins by using very simple models in preliminary analyses which are designed either to screen out unacceptable sites and engineering options or to indicate research priorities. As knowledge of the system increases, more complex models are developed and utilized. However, a point may be reached where it becomes prohibitively expensive to employ complex models, for example when a large number of model runs are required for sensitivity analysis or uncertainty analysis (Sections 4.2 and 4.3). In this case it is necessary either to apply an existing simpler model or to use the results obtained with the complex model to produce a simpler model which is efficient in terms of computer time and adequately represents the system or subsystem [10].

Thus, in selecting models the question is not which of the many models available should be used throughout an assessment, but which one is appropriate for each stage in the analysis.

3.4.1. Model selection based on application

In analyses carried out to identify important parameters or screen out unacceptable sites and engineering options, the need is for simpler models which are efficient in terms of computer time. For these purposes it is often appropriate to run models based on analytical solutions to the equations representing the governing processes. Examples of such solutions are the analytical solutions for equations describing the major processes governing radionuclide transport in porous media [11, 12, 13, 14]. Such solutions have been very valuable in identifying important parameters determining radionuclide transport in the geosphere. Analytical solutions have also been used with limited success in evaluating the influence of waste form performance on the overall disposal system performance, and they have proved very useful in benchmarking for computer code verification (Section 4.4). An advantage of using analytical solutions is that one has the capability to evaluate performance at a specific time and point in space without calculating performance at all past times and points in the disposal system as required by numerical techniques.

One limitation of analytical solutions is imposed by boundary conditions. If the model is a geosphere model, for example, the waste form release model determines the boundary conditions. As a consequence, the form of the geosphere model is constrained by boundary conditions for which solutions exist, rather than by the actual performance of the waste form. The solubility-limited model used in a study by the US National Academy of Sciences is an example of the application of such an analytical solution [8]. A second limitation of analytical solutions is their inability to include the complex geometrical details which are needed to properly represent many components within the repository system.

When it is desired to include details of the system components which cannot be treated in analytical solutions, numerical methods, such as finite-difference and finite-element methods, are frequently the only alternative. For example, numerical codes are used to evaluate coupled fluid and nuclide transport in complex geometry. Similarly, thermo-mechanical codes have been developed to analyse the performance of host media affected by repository excavations and waste emplacement, including the effects of heat on groundwater flow.

In the more comprehensive performance analyses which are needed for deciding on the acceptability of specific disposal systems, models based on numerical methods are usually employed to obtain best estimates of system performance. For the sensitivity and uncertainty analyses which also form part of a comprehensive performance analysis, both numerical and analytical models may be used. Examples of combinations of different types of subsystem models can be found in the various versions of the SYVAC system model which have been and are being developed in Canada and the United Kingdom [10, 15], and in the LISA code being developed at the Joint Research Centre of the Commission of the European Communities in Ispra, Italy [16].

3.4.2. Availability of data

In many cases mathematical models can be developed in exquisite detail for waste disposal systems, subsystems or components. However, sometimes the details can be rendered useless by the lack of knowledge concerning parameters that represent those details. Any choice of models for performance analysis must therefore take into account the availability of sufficient data to meet the needs of the models.

Often it is possible that more detailed models can be used as more is learned about the system parameters. For example, characterization of potential waste disposal sites will permit use of more detailed models than may be used in earlier phases of site selection. Also, field and laboratory tests of interactions between geological media and waste forms or canisters may eventually permit more detailed models of those interactions to be developed.

In general, model development should proceed in parallel with field and laboratory research, so that the level of complexity of models is always commensurate with the availability of data. In practice, however, model development often proceeds more rapidly than data collection. This is useful in that models can then be used in sensitivity analyses which have the objective of identifying potentially important parameters and processes, and hence of indicating research priorities. However, there is an inherent danger that the results obtained with models may be assigned more absolute value than is warranted by the quality of the input data. This situation can be avoided to some extent by including suitable caveats when analysis results are presented (Section 5). When the model is more detailed than the data available, it should be clearly stated that this fact has been recognized when selecting the model, and the effect of data quality upon predicted results must be considered in the light of the purpose of the analysis.

3.4.3. Matching models to scenarios

As explained in Section 3.3, the most convenient way of classifying phenomena for analysis purposes is in terms of their influence on the analytical procedures required. With this type of classification scheme, model selection is closely linked to scenario selection, and thus the possibility of inconsistency between the model selected and the scenario under consideration is substantially reduced. Nevertheless, care is required in the application of models to physical situations which were not considered when the models were developed.

As a specific example, it is helpful to examine the use of the porous medium approximation in the modelling of radionuclide migration in fractured geological media. This approximation is reasonable when the groundwater flowpaths are much longer than the average fracture length and spacing. It can therefore be used for many of the groundwater flow scenarios which are considered in analyses for repositories in, or surrounded by, fractured media. However, there will be some low-probability scenarios in which path lengths become so short that the porous medium approximation becomes invalid and a model which deals with discrete fractures is required.

Another example is the use of near-field models in which it is assumed that the rate of release of radionuclides from waste into groundwater is solubility limited. This assumption breaks down for high groundwater flow rates, and thus different near-field models are needed.

4. COMMENTS ON SELECTED TECHNIQUES FOR PERFORMANCE ANALYSIS

4.1. MODEL DEVELOPMENT

4.1.1. Steps in development

The steps in the development of mathematical models of systems or subsystems are shown in Fig.2. After the system or subsystem has been defined, the first stage is to build a conceptual model of it. This is done by reviewing knowledge about the behaviour of the type of system under consideration, by examining any existing models and by consulting scientific experts.

Once the conceptual model is available, the next step is to formulate the mathematical equations which describe it, together with appropriate initial and boundary conditions. The equations are then solved, by either analytical or numerical methods, and the model is then verified using one or more of the methods described in Section 4.4.

Ideally, the model should then be validated by comparing its predictions with observations. In practice, however, direct complete validation of the models used in performance analysis of waste disposal systems is rarely possible and it is often necessary to apply models for which no complete validation has been carried out (Section 4.5). At both the verification and validation stages, errors or deficiencies in the model may be identified, leading to a need to reformulate either the conceptual model or the equations and boundary conditions, or both. The final step before routine application of the model is to confirm that it is indeed adequate for its purpose (Section 3.4).

Model development is an iterative process in which ideas about system behaviour are continuously revised as knowledge of the system increases. Moreover, of all the stages in model development the formulation of valid conceptual models is probably the most important, and the most difficult.

4.1.2. Subsystem model development

Only by use of highly simplified approaches can the performance of a total waste disposal system be analysed with a single model. The normal procedure is

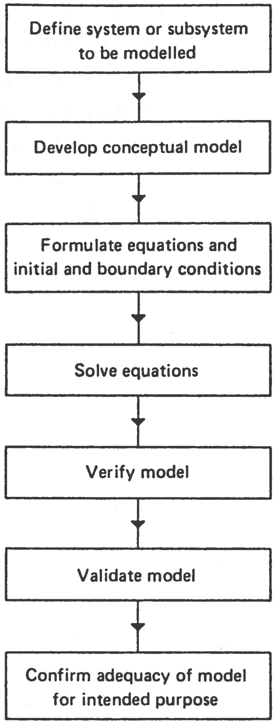

FIG.2. Steps in model development.

to work with a series of more detailed models treating parts of the system, whereby the degree of automation of the linkage between subsystem models varies widely.

Selection of subsystems for analysis, either simple or detailed, should be based upon three principal criteria:

(a) The importance of interactions with other subsystems. If coupling is strong, one may require efficient iterative linking or else integration within a single, larger subsystem model.
(b) The practicability of aggregating the subsystem with others. Computer storage capacities and running times can often be restricting.
(c) The level of detail needed in subsystem modelling. If one can ignore components of a subsystem for reasons of simplification or conservatism, it may become feasible to integrate the subsystem model into another model. For example, by neglecting detailed design features and by disregarding the presence of corrosion products, one can more easily include the waste container subsystem model in a larger model of the vault.

At a subsystem modelling level, it is often necessary to demonstrate a more fundamental understanding of processes that control performance than may be needed for total system analysis. Because of the requirement to predict long-term behaviour, a sound theoretical basis is essential for such modelling. Models developed to study such behaviour are usually based on correlations between theory and experiment. An example of a theoretical model is the inverse relation between the diffusion coefficient of a solute in a liquid and the absolute temperature.

Although simple theories such as that mentioned above are the ideal, there are frequently many interacting phenomena governing the performance of a subsystem. Statistical design of experiments is a useful technique for identifying dominant processes. The model then is based on the dominant processes, with coefficients adjusted to account for lesser processes. For instance, in the analysis of the corrosion behaviour of a canister the dominant process is controlled by temperature and the chemical environment outside the canister, and radiation is treated as a secondary factor enhancing the dominant process.

4.1.3. Coupling of models

If the application requires coupling many interactive processes, one may choose either to iteratively couple subsystem and/or component models or to develop a new model that treats the processes simultaneously. Coupled models, because they retain the details of each model, are easier to integrate but can result in computing difficulties and inefficiencies. In the case of finite-element or finite-difference methods, the mesh size is determined by the most restrictive process. The calculating efficiency for the coupled model is therefore lower than for most of the separate models. In addition, the iterative calculating processes can introduce instabilities that further decrease operating efficiency and hamper accuracy. A common solution is to design a simpler, combined computer code that treats only those phenomena that are important for a particular application.

When one parameter significantly affects another but not the reverse, it is normally feasible to run codes sequentially. As an example, because heat transfer is largely unaffected by the mechanical state of the host rock, the thermal field can be calculated, followed by the mechanical response of the host medium to the thermal field. However, there are cases where it is not possible to decouple phenomena so that sequential coupled models can be applied. For example, the effects of density changes should not be excluded from flow models for brine systems.

4.2. SENSITIVITY ANALYSIS

The process of determining the degree to which the predicted system behaviour depends on particular assumptions or parameters is called sensitivity analysis. These assumptions and parameters are of four types:

(a) Initial conditions;
(b) Boundary conditions;
(c) Implicit parameters, i.e. parameters (usually constants) which are built into the code;
(d) Explicit parameters, i.e. parameters which have to be provided as input data.

Sensitivity analyses with a given model are simplest when examining the influence of changing initial and boundary conditions, and explicit parameters, on model results. Sensitivity to changes in implicit parameters cannot be examined without modifying the code itself.

In a sensitivity analysis the influence of changing parameters on the predicted behaviour of the system is evaluated, usually for the purpose of identifying parameters which affect the system behaviour strongly or else to a negligible extent. For example, in hydrogeological modelling, the hydraulic conductivities in different geological formations may be varied to identify those parameters to which the predicted flow through the repository is most sensitive. The value of a parameter used in a sensitivity analysis run can be selected arbitrarily from within the range of experimental values or from outside this range to observe its influence on system behaviour. It is generally agreed that sensitivity analysis is most transparent using simple mathematical models. On the other hand, the need for sensitivity analysis increases with the complexity of the model. Sensitivity analysis should, of course, be performed using only verified models (Section 4.4).

Sensitivity analysis is also helpful in model development, because it can be used to test the influence of various assumptions on predicted system behaviour. It may show that a simplified model is adequate, or that certain areas should receive more resources for future work. It can also indicate needs for changes in subsystem design.

4.2.1. Single-parameter variation

The simplest approach to sensitivity analysis is to vary one parameter and hold all the others constant, and to repeat the exercise for each parameter of interest. For any mathematical model with a large number of parameters this approach is tedious, time consuming and costly in terms of computing needs. In performance analyses of radioactive waste disposal systems, even relatively simple mathematical models can have more than thirty parameters, making full sensitivity analyses expensive. Consequently, more efficient methods of sensitivity analysis are beginning to be used. A further disadvantage of single-parameter variation is that the sensitivity of the varied parameter is often strongly dependent upon the fixed values assumed for other parameters, which can themselves be very uncertain. An example of single-parameter variation in sensitivity analysis is given in Ref. [17].

4.2.2. Multiparameter variation

Another technique which can be used for sensitivity analysis is based on Monte Carlo or similar methods (see also Section 4.3). The parameter of interest is held constant at one value while all the other parameters are sampled over their ranges or distributions. The procedure is then repeated with the parameter of interest held constant at a different value. The advantage of this technique is that it produces more quantitative, statistical information about the sensitivity of model results to variations in parameters than does the simpler method of single-parameter variation. Its disadvantage is that it requires a large number of model runs [10].

4.2.3. Adjoint method

The adjoint method is applicable to mathematical models defined by particular types of differential or integral equations [18]. The adjoint equations corresponding to the original partial differential equations are derived and expressed in such a way that their dependent variables are the desired sensitivity coefficients. The solution of the adjoint equations yields the values of all the sensitivity coefficients, for a given set of values of the independent variables, in a single set of calculations. The chief advantage of the adjoint method is that fewer calculations are required to determine the sensitivity coefficients. The adjoint method appears to be best suited to situations in which the number of dependent variables is small and the number of input parameters is large. No extensive use of this method has been made, but an example of its application can be found in Ref. [19].

4.3. UNCERTAINTY ANALYSIS

The sensitivity analysis techniques mentioned above are intended to indicate which issues strongly affect system behaviour and to quantify their influence on predicted performance. Uncertainty analysis is used to quantify the extent to which the predicted performance of any system may differ from the actual performance. Uncertainties in the projected performance of radioactive waste disposal systems have several causes, including: (a) the inability of the models to represent the system completely, (b) approximations used in solving the model equations, and (c) uncertainties in the values of the parameters needed as inputs to the models.

There is also the inherent, irreducible type of uncertainty represented by gaps in our current understanding of the system. However, there is little that can be done to resolve this type of uncertainty – unlike our attempts to deal with the first three types of uncertainty mentioned above.

The simplest kind of uncertainty analysis consists of making calculations using bounding values of parameters in order to estimate maximum and minimum results. In more complex models, however, it is not always obvious that values bounding predicted system performance are produced by using extreme values of all input parameters. It is also possible to determine the whole scope of uncertainties by comparing the results obtained when simplified conceptual models of the system are used. For example, in near-field modelling, calculations can be carried out assuming that buffering and backfilling materials do not sorb radionuclides and that canister corrosion products do not delay radionuclide migration.

The errors or uncertainties in performance projections that are introduced by incomplete model specification or by approximations made in solving the model equations can be determined only by making additional calculations using more complete models and/or fewer approximations. The performance projections thus generated can be compared with those developed using simpler models and more coarse approximations. For example, if finite-element solutions are used to represent continuous phenomena, the number and size of the elements must be chosen by the modeller. To check the effect of choosing a limited number of elements, the same phenomena can be modelled with smaller, more numerous elements. If no significant differences in performance projections occur, the modeller has chosen a sufficient number, though he may still have chosen more elements than the minimum number necessary.

Input parameters are generally variables, reflecting spatial and temporal variations and the imprecision of measurements. Thus, these parameters can often be better characterized by probability distributions rather than by single values, such as the mean or median. Uncertainty analysis seeks to investigate the system response when individual parameters take any value within the range of experimental values. Although in sensitivity analysis (described in the last section) arbitrary values for individual parameters can be used just to observe the effect, in uncertainty analysis only values within the probability distribution should be used.

Since input parameters are often described in terms of probability distributions, one common method of uncertainty analysis is random sampling or the Monte Carlo approach. In this method, a value for each input parameter is selected randomly from its respective probability distribution. A 'realization' is then obtained for a run using this randomly selected set of parameter values, termed the input vector. The model is run repeatedly for different input vectors, with each realization representing a possible state of the system. The output is then in the form of a distribution which can be analysed statistically.

Often parameters in performance analysis models are correlated spatially or functionally. This is usually represented in some specified relationship between parameters. For instance, rock porosity and permeability may be related. Important correlations should be accounted for in the sampling process.

For completely random sampling there exists the possibility that low-probability parameter combinations may be missed if a relatively small number of input vectors is used. To circumvent this possibility, stratified sampling procedures have been developed. One example is Latin Hypercube Sampling, which was designed to ensure that extreme parameter value combinations are accounted for and to eliminate possible duplication of parameter sets. This technique yields an ensemble of a minimum number of sets of input vectors which is complete in the sense that parameter values from all (user defined) intervals of equal probability are selected and used. Stratified sampling techniques can result in significant savings in computing time, but can also complicate the interpretation of analysis results. The merits of stratified sampling techniques depend also upon the relative importance of fixing the general shape of a predicted distribution (e.g. of container lifetimes), as opposed to precise definition of a particular part of the distribution (e.g. the high-consequence, low-probability tail of a risk curve).

There are many ways of presenting the results of uncertainty analyses which have been carried out using sampling techniques. They include probability density functions and cumulative distribution functions of important performance measures, such as doses to individuals or populations, and correlations between important performance measures and model input parameters.

4.4. MODEL VERIFICATION

A mathematical model, or the corresponding computer code, is verified when it is shown that the 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 is an activity separate from validation because the latter deals with the correspondence between the conceptual and mathematical models and the processes in the real system.

Verification consists of:

(a) Checking the computer code to see whether the programming is correct, i.e. that the program represents the sets of equations to be solved;
(b) Comparing the computed results with problem solutions obtained from either analytical solutions or other, more accurate numerical solutions.

The verification activity need not attempt to demonstrate that the model performs under all sets of conditions, but rather that the code functions properly under the sets of conditions that bound its intended usage. While it is important to recognize and appreciate the 'robustness' of a computer code, this should not be the primary objective of verification.

There is no single approach to model verification. The model builder or analyst must determine which techniques are needed to obtain the degree of confidence desired, and this selection process should take into account the nature of the problem solved. The extent of the verification needed will depend on the intended use of the model.

A structured approach towards model verification is recommended. The need for model verification should be acknowledged during the early stages of computer code development. Aspects of verification include reviews, analyses (i.e. applying the code) and documenting results.

A test plan can be prepared to help direct the verification activities. The plan employs as a primary input the basic requirements that are specified to direct the preparation of the model. To assist in the preparation of the test plan, it is suggested that the tester construct a matrix that relates the computer model attributes selected for testing to the type of test to be performed. The type of test could consist of either a defined (physical type) problem or a procedure designed to check program logic. The test plan should contain a description for each of the problems (types of test) selected for verification.

The USNRC has identified for a range of subsystem models a set of problems with known solutions that could be incorporated into verification [20]. This set is generally consistent with the nuclide transport verification problems selected in the INTRACOIN study for its level 1 code comparisons for numerical accuracy [21].

Verification analyses can make use of another computer model for purposes of comparison. This is called benchmarking. The selection of the benchmark computer code is important. As a rule, this code should either be an acceptable standard or have undergone similar verification testing to the code being tested. If a standard exists, it should be used. If a new code is developed for comparison with an existing version it should be developed by someone other than the model builder to avoid bias in the verification.

Verification of code design and adequacy of computer code programming is best done during development of the code, using both manual and automated techniques. Manual techniques can consist of step-by-step checking of the logic of the models or line-by-line checking of the codes; these checks can be made internally or by independent experts. Options for a number of automated techniques for quality assurance and code verification are normally available in most modern computer systems [22, 23].

Once the code design and programming features have been reviewed and approved, the computer model is ready for formal testing using the problem sets described in the test plan. Obviously, during development of the computer model the builder or analyst will already have exercised the entire computer model or parts of it.

As in any evaluative activity, the results of model testing must lead either to acceptance or to rejection of the model as it is. Prior to testing, criteria should be set based on a numerical difference, e.g. the root mean square error, or could be expressed in terms of a numerical solution characteristic such as stability or convergence.

Requirements for documentation can be specified in the verification test plan. It is assumed that the computer model will be used by other investigators; consequently, the test history of the model should be preserved. An example of a documentation requirement promulgated by the USNRC may be found in Ref. [24].

Reporting of errors that are experienced during testing is extremely important because this information will be used either to improve the computer model or to define limits for its use.

In summary, verification consists of five basic steps:

(a) Preparation of a test plan
(b) Preparation of operational and maintenance procedures to assure control during testing
(c) Test runs using methods mentioned above
(d) The reporting of results of verification
(e) Review and approval of the verification.

4.5. MODEL VALIDATION

A conceptual model and the computer code derived from it are validated when it is shown that they provide a good representation of the processes in the real system. Validation is carried out by comparison of calculations with field observations and experimental measurements. A general discussion of validation is included in IAEA Safety Series No. 58 [4] and the reader is encouraged to read this material.

It is clear that not all the models used in system performance analysis can be fully validated because of the long periods and subtle effects involved. For similar reasons, the degree to which the subsystem and component performance analysis models can be validated by in situ experiments is often limited. In most cases validation will rely upon the use of laboratory and field experimental data.

In some cases less controlled types of validation can be performed by making comparisons with natural systems that contain natural or artificially produced nuclides. Examples of the former type are Oklo [25] and Carrizo [26] and of the latter are fallout nuclides in the ocean [27]. The difficulty of this type of validation is that the experimental conditions are not generally well understood. If natural systems or analogues are to be used as a basis for validation, a plan for using each of the selected cases should be developed.

Another type of limited validation is external peer review. This consists of a careful review of the assumptions used in developing the model at the system, subsystem or component level. Although such a review is not a formal validation, it can increase confidence in the validity of the results.

The procedure used for validation is similar to that used for verification. A validation test plan should be prepared for the validation activities that involve comparing simulation results with experimental data. This planning activity could be initiated by defining the model features that will be tested and the data that will be used to test them. The question how to obtain the necessary data (i.e. data availability) must be considered carefully. The validation test plan should describe the use of the model to predict behaviour and then the collection of the necessary data to compare with predicted values.

A description for each of the validation test cases should be prepared. The descriptions will be provided to the field and laboratory researchers for review and comment on the feasibility of collecting the data. An interactive process will continue until agreement between the experimenter and the performance analyst is obtained. Results of the validation test activities should be documented. The plans for documenting the results should be outlined in the validation test plan.

Level 2 of the INTRACOIN study mentioned in Section 4.4 is an example of an exercise to select and use field experiments for the purpose of validation [28].

Validation is an extremely important, but often difficult, aspect of modelling. Even extensive verification of a model does not reduce the requirements for validation.

5. GUIDANCE FOR PRESENTATION OF ASSESSMENTS

To avoid misunderstanding or misinterpretation of the results of various types of performance analyses and assessments, it is essential that special care be taken to give a comprehensive account of the intentions of the study, the methods used, the assumptions made, the data employed and the relevance of the results. To facilitate understanding and allow comparisons between different assessments, a list of subjects and a list of special features that should be covered in the description of a performance assessment are presented below.

5.1. INFORMATION TO BE PRESENTED

(1) State the purpose of the study. It should be made clear what the results are going to be used for. If there are criteria or performance targets to comply with or ranking methods to be used, they should be identified. An identification of the phase of system development for which the analysis was made would also be an informative part of the purpose statement.

(2) Describe the system. Any subsystem to be analysed should be defined and its role in the total system indicated (possibly in terms of the general reference waste disposal system definition in Section 2.2), as well as the internal and external interactions of the subsystem.

(3) Define explicitly the database used in the assessment, either by including it in the assessment report or by referencing. It should include site-specific, system-specific and more general data (e.g. dose per unit intake value). Data limitations should be carefully discussed and documented.

(4) Describe the methods for scenario selection. Restrictions on scenario selection caused by the framework of the total system or the site should be identified. Methods for scenario generation should be indicated. The probabilities of the selected scenarios should be discussed.

(5) Describe the methods used in the analyses. The type of analysis should be stated (probabilistic/deterministic, identification of bounding value/best estimate, numerical/analytical, etc.). The mathematical models used should be identified, with implicit assumptions and uncertainties clearly defined.

(6) Present the results. These should be in a format which is, as far as possible, readily understandable, and the framework in which the results are to be interpreted should be made clear. The uncertainties should be stated.

5.2. FACTORS TO BE DISCUSSED

(1) The degree of generality. Indicate the degree of dependence of the system and subsystems on site-, system- or goal-specific data, models or methods.

(2) The coverage achieved by the selected scenarios. Examples are extreme values from a span of possible scenarios, or a most probable scenario, or scenarios covering the loss of a specific component in the total system.

(3) The relevance and quality of the data and the validity of the models.

(4) The degree of conservatism. How extreme is the conservatism? How is the conservatism introduced (e.g. through data, simplifying assumptions and disregarding favourable phenomena)? Describe the consequences of the conservatism on the uncertainty and sensitivity analyses.

(5) The simplifications and judgements introduced. The reasons for introducing simplifications should be discussed, as well as the possible filtering or biasing effects of the human judgements involved.

(6) Confidence in or relevance of the results. The relevance of the performance measure chosen should be discussed in the light of the results achieved, existing criteria and the above-mentioned characteristics of the analysis.

5.3. TERMINOLOGY

Since performance assessment of nuclear waste disposal systems is undergoing rapid change, special care should be taken to avoid the development of local 'dialects' caused by ad hoc definitions. The IAEA recommends the use of its Radioactive Waste Management Glossary [29] and the glossaries in the IAEA Safety Series. Deviations from these glossaries should be clearly indicated in programme publications from each country to prevent needless misunderstandings by readers from other nations.

6. CONCLUDING REMARKS

It is internationally recognized that performance assessments, and in particular safety assessments, play a central role in the development and implementation of methods for the disposal of solid radioactive wastes. To promote consistency in waste disposal standards, it is desirable to reach a consensus on general approaches to these assessments and on some of the techniques to be used in analyses of disposal systems.

Although assessments of the complete disposal system are of primary importance, assessments of subsystems are also necessary in the planning of waste disposal projects. Accordingly, this document has attempted to provide practical guidance to those carrying out both system and subsystem performance assessments.

The field of work covered here is developing very fast. Technical developments are occurring because simple models are being used as a basis for more complex approaches, because more experience is being acquired, and because in many countries increased effort is being devoted to the analysis of waste disposal systems. These developments are also necessary because increasingly detailed analyses are required as disposal projects mature. Several countries, for example, are now at the stage of site-specific studies. Such rapid progress will justify a new comprehensive performance assessment guide within the next few years.

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