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Edition 1

HMIP Assessment of Nirex Proposals

Technical Report IZ3185-TR1 (Edition1)

Identification of Relevant Processes

(System Concept Group Report)

W M Miller and N A Chapman

This report has been prepared by Intera Information Technologies for Her Majesty's Inspectorate of Pollution (HMIP) of the United Kingdom Department of the Environment (DoE) under the terms of DoE Contract Reference PECD 7/9/608.

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INTERA
Environmental Division

August 1993

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HMIP

Disposal Assessments

HMIP Assessment of Nirex Proposals
Performance Assessment Project
(Phase 1)

Identification of Relevant Processes
(System Concept Group Report)

DA Ref: TR-ZI-11

Summary:

This report presents a record of a meeting of a group of eight experts in various subjects of relevance to the post-closure assessment of deep underground disposal of radioactive wastes. This group – The System Concept Group – was set the task of providing a preliminary but comprehensive overview of processes that could be important in an assessment of post-closure safety of the proposed repository for L/ILW at Sellafield.

The basis for the meeting was very preliminary information on the Sellafield site and proposed repository and the Group carried out its work mainly over an intensive two day period.

Hence, the record produced is not to be taken as a final or complete statement on the various processes that might eventually need to be considered in either Nirex or HMIP assessments.

However, the record has been used in HMIP assessments as a starting point for discussions by Working Groups charged with more detailed examination of various aspects of the disposal system (see TR-ZI-2, 3, 4, 6 and 7).

Edition: 1 **Date:** August 1993

Authors: W M Miller and N A Chapman

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Summary

The System Concept Group (SCG) consisted of a group of eight experts in various aspects of deep disposal of radioactive wastes and was conceived as a means of providing a preliminary but comprehensive overview of processes and factors which could be important in the post-closure safety assessment of the proposed repository at Sellafield. Part of the Dry Run 3 exercise involved the elicitation of a list of processes relevant to the Harwell site considered in Dry Run 3. For the current assessment it was considered appropriate to use the Dry Run 3 Process List as the starting point for the SCG.

In general the Dry Run 3 Process List was found to be comprehensive and few additional processes were added. A number of processes were removed or substituted where they were obviously specific to the Harwell site environment. In addition the list was restructured to take into account, (a) the necessary re-ordering of the biosphere component processes which were generally thought to be far too complex, given the inherent uncertainties in the earlier parts of the release chain (near and far-fields), and (b) to bring to prominence the following processes which the SCG felt were critical to the behaviour of a repository at the Sellafield site.

- Stability of the repository – The backfill used in the ILW vaults is seen as having no structural function. There will be no backfill in the LLW vaults and, possibly, no backfill above the ILW concrete cells. Vault roof stability, therefore, becomes and issue. Progressive collapse of the roof onto the degrading wastes and upwards migration of the collapse-damaged rock is anticipated producing an extensive zone of increased porosity and permeability in the host rock.

- ILW near-field chemical environment – The long-term maintenance of low-flow, stable flux, highly alkaline, reducing conditions in the ILW vaults are central to the Nirex disposal concept and safety case. Consequently, this aspect requires close scrutiny to determine that chemical homogeneity will develop rapidly, persist and behave as predicted.

- Hydrology at repository depth – Groundwater fluxes at depth will require careful evaluation given the proximity of the repository to the Ravenglass sub-basin and other features. It must be determined whether the system can be evaluated exclusively in terms of steady-state topographically related head differences, or if other driving forces need to be taken into consideration.

- Groundwater flow and radionuclide transport modelling – It is likely that models used to date to represent groundwater flow and radionuclide transport are based on overly simplistic assumptions and do not adequately characterise the system. Alternative concepts should be considered to model planar and fracture flow.

- Consequences of glaciation – It is likely that climatic cycling will continue for the whole period covered in the quantitative assessment and that significant climate changes will be apparent within 5,000 years from present. Evidence exists to suggest that there is potential for deep incision to occur as a consequence of glaciation and that the effect on deep groundwater flows may be significant.

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1 Introduction

This report describes work carried out in the framework of Department of the Environment contract PECD 7/9/608 (Post-closure radiological safety assessment of Nirex proposals) let on behalf of Her Majesty's Inspectorate of Pollution (HMIP) to Intera Information Technologies Ltd. It is a component of the independent assessment by HMIP of the UK Nirex Ltd proposals for a deep, low and intermediate-level radioactive waste (L/ILW) repository at Sellafield in Cumbria.

The System Concept Group (SCG) was conceived as a means of providing a preliminary but comprehensive overview of processes and factors which could be important in the post-closure safety assessment of the proposed repository at Sellafield. The SCG was charged with making a preliminary qualitative evaluation of which processes and features are likely to be significant in affecting repository performance, the possible interactions of these processes and features, the timescales over which they may be relevant and the scope and levels of assessments in which these processes could usefully be evaluated.

The results of the SCG deliberations are intended to provide guidance for the specialist working groups charged with developing detailed modelling approaches for the various components of the system (hydrology, near field, surface environment etc.). The list of phenomena and comments may also be used as the basis for auditing the phenomenological scope of assessments as documented in submissions expected from Nirex. The overall structure of the HMIP assessment (Phase 1), and the position of the SCG, are shown in Figure 1.

The main output of the SCG, presented in this report, is an annotated list of processes with associated discussion on their nature, significance and interactions, together with suggestions for which of these might comprise the inputs to various levels of assessment (Table 3). The report is structured as follows:

- an introductory description of the methodology adopted and the principal issues raised during the work,
- suggestions for the structure and content of various levels of assessment,
- a compilation of the final list of processes considered by the group with discussion of their significance,
- appendices containing guidance notes, other working documents used by the SCG and information on the expertise of SCG members.

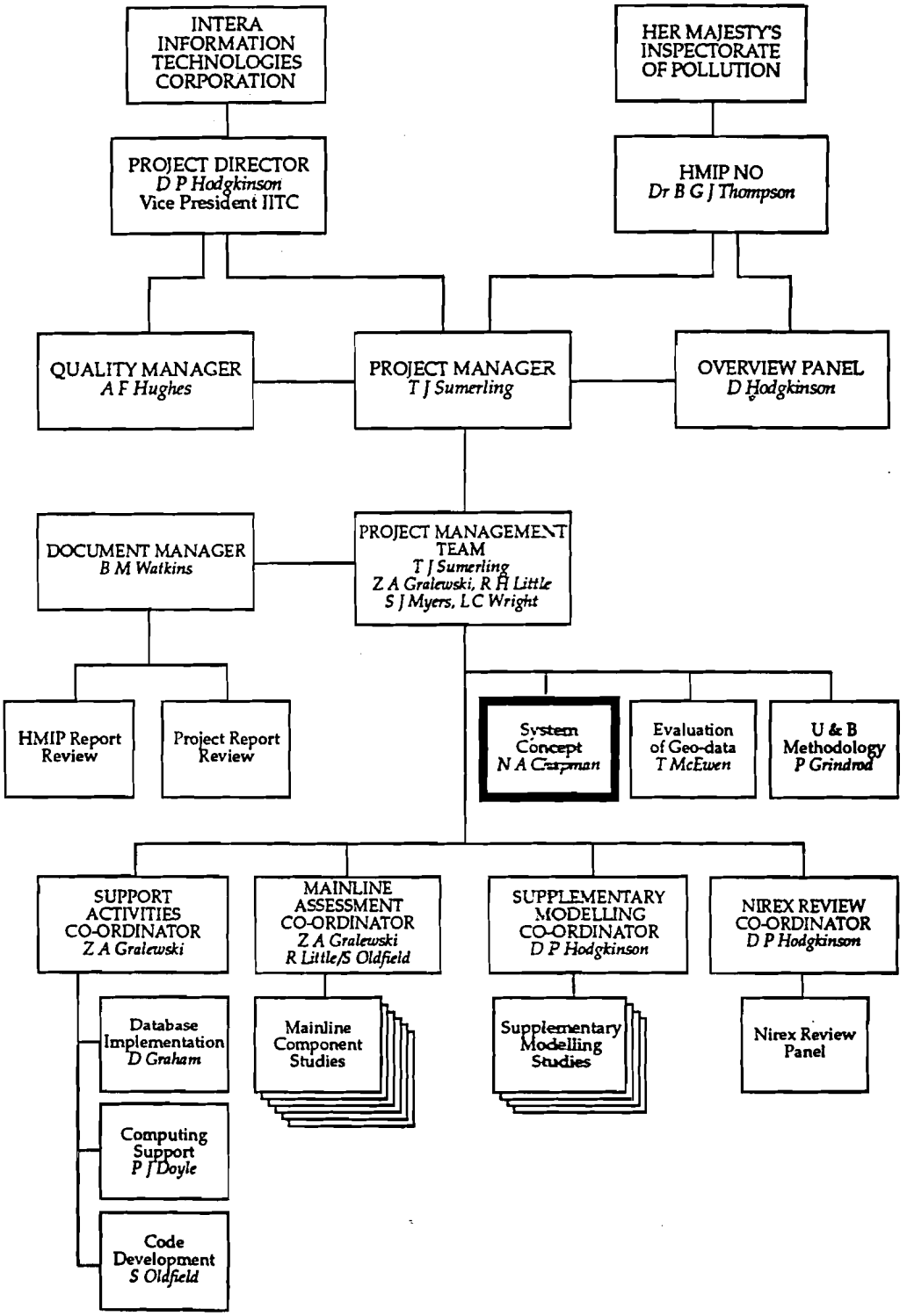

Figure 1: Organisation and Management Structure of the HMIP Assessment Project (Phase 1)

2 Methodology

The basis for the SCG was developed as part of the HMIP Dry Run 3 assessment of a hypothetical deep repository for low and intermediate level wastes situated beneath the Harwell site in Oxfordshire (Sumerling, 1992). In parallel with this assessment, an 'Uncertainty and Bias Audit' was performed, part of which involved a pilot exercise to identify and consider processes and features of significance in an assessment (Thorne, 1992). The pilot exercise involved the progressive elicitation of a list of processes which needed to be considered and the inclusion of relevant processes in influence diagrams which could be used as the bases for quantitative performance assessment. The exercise was performed by a group of scientists with expertise in the required scientific, technical and engineering fields. The expert group was guided by a secretariat and care was taken to try to avoid the introduction of biases which could subsequently affect the outcome of an assessment.

For the current assessment of the UK Nirex Ltd. proposals for Sellafield, it was considered appropriate to build on the foundations laid in the previous exercise and to use the output of the Dry Run 3 Uncertainty and Bias Audit (Thorne, 1992) as a starting point for the SCG.

2.1 The Issue of Bias

A fundamental problem of any type of predictive evaluation of the behaviour of a system is that the conceptual models used may be biased[1]. A typical bias may be that emphasis is put on evaluating the consequences of a particular mode of behaviour which is thought to be dominant, while other modes are overlooked. In repository safety assessment, such a bias might be that only topographically produced driving forces are assumed to influence deep groundwater flow, while thermal, tectonic and density difference effects are overlooked. Whilst it may be acceptable to make such omissions, the assessment process needs to record and justify any such assumptions and consequent conceptual limitations or simplifications. The important issue is that alternative conceptual models should not be ignored or overlooked and that every effort is made to identify potentially significant processes at an early stage.

Inevitably, the process of eliciting information from experts can introduce biases arising both from the previous experience of each expert and from that of the elicitor. Using a group with overlapping fields of expertise, including a number of specialists who can also be considered generalists in the radioactive waste field, was considered to be a reasonable precaution against undue bias. The use of the output of the earlier HMIP exercise, prepared by a different expert group, was a pragmatic decision, but was thought to provide an additional guard against bias or omissions, since the SCG experts could not only develop their own ideas, but could superimpose their own views on those of others, without starting from scratch.

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[1]The SCG did not define bias. However in the Project Glossary of the DoE Disposal Assessment Team Management Report (MR-DoE-22) bias is defined as "an effect which deprives a result of representativeness by systematic distortion".

2.2 The System Concept Group

The SCG was set up in April 1992 and completed its work in July 1992. The task was divided into four phases:

- Appointment and briefing of experts.
- Individual evaluation of documents on the Sellafield repository concept and site by the experts and consideration of the Dry Run 3 process list and influence diagrams. Each expert spent about 3 or 4 days on this.
- A two-day group meeting to consider the processes together, refine the list and suggest structures and contents of various levels of assessment.
- Individual review of final compiled results by the experts.

The SCG comprised eight experts, a chairman/facilitator and a secretary (Table A). Brief summaries of the relevant expertise and competence of the experts are given in Appendix 5. In addition, an observer was present for part of the meeting to evaluate possibilities for the introduction of bias into the proceedings. The report of this observer is included here as Appendix 4.

Table A. Expert Group List

Expert Group	*Field*
Professor G Boulton	Climatology; geomorphology
Professor F Glasser	Chemistry; near-field
Dr H Grogan	Biosphere processes
Dr E Hamilton	Marine processes
Dr S Horseman	Geotechnical aspects
Professor G de Marsily	Hydrogeology
Dr T McEwen	Geology
Professor I Neretnieks	Chemistry; transport processes
Secretariat	
Dr N A Chapman	Chairman; facilitator
Dr W M Miller	Secretary
Observer	
Professor S Watson	Management Studies

The guidance notes issued to the experts prior to starting work are included in Appendix 1. The essential features of this guidance are:

- each expert was asked to give an opinion on each process, on which they

felt competent to comment, contained in the final list of processes elicited in the Dry Run 3 Uncertainty and Bias Audit and to check for omissions from this list;

- opinions were sought on the significance of each process within three timeframes; 0 to 10,000 years, 10,000 years to 1 million years and beyond 1 million years;

- having considered the significance of each process, the experts were asked to say whether they should be included in a 'minimal assessment' or whether they should be evaluated by separate scoping calculations[2]. The minimal assessment definition of 'lowest level of complexity which would not exhibit gross bias as a result of excluding phenomena' was taken from Dry Run 3 Uncertainty and Bias Audit;

- it was stipulated that the HMIP assessment would not be concerned with non-radiological hazards (eg. toxic but nonradioactive materials) or with pre-closure safety of the repository;

- it was noted that the HMIP assessment would only attempt quantitative evaluation for a period of up to 1 million years; any evaluations for times beyond this would be qualitative;

- each expert received the same basic information package and was invited to comment on the processes as widely or narrowly as they felt able or confident;

- the experts were asked to take no account of how the processes might actually be addressed or modelled in a quantitative assessment, as this would be a problem for other working groups since perception of difficulty in modelling a process could have biased the SCG away from including it in an assessment;

- it was requested that experts not bias themselves by seeking out documents describing either the UK Nirex approach to building a safety assessment or the modelling capabilities of HMIP.

Several of these aspects of the guidance notes resulted in discussions at the SCG meeting which, in some cases, caused modifications in the approach taken to the overall task. These are discussed in Sections 2.4 and 3 below.

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[2]There is clearly some terminological inexactitude in the Guidance notes in this respect. If a process is evaluated by 'separate scoping calculations', then it is, in fact, being assessed, and is consequently part of the assessment. The rationale for the use of the term was simply to identify processes and features which might reasonably be omitted from the mainstream integrated assessment calculations and treated separately. The assignment of a process to a 'scoping calculation' list may mean that it is either influential or of little consequence; only quantitative evaluation will tell which. If it is significant, then it may then need to be placed in a 'minimal assessment'. See also section 3.1.

2.3 Documents Considered

The range of available documents describing the site, the repository concept and the wastes was limited and of variable quality. The following reports were considered to give the most reasonable and up-to-date coverage and comprised the only material provided to each expert:

1. UK Nirex Ltd (1991) The repository project: an engineering progress report describing the preferred design concept.

2. UK Nirex Ltd (1991) Waste volumes, radionuclide content, heat output and material composition for RSD. Nirex Report, 277. (DRAFT).

3. UK Nirex Ltd (1992) The geology and hydrogeology of Sellafield, March 1992 interpretation. Volumes 1 and 2. Nirex Report, 263.

4. UK Nirex Ltd (1992) Repository design data for stage 2 performance assessment in support of RSD. Nirex Technical Note, TN(92)1.

5. Hills, D L (1991) A deep repository for the disposal of low-level and intermediate-level radioactive waste: summary of Nirex intentions based on published information. Building Research Establishment.

6. Waters D, Little R (1992) Description of present-day surface environment at Sellafield. Intera Technical Note, IZ3191-TN1 (Version 1).

2.4 Approach to the SCG Meeting

During the Dry Run 3 Uncertainty and Bias Audit, a list of relevant processes had been compiled and organised into a process classification scheme with four different classification levels (Table 1). This process list was circulated to the SCG members prior to the meeting for their consideration. The experts' views on the significance of each of the processes on this list were compiled (Appendix 2) and this compilation list was used as the basis for discussion during the meeting. The programme for the joint evaluation of the compilation list given at the beginning of the meeting was as follows:

- go through the process at the tertiary level (eg. 1.1.1) and discuss freely the nature, effects and interactions of these processes;

- use the earlier HMIP influence diagram (see Figure 2) as an aide memoire to check for possible interactions and encourage lateral thought, consider appropriateness and modify as necessary;

- discuss significance and interactions of each group of processes and evaluate the timescales (unconstrained by specific timeframes) over which they are significant;

- consider quaternary level processes (eg. 1.1.1.4) as tertiary level processes were discussed but, where possible, make decisions at tertiary level only;

- add to the list of processes and features, modify and upgrade quaternary level processes to tertiary level where they are considered significant;
- decide whether processes should be in or out of an ideal assessment, independently of how the process is modelled; seek consensus and ask for dissenting views[3];
- decide whether an assessment would be adequate without each process ie. define the scope of an 'adequate assessment';
- record decisions, together with a commentary on views and discussion (Table 3 of this report);
- finally, outline a revised influence diagram for the ideal assessment and, if markedly different, repeat for the adequate assessment.

The terminology of a 'minimal assessment' used in the Dry Run 3 Uncertainty and Bias Audit was judged to be insufficiently defined. Therefore, for the purposes of the work of the SCG, the concept of 'ideal' and 'adequate' assessments were introduced at the beginning of the meeting and substituted instead.

An 'ideal assessment' considers all processes and interactions which ought to be evaluated in order to predict reasonably the radiological performance of the disposal system without introducing undue bias. How to consider them is a modelling decision and was not the concern of the SCG, eg. whether they are in an integrated system model or separate scoping calculations. The SCG was only concerned with whether processes are IN or OUT of the assessment.

Some processes/interactions will have marked effects on the system but will be beneficial in terms of radiological safety. Some may be apparently significant but their effects may be swamped by irreducible uncertainty in other related processes that are already being taken into account. All these can be omitted to produce an assessment with acceptable bias which is termed the 'adequate assessment'. If processes or interactions are removed such that the overall estimates produced have unacceptable bias, then the assessment becomes inadequate. The SCG did not attempt to define what would constitute acceptable or unacceptable degrees of bias.

[3]The decision to seek dissent from consensus rather than positive individual agreement was seen as the most efficient way to proceed and the least likely to produce bias.

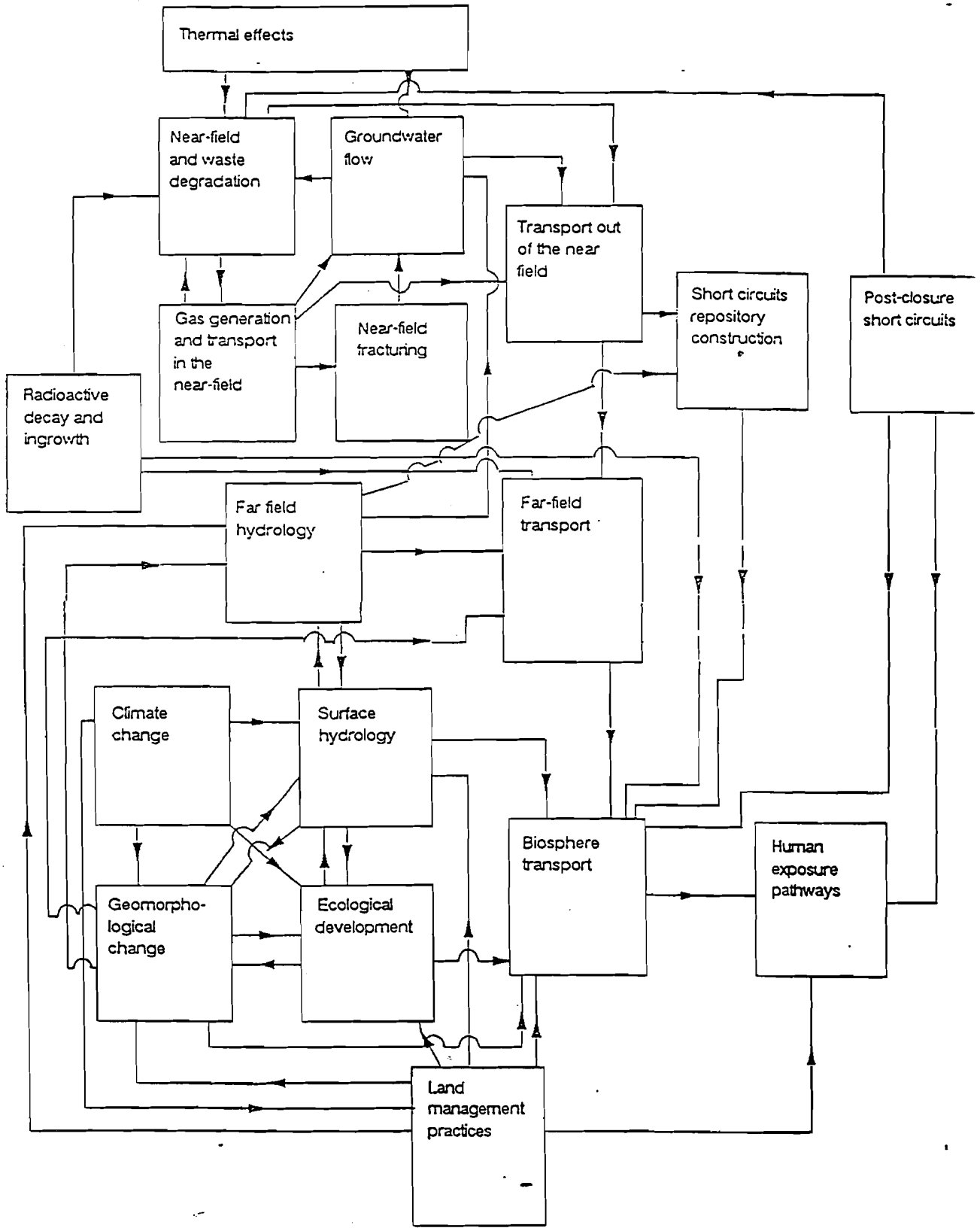

Figure 2. The Minimal Assessment Influence Diagram from the Uncertainty and Bias Audit of Dry Run 3

The meeting proceeded as follows. After an introduction by the Chairman, explaining the background to the HMIP assessment, the place of the SCG within it, and the programme outlined above, the Group began its evaluation of the processes and features shown in Table 1. As noted above, each group of processes and features was considered at the tertiary level within Table 1. After a brief explanation of the processes the Group was invited to discuss them freely, and to consider their significance, likely overall consequences on repository system behaviour, timescales of importance, and position within an ideal or an adequate assessment. At the end of the discussions, the Chairman summarised the consensus views of the Group, and sought dissenting views, if any. If necessary, further discussion then took place. The discussions were tape-recorded to facilitate reporting.

During the course of the two days of discussion, these ideas developed and were modified as the group discussed the processes, their interactions and the best way to incorporate them into different types of assessment. Inevitably, the expert group found it impossible to consider the significance of all the processes (especially where they were subdivided in considerable detail) without commenting on the nature and rationale of the assessment process itself.

Thus, a number of critical issues emerged in terms of the philosophy of the assessment as well as in the perceived behaviour of the disposal system. Many of these views are felt to be valuable and are recorded and discussed in the next section.

3 Critical Issues Identified by the SCG

3.1 Levels of Assessment

Prior to the meeting, the experts had been asked to classify significant processes according to whether they should be in a 'minimal assessment' of the type envisaged in the Dry Run 3 Uncertainty and Bias Audit or should be treated by separate scoping calculations. At the meeting, they were asked rather to place them in either an ideal or adequate assessment, as defined in Section 2.4. It became clear that, for many of the processes, their significance, particularly in interaction with other processes, could not readily be evaluated to the extent required to include or omit them from an adequate assessment. Thus, in the final listings (Table 2) most processes appear in both columns. This effectively means that scoping evaluations would need to be performed as part of an ideal assessment in order to eliminate them from a less comprehensive assessment which still retains the principal interactions and features envisaged in the minimal assessment proposed in the Dry Run 3 Uncertainty and Bias Audit. The end result of these deliberations can be summarised as follows:

1. Very few processes could be omitted from an ideal assessment. This is, perhaps, unsurprising and reflects the paucity of currently available data defining the repository system and external influences on which to base such decisions.

2. It is not justifiable to produce a less comprehensive assessment which still remains as complex in structure as the minimal assessment proposed in the Dry Run 3 Uncertainty and Bias Audit, without going through the various components of an ideal assessment first and performing numerous scoping evaluations in order to attribute quantitative significance.

3.2 Influence Diagrams

The influence diagram shown in Figure 2 was 'on the table' throughout the meeting as an intended aide memoire to the SCG. Towards the end of the meeting, the utility of this type of diagram was discussed. It was felt that, within the scope of the meeting, the diagram did little to facilitate discussion. At the level of an ideal assessment, the potential for further complexity in such a diagram was high whilst, at the same time, it actually imparts very little real information, particularly at the full system level. In effect, at the level being discussed by the SCG, influence diagrams were of little value. However, such diagrams may be interesting when considering detailed interactions within and between system sub-components, such as the physicochemical evolution of the disposal vault, but the interactions portrayed must then be discussed and elaborated in detail.

3.3 Revised Structure of the Process List

In general, the SCG found the initial process list (Table 1) very comprehensive and few additional processes were required. A number of processes which were clearly specific only to the Harwell site environment addressed in Dry Run 3 were removed or substituted. In addition, it was found useful to restructure the list to take into account: (a) the necessary reordering of the biosphere (see Section 3.4) including the transfer of geomorphological processes to the far-field section and transfer of climatological processes to an entirely new section, and (b) to bring to prominence certain processes which the SCG felt were critical to the behaviour of the repository (see Section 3.6). In the restructured list the quaternary level process headings (eg. 1.1.1.1) have been dropped because this level of subdivision was seen as overly complex. The issues highlighted by these quaternary level headings were considered by the SCG during discussion of the tertiary level processes. Where considered necessary, the original quaternary level processes are explicitly referred to within the detailed comments for each process (Table 3).

There was a strong feeling within the SCG that the complexity of the list of biosphere processes which was proposed for consideration would lead to incompatibilities in an assessment, given the inherent uncertainties in the earlier parts of the release chain (near- and far-field) and in the lack of ability to predict future changes in the surface environment. Unlike the near and far-field features and processes, the behaviour of the biosphere does not contribute to the safety of the repository system. It is effectively a yardstick, providing a means of translating a radionuclide flux exiting the geosphere into a radiation dose. This led to a restructuring of the biosphere component which, in any case, had contained a number of geomorphological and climatological processes which it

was considered needed to be placed in a separate section, as they influence the system as a whole, and not just the biosphere.

Restructuring of the process list inevitably led to renumbering and renaming of some processes. Appendix 3 correlates the initial process numbers with 'new' process numbers allocated in the restructured list. In the remainder of this report, all process numbers refer to the restructured list as given in Table 2.

3.4 Timeframes

The final list of processes suggests very approximate timeframes within which processes may be of significance. It was accepted that, in the assessment, any individual model of a process or group of processes would be used to make quantitative predictions over periods of time up to the point where confidence in the results were lost. This will vary from one part of the repository system to another. The SCG found it impractical to be precise on the timescales over which processes may be significant and the broad categories used in the descriptions of each process reflect this difficulty. It seemed to the SCG that only three, almost qualitative, timeframes may be useful:

1. short-term (up to 10,000 years), the majority of near-field processes will be most influential in this period;

2. long-term (10,000 to hundreds of thousands of years); a period in which climatic changes will significantly affect some parts of the system; and

3. indefinite, since many processes need to be considered regardless of whether the timescale of evaluation is hundreds of years or millions of years.

For a very few processes it was considered that the important timeframe was up to 1,000 years. Further subdivision was felt to be unprofitable at this level of evaluation.

3.5 Principal Issues in System Behaviour

During the course of the SCG discussions, a number of features of the Sellafield concept emerged as being apparently of central importance to the assessment. These have been abstracted from the detailed analysis of individual processes in Table 3, and are discussed below.

3.5.1 Repository stability

In the Nirex reference design, backfill is used primarily as a way of chemically conditioning the near-field of the ILW vaults and is seen as having no structural function. There will be a large void around and above the stacked LLW and, possibly, above the concrete cells containing the ILW. Vault roof stability, therefore, becomes an issue. Although the vault roofs will be shotcreted and rockbolted, this system of support is expected to degrade within a few tens or hundreds of years, the period over which the repository is resaturating.

Progressive collapse of the roof onto the degrading wastes and upwards stoping of the collapse-damaged rock is anticipated. The extent to which this process might continue upwards above the repository in the long-term is difficult to predict, but it was considered likely that it would stabilise within some hundred or so metres above the roof, and within the Borrowdale Volcanic Group (BVG). Owing to the proximity of vaults both laterally, and vertically (in the case of LLW), damaged zones may interact leading to the formation of an extensive destressed zone of high porosity and conductivity which could stretch across the full upper surface subtended by the repository, and could cause the collapse of individual LLW vaults and their contents into their subadjacent neighbours. The effect of this instability could be:

- to produce a high conductivity hydraulic pathway across much of the repository, potentially connecting bounding fault structures within which the repository rock volume is situated;
- to cause premature damage to ILW containers which may otherwise have remained intact for considerably longer periods;
- to damage or bypass the sealing systems emplaced within repository access tunnels and shafts adjacent to or above the vaults themselves;
- to produce gross physicochemical heterogeneities in the LLW near-field (collapsed rock blocks, large water-filled voids, disturbed waste containers) and above the ILW (highly porous zone above wastes, fragmented cementitious material);
- to facilitate transfer of material eg. chemical complexants, gases from the LLW to the ILW vaults by possibly opening new pathways;
- to introduce a zone of weakness and high conductivity which could focus far-field stresses and hydrogeological changes produced by climatically-driven changes.

Whilst not suggesting that this type of behaviour will necessarily cause problems for the overall system performance, it was considered that the impact of significant void spaces in the caverns will need to be addressed by the assessment. This may make the assessment task considerably more difficult, and involve some additional uncertainties in the analysis.

3.5.2 ILW near-field chemical environment

In the Nirex proposals the long-term maintenance of low-flow, stable flux, highly alkaline, reducing conditions in the ILW vaults appears central to the disposal concept and safety case. Consequently, this aspect needs very close scrutiny in the assessment. In particular, the following issues need to be examined:

- the basis for assuming that chemical homogeneity will develop rapidly in the ILW vaults;

- the degree to which processes may disturb this development, eg. repository instability, heterogeneous groundwater flow into the near-field, changes in groundwater flux etc;

- the extent to which LLW vault derived materials may interact with the ILW vaults;

- the kinetics and longevity of processes producing or reducing the high pH environment and associated redox changes; and

- the SCG considered that there was no evidence to support a 300 year lifetime for the LLW mild or low-carbon steel containers.

3.5.3 Hydrogeology at repository depth

The proximity of the repository to the Ravenglass sub-Basin together with other features of the site, suggest that groundwater fluxes, particularly in the basement rocks which form the host rock for the repository, will require careful evaluation. In particular, it will need to be determined whether the hydrogeological system can be evaluated exclusively in terms of steady-state flow driven by topographically related head differences, given that a number of other potential driving mechanisms exist:

- density contrasts within different bodies of groundwater caused by evaporite dissolution, marine/freshwater interfaces, and deep flushing of parts of the system (eg. possibly the Ravenglass sub-Basin) during ice-sheet advance and retreat. The flow regime at present may be the result of a long transient due to such processes, and may not be in a steady state,

- potential gradients determined by the ice sheet surface slope during glacial phases,

- buoyancy contrasts caused by heterogeneous heat flow in the BVG and basinal sediments (radiogenic heat flows may be significant in this area) combined with the heat output of the repository,

- tectonically produced fluxes in the basement rocks, for example contributing fluids from greater depth within the basement to fluxes at repository level,

- fluids migrating updip from the Irish Sea Basin,

- groundwater flow driven by fluxes of repository gases or, in extreme circumstances, natural gases.

The extent to which any of these driving forces may affect deep fluxes is uncertain but, in a regime where fluxes are expected to be low, their relative significance on timescales of 10,000 to 100,000 years needs to be evaluated.

3.5.4 Groundwater flow and radionuclide transport modelling

Although not part of its remit, in discussing the many processes affecting flow and transport in the near- and far-fields, the SCG allowed itself the luxury of suggesting that the forthcoming assessment should make every effort to develop both a more realistic understanding of, and techniques for modelling, these mechanisms than had been used in other assessments to date. These views are included here for the record. It was suggested that particular attention should be paid to incorporating processes and parameters such as flow-wetted surface areas, channelling within fractures, heterogeneities in rock hydraulic properties and heterogeneities in geochemical properties.

Groundwater flow is usually represented by three types of model:

1. porous medium,
2. fractured medium, or
3. dual-porosity medium.

It is likely that none of these models adequately characterise the system and the basic assumptions underlying the models may be overly simplistic. Consequently, although these models may provide good correspondence with observed hydrogeological observations, they may not necessarily be a good basis on which to base radionuclide transport calculations. Radionuclide transport is a combination of water/solute/rock interactions and is, therefore, dependent on the flow wetted surfaces and residence time distributions. Radionuclide transport is not necessarily well supported by the assumption of constant dispersivity inherent in most groundwater flow models.

The SCG recommended that alternative concepts are considered to model the potential geometries of planar and fracture flow. Possible concepts are: channel networks, fracture networks, capillary bundles (flow-tubes), idealised channelling, and spatial heterogeneity. However, other concepts could be developed and assessed.

3.5.5 Deep glacial incision

Various evidence discussed under Process 2.1.8 (Major incision) suggests that the potential exists for deep incision of erosion channels beneath an ice sheet that may overlie the site in the future. Such channels can be sinuous features, and may be many kilometres long and up to 400m deep. Their mode of formation is not well understood. The presence of possibly similar, but relatively shallow, drift-filled features on the Sellafield site itself indicates that the potential does exist in this area for the formation of such a feature. The effect of such erosion on groundwater flows at depths could be very significant and requires evaluation.

3.5.6 Duration of future glacial cycling

It is generally accepted that natural climatic forcing factors will result in a continuation of the glacial cycling which has been characteristic of the last two

and a half million years. In the view of the Group, it can be assumed that such climatic cycling is likely to continue for the whole period of HMIP's quantitative assessment (ie. 1 million years), and that significant climatic changes are likely to become apparent within 5,000 years from the present. Consequently, any component of the assessment evaluating processes beyond this time should account for continued glacial cycling.

3.5.7 Human intrusion

The SCG was asked to review a number of potential short-circuit pathways, many of which could be grouped under the heading of 'human intrusion'. Without wishing to reiterate the considerable literature on the subject of how best to evaluate the impacts of future human intrusion into the repository, it was felt that some clear position needed to be taken in the HMIP assessment. Three approaches seemed to be possible:

- detailed analysis of many possible intrusion events, with consideration of probabilities, consequences, and effects of sequences of events;
- the adoption of a position or attitude that accepts that human intrusion is a fundamentally insoluble and unquantifiable problem and should not be accepted as constituting an obstacle to the development of a waste disposal system (ie. special regulatory treatment);
- quantitative analysis of one or two 'probable' and 'critical' intrusion scenarios as illustrations of potential consequence.

Given that, at the very least, some reassurance may be required (especially for local residents) that intrusion would not be catastrophic, the third course seems most appropriate, even though, in regulatory terms, it may still be necessary to adopt the second course in the final analysis.

Although not directly within its brief, given this background, the SCG thought it worthwhile to record discussions which suggested two possible scenarios for analysis in an assessment:

1. Intrusion into the repository or the deep groundwater pollution plume by means of a shaft or borehole, with subsequent exposure to solid contaminated material and ingestion of contaminated waters.
2. Deep injection by borehole disposal of chemically active organic or inorganic liquid wastes into the highly porous collapsed repository volume causing significant changes to the solubility, speciation and transport properties of radionuclides.

3.5.8 Treatment of the biosphere

In an ideal assessment, the SCG suggested that it may be worth considering the concept of a limited number of radionuclide entry points or 'gateways' to the biosphere, subsequent transfer processes which may lead to dilution or reconcentration of radionuclides, and a limited number of critical human

exposure mechanisms to radiation.

The simplified biosphere process structure shown in Table 2 thus envisages groundwater, solid and gaseous entry of radionuclides to the biosphere through land, sediment and surface water body 'gateways' which would be representative of any potential future surface conditions. Examination of transfer mechanisms would be fundamentally concerned with identifying reconcentration mechanisms (eg. redox changes) and any temporary sinks and re-release processes which may lead to exposures of more significance than the direct routes.

In carrying out this evaluation, it would be necessary to consider time-dependent changes in the surface environment which may affect the nature or rates of the transfer processes. The effects of discontinuous, time-dependent mechanisms should not be overlooked, and care should be taken to identify potential reconcentration and re-release mechanisms, where the rates of transfer into and out of 'storage' would be important. These time-dependent changes would not affect either the generic nature of the gateways or the exposure mechanisms. Additionally, it was felt that many of the speculative features of future biospheres and changes in surface environment could be dealt with by a discussion of impacts on the simple model presented above, without recourse to numerous scenarios or calculations.

4 Conclusions

The main value of the work of the SCG is seen to have been in the consideration and description of processes and features, and in sifting and categorising them for future use by the various Working Groups charged with modelling each part of the repository system. It was particularly valuable for the same group of experts over a short period of time to consider both the processes individually and the totality of the system. This, perhaps, enabled the Group to provide a better focused view of the most significant features and processes.

The record of the discussions presented in Table 3 is the core of the work, and is laid out in such a way as to provide a catalogue and accessible accounts of features and processes for subsequent users. It also should provide a template against which to compare the content of both the Nirex and HMIP assessments as they develop.

The underlying idea of the SCG is considered to have worked well, and in practice to have avoided the introduction of bias into the deliberations. It may be worth extending the idea of such relatively short-lived and focused projects to the development or evaluation of other aspects of the HMIP assessment as it develops.

5 References

Sumerling T J (1992) Dry Run 3. A trial assessment of underground disposal of radioactive wastes based on probabilistic risk analysis: Overview. Department of the Environment (London) Report No. DoE/HMIP/RR/92.039, 120pps.

Thorne M C (1992) Dry Run 3. A trial assessment of underground disposal of radioactive wastes based on probabilistic risk analysis: Volume 8: Uncertainty and bias audit. Department of the Environment (London) Report No. DoE/HMIP/RR/92.040, 93pps.

Table 1

The Process List from the Uncertainty and Bias Audit of Dry Run 3

PROCESSES CONSIDERED IN DRY RUN 3	Excluded from DR3	SIGNIFICANCE 0-10 ka	10 ka-1 Ma	1 Ma plus	How to-evaluate
1: NEAR-FIELD					
1.1 Chemical/physical degradation					
1.1.1 Structural and container metal corrosion					
1.1.1.1 Localised pitting	x				
1.1.1.2 Bulk					
1.1.1.3 Crevice	x				
1.1.1.4 Stress corrosion cracking	x				
1.1.2 Physical degradation of concrete					
1.1.2.1 Cracking					
1.1.2.2 Sealing of cracks					
1.1.2.3 Pore blockage					
1.1.2.4 Alkali-aggregate reaction					
1.1.2.5 Cement-sulphate reaction					
1.1.3 Chemical degradation of concrete					
1.1.3.1 Changes in pore water composition, pH, Eh					
1.1.3.2 Exchange capacity exceeded					
1.1.3.3 Alkali-aggregate reaction					
1.1.3.4 Cement-sulphate reaction					
1.1.4 Degradation of wastes					
1.1.4.1 Metal corrosion					
1.1.4.2 Leaching					
1.1.4.3 Complex formation					
1.1.4.4 Colloid formation					
1.1.4.5 Microbial degradation of organic wastes					
1.1.4.6 Microbial corrosion					
1.1.4.7 Radiolysis					
1.2 Gas production, transport and flammability					
1.2.1 Hydrogen by metal corrosion					
1.2.1.1 Structural steel					
1.2.1.2 Container steel					
1.2.1.3 Waste steel					
1.2.1.4 Waste Magnox					
1.2.1.5 Waste aluminium	x				
1.2.1.6 Waste Zircaloy	x				
1.2.1.7 Waste other metals	x				
1.2.1.8 Effects of microbial growth on concrete					
1.2.2 Methane and carbon dioxide by microbial degradation					
1.2.2.1 Cellulosics					
1.2.2.2 Other susceptible organic materials	x				
1.2.2.3 Aerobic degradation					
1.2.2.4 Anaerobic degradation					
1.2.2.5 Effects of temperature					
1.2.2.6 Effects of lithostatic pressure	x				
1.2.2.7 Effects of microbial growth	x				
on properties of concrete					
1.2.2.8 Effects of biofilms	x				
1.2.2.9 Effects of hydrogen from metal corrosion					
1.2.2.10 Inhibition due to the presence of					
toxic materials					

1.2.2.11 Carbonate/bicarbonate exchange	x				
with concrete					
1.2.2.12 Energy and nutrient control of metabolism					
1.2.2.13 Effects of radiation on microbial populations	x				
1.2.3 Gas generation from concrete	x				
1.2.4 Active gases					
1.2.4.1 Tritiated hydrogen					
1.2.4.2 Active methane and carbon dioxide					
1.2.4.3 Other active gases	x				
1.2.5 Toxic gases	x				
1.2.6 Transport					
1.2.6.1 In the waste container	x				
1.2.6.2 In the vault between containers					
1.2.6.3 Between vaults					
1.2.6.4 In the near-field, including up and					
around access shafts and adits					
1.2.6.5 Into and through the far-field					
1.2.7 Flammability	x				
1.2.7.1 Fires	x				
1.2.7.2 Explosions	x				
1.3 Radiation phenomena					
1.3.1 Radioactive decay and ingrowth					
1.3.2 Nuclear criticality	x				
1.4 Mechanical effects					
1.4.1 Canister or container movement					
1.4.2 Changes in situ stress field					
1.4.3 Embrittlement					
1.4.4 Subsidence/collapse					
1.4.4.1 Repository induced					
1.4.4.2 Natural					
1.4.5 Rock creep					
1.4.6 Fracturing					
1.5 Hydrological effects					
1.5.1 Changes in moisture content					
1.5.1.1 Due to dewatering					
1.5.1.2 Due to stress relief					
1.5.2 Groundwater flow (unsaturated conditions)					
1.5.2.1 Initial					
1.5.2.2 Due to gas production					
1.5.3 Groundwater flow (saturated conditions)					
1.5.4 Transport of chemically active					
substances into the near-field					
1.5.4.1 Inorganic ions					
1.5.4.2 Humic and fulvic acids					
1.5.4.3 Microbes					
1.5.4.4 Organic complexes					
1.5.4.5 Colloids					
1.6 Thermal effects					
1.6.1 Differential elastic response					
1.6.2 Non-elastic response					
1.6.3 Fracture changes					

1.6.3.1 Aperture					
1.6.3.2 Length					
1.6.4 Hydrological changes					
1.6.4.1 Fluid pressure					
1.6.4.2 Density					
1.6.4.3 Viscosity					
1.6.5 Chemical changes					
1.6.5.1 Metal corrosion					
1.6.5.2 Concrete degradation					
1.6.5.3 Waste degradation					
1.6.5.4 Gas production					
1.6.5.5 Complex formation					
1.6.5.6 Colloid production					
1.6.5.7 Solubility					
1.6.5.8 Sorption					
1.6.5.9 Species equilibrium					
1.6.6 Microbiological effects					
1.6.6.1 Cellulose degradation					
1.6.6.2 Microbial activity					
1.6.6.3 Microbial product reactions					
1.7 Transport out of the repository					
1.7.1 Solubility					
1.7.2 Sorption					
2: FAR-FIELD					
2.1 Extra-terrestrial					
2.1.1 Meteorite impact					
2.2 Geological					
2.2.1 Regional tectonic					
2.2.1.1 Uplift					
2.2.1.2 Subsidence					
2.2.1.3 Lateral and/or vertical flexure					
2.2.2 Magmatic	x				
2.2.2.1 Intrusive	x				
2.2.2.2 Extrusive	x				
2.2.2.3 Hydrothermal	x				
2.2.3 Metamorphism	x				
2.2.3.1 Contact	x				
2.2.3.2 Regional	x				
2.2.3.3 Dislocation	x				
2.2.4 Diagenesis	x				
2.2.5 Diapirism	x				
2.2.6 Seismicity					
2.2.6.1 Repository-induced					
2.2.6.2 Externally-induced					
2.2.6.3 Natural					
2.2.7 Faulting/fracturing					
2.2.7.1 Activation					
2.2.7.2 Generation	x				
2.2.7.3 Change of properties					

2.2.8	Major incision					
2.2.9	Weathering					
2.2.10	Effects of natural gases	x				
2.2.11	Geothermal effects	x				
2.3	Hydrological					
2.3.1	Variation in groundwater recharge					
2.3.2	Groundwater losses (direct evaporation, springflow)					
2.3.3	Rock property changes					
2.3.3.1	Porosity					
2.3.3.2	Permeabilty					
2.3.3.3	Microbial pore blocking					
2.3.3.4	Channel formation/closure					
2.3.4	Groundwater flow					
2.3.4.1	Darcy					
2.3.4.2	Non-Darcy					
2.3.4.3	Intergranular (matrix)					
2.3.4.4	Fracture					
2.3.4.5	Effects of solution channels					
2.3.4.6	Unsaturated					
2.3.5	Salinity	x				
2.3.5.1	Effects of differences in salinity	x				
2.3.5.2	Effects at the saline-freshwater interface	x				
2.3.5.3	Implications of evaporite deposits/minerals	x				
2.3.6	Variations in groundwater temperature	x				
2.4	Transport and geochemical					
2.4.1	Advection					
2.4.2	Diffusion					
2.4.2.1	Bulk					
2.4.2.2	Matrix					
2.4.2.3	Surface	x				
2.4.3	Hydrodynamic dispersion					
2.4.4	Solubility constraints	x				
2.4.4.1	Effects of pH and Eh	x				
2.4.4.2	Effects of ionic strength	x				
2.4.4.3	Naturally-occurring complexing agents	x				
2.4.4.4	Complexing agents formed in the near-field	x				
2.4.4.5	Naturally-occurring colloids	x				
2.4.4.6	Colloids formed in the near-field	x				
2.4.4.7	Major ions migrating from the near-field	x				
2.4.4.8	Effects of microbial activity	x				
2.4.5	Sorption					
2.4.5.1	Linear					
2.4.5.2	Non-linear					
2.4.5.3	Reversible					
2.4.5.4	Irreversible					
2.4.5.5	Effects of pH and Eh					
2.4.5.6	Effects of ionic strength					
2.4.5.7	Effects of naturally-occurring					
	organic complexing agents					
2.4.5.8	Effects of naturally-occurring					
	inorganic complexing agents					
2.4.5.9	Effects of complexing agents					
	formed in the near-field					

2.4.5.10 Effects of naturally-occurring colloids					
2.4.5.11 Effects of colloids formed in the near-field					
2.4.5.12 Effects of major ions migrating					
from the near-field					
2.4.5.13 Effects of microbial activity					
2.4.6 Fracture surface changes					
2.4.7 Organic colloid transport					
2.4.7.1 Porous media					
2.4.7.2 Fractured media					
2.4.7.3 Effects of pH and Eh					
2.4.7.4 Effects of ionic strength					
2.4.8 Inorganic colloid transport					
2.4.8.1 Porous media					
2.4.8.2 Fractured media					
2.4.8.3 Effects of pH and Eh					
2.4.8.4 Effects of ionic strength					
2.4.9 Transport of radionuclides bound to microbes					
2.4.10 Isotopic exchange					
2.4.11 Gas transport					
2.4.11.1 Solution					
2.4.11.2 Gas phase					
2.4.12 Gas-induced groundwater transport					
2.4.13 Thermally-induced groundwater transport					
2.4.13.1 Repository-induced					
2.4.13.2 Naturally-induced	x				
2.4.14 Biogeochemical changes	x				
3: BIOSPHERE					
3.1 Climatology					
3.1.1 Transient greenhouse gas induced warming					
3.1.1.1 Precipitation					
3.1.1.2 Temperature					
3.1.1.3 Sea level rise	x				
3.1.1.4 Storm surges	x				
3.1.1.5 Ecological effects					
3.1.1.6 Potential evaporation					
3.1.2 Glacial/interglacial cycling					
3.1.2.1 Precipitation					
3.1.2.2 Temperature					
3.1.2.3 Sea level fall					
3.1.2.4 Storm surges	x				
3.1.2.5 Ecological effects					
3.1.2.6 Seasonally frozen ground					
3.1.2.7 Permanently frozen ground					
3.1.2.8 Glaciation					
3.1.2.9 Deglaciation					
3.1.2.10 Potential evaporation					
3.1.3 Exit from glacial/interglacial cycling					
3.1.3.1 Greenhouse gas induced					
3.1.3.2 Other causes					
3.2 Geomorphology					
3.2.1 Generalised denudation					

	3.2.1.1	Fluvial				
	3.2.1.2	Aeolian				
	3.2.1.3	Glacial				
3.2.2	Localised denudation					
	3.2.2.1	Fluvial (valley incision)				
	3.2.2.2	Fluvial (weathering/mass movement)				
	3.2.2.3	Glacial				
	3.2.2.4	Coastal	x			
3.2.3	Sediment redistribution					
	3.2.3.1	Fluvial				
	3.2.3.2	Aeolian				
	3.2.3.3	Glacial				
3.2.4	Effects of sea level change					
	3.2.4.1	River incision/sedimentation				
	3.2.4.2	Coastal erosion	x			
3.3	Hydrology					
3.3.1	Soil moisture and evaporation					
3.3.2	Surface hydrology					
	3.3.2.1	Overland flow				
	3.3.2.2	Interflow				
	3.3.2.3	Return flow				
	3.3.2.4	Macropore flow				
	3.3.2.5	Variable source area response				
	3.3.2.6	Stream/aquifer interactions				
3.3.3	Groundwater recharge					
3.3.4	Surface flow characteristics (freshwater)					
	3.3.4.1	Stream/river flow				
	3.3.4.2	Sediment transport				
	3.3.4.3	Meander migration or other fluvial response				
	3.3.4.4	Natural lake formation/sedimentation				
	3.3.4.5	Effects of sea level change				
3.3.5	Surface flow characteristics (estuarine)					
	3.3.5.1	Tidal cycling				
	3.3.5.2	Sediment transport				
	3.3.5.3	Successful development				
	3.3.5.4	Effects of sea level change				
3.3.6	Coastal waters					
	3.3.6.1	Tidal mixing				
	3.3.6.2	Residual current mixing				
	3.3.6.3	Effects of sea level change				
3.3.7	Ocean waters		x			
	3.3.7.1	Water exchange	x			
	3.3.7.2	Effects of sea level change	x			
3.4	Ecological development					
3.4.1	Terrestrial					
	3.4.1.1	Agricultural systems				
	3.4.1.2	Semi-natural systems				
	3.4.1.3	Natural systems				
	3.4.1.4	Effects of succession				
3.4.2	Estuarine					
3.4.3	Coastal waters					
3.4.4	Oceans		x			

3.5 Radionuclide transport					
3.5.1 Erosive					
3.5.1.1 Fluvial					
3.5.1.2 Aeolian					
3.5.1.3 Glacial					
3.5.1.4 Coastal					
3.5.2 Groundwater discharge to soils					
3.5.2.1 Advective					
3.5.2.2 Diffusive					
3.5.2.3 Biotic					
3.5.2.4 Volatilisation					
3.5.3 Groundwater discharge to wells or springs					
3.5.4 Groundwater discharge to freshwaters					
3.5.5 Groundwater discharge to estuaries					
3.5.6 Groundwater discharge to coastal waters					
3.5.7 Surface water bodies					
3.5.7.1 Water flow					
3.5.7.2 Suspended sediments					
3.5.7.3 Bottom sediments					
3.5.7.4 Biogeochemical cycling					
3.5.7.5 Effects of fluvial system development					
3.5.8 Estuaries					
3.5.8.1 Water flow					
3.5.8.2 Suspended sediments					
3.5.8.3 Bottom sediments					
3.5.8.4 Effects of salinity and pH variation					
3.5.8.5 Biogeochemical cycling					
3.5.8.6 Effects of estuarine development					
3.5.8.7 Effects of sea level change					
3.5.9 Coastal waters					
3.5.9.1 Water transport					
3.5.9.2 Suspended sediment transport					
3.5.9.3 Bottom sediment transport					
3.5.9.4 Effects of sea level change					
3.5.9.5 Effects of estuarine development					
3.5.9.6 Effects of coastal erosion					
3.5.9.7 Effects of sea level change					
3.5.10 Plants					
3.5.10.1 Root uptake					
3.5.10.2 Deposition on surfaces					
3.5.10.3 Vapour uptake					
3.5.10.4 Internal translocation and retention					
3.5.10.5 Washoff and leaching by rainfall					
3.5.10.6 Leaf-fall and senescence					
3.5.10.7 Cycling processes					
3.5.11 Animals					
3.5.11.1 Uptake by ingestion					
3.5.11.2 Uptake by inhalation					
3.5.11.3 Internal translocation and retention					
3.5.11.4 Cycling processes					
3.5.11.5 Effects of relocation and migration					
3.6 Planning considerations					
3.6.1 Urbanisation					
3.6.2 Management of water resources					

3.6.2.1 Lake formation					
3.6.3 Agricultural policy					
3.6.4 Recreation policy					
3.7 Human exposure					
3.7.1 External					
3.7.1.1 Land					
3.7.1.2 Sediments					
3.7.1.3 Water bodies					
3.7.2 Ingestion					
3.7.2.1 Drinking water					
3.7.2.2 Agricultural crops					
3.7.2.3 Domestic animal products					
3.7.2.4 Wild plants					
3.7.2.5 Wild animals					
3.7.2.6 Soils and sediments					
3.7.3 Inhalation					
3.7.3.1 Soils and sediments					
3.7.3.2 Gases and vapours (indoor)					
3.7.3.3 Gases and vapours (outdoor)	x				
3.7.3.4 Biotic material					
3.7.3.5 Salt particles	x				
4: SHORT CIRCUIT PATHWAYS RELATED TO HUMAN ACTIVITIES					
4.1 Related to repository construction					
4.1.1 Loss of integrity of borehole seals					
4.1.1.1 Failure					
4.1.1.2 Degradation					
4.1.2 Loss of integrity of shaft or access tunnel seals					
4.1.2.1 Failure					
4.1.2.2 Degradation					
4.1.3 Damage of host rock through subsidence					
4.2 Post-closure					
4.2.1 Deliberate recovery of wastes or associated materials	x				
4.2.2 Malicious intrusion	x				
4.2.3 Exploratory drilling					
4.2.4 Exploitation drilling					
4.2.5 Geothermal energy production	x				
4.2.6 Resource mining					
4.2.7 Tunnelling					
4.2.8 Construction of underground storage/					
disposal facilities					
4.2.9 Construction of underground dwellings/shelters					
4.2.10 Archaeological investigations					
4.2.11 Injection of liquid wastes					
4.2.12 Groundwater abstraction					
4.2.13 Underground weapons testing	x				

Table 2

The Final Process List of the System Concept Group

SYSTEM CONCEPT GROUP PROCESS LIST	Ideal assessment	Adequate assessment	Time frame
1: NEAR-FIELD			
1.1 Chemical/physical degradation			
1.1.1 Container metal corrosion	•	•	0 to 10 000
1.1.2 Physico-chemical degradation of concrete	•	•	all
1.1.3 Waste corrosion & solubility & speciation of radionuclides	•	•	all
1.1.4 Electrochemical effects of metal corrosion	•		0 to 10 000
1.2 Gas production, transport and flammability			
1.2.1 Hydrogen by metal corrosion	•	•	0 to 10 000
1.2.2 Methane and carbon dioxide by microbial degradation	•	•	0 to 10 000
1.2.3 Gas generation from concrete		•	
1.2.4 Radioactive gases	•	•	0 to 10 000
1.2.5 Chemotoxic gases			
1.2.6 Gas transport	•	•	0 to 10 000
1.2.7 Flammability	•		0 to 10 000
1.2.8 Thermo-chemical effects	•		0 to 10 000
1.3 Radiation phenomena			
1.3.1 Radioactive decay and ingrowth	•	•	all
1.3.2 Nuclear criticality			
1.4 Structural integrity			
1.4.1 Waste-form and backfill consolidation	•	•	0 to 10 000
1.4.2 Vault collapse	•	•	all
1.5 Hydrogeological effects			
1.5.1 Desaturation (pumping) effects	•	•	0 to 1 000
1.5.2 Disturbed zone (hydromechanical) effects	•	•	all
1.5.3 Unsaturated flow due to gas production	•	•	0 to 10 000
1.5.4 Saturated groundwater flow	•	•	all
1.5.5 Transport of chemically active substances into the near-field	•	•	all
1.6 Thermal effects			
1.6.1 Rock-mass changes	•		0 to 10 000
1.6.2 Hydrogeological changes	•	•	0 to 10 000
1.6.3 Chemical & microbiological changes	•	•	0 to 10 000
1.6.4 Transport (diffusion) effects	•	•	0 to 10 000
2: FAR-FIELD			
2.1 Geological			
2.1.1 Regional tectonic	•	•	> 10 000
2.1.2 Magmatic activity			
2.1.3 Regional metamorphism			
2.1.4 Diagenesis			
2.1.5 Diapirism			
2.1.6 Seismicity	•		all
2.1.7 Faulting/fracturing	•		> 10 000
2.1.8 Major incision	•	•	> 10 000
2.1.9 Effects of natural gases	•		> 10 000

2.2 Hydrogeological			
2.2.1 Changes in geometry & driving forces of the flow system	•	•	all
2.2.2 Rock property changes	•	•	all
2.2.3 Groundwater flow	•	•	all
2.3 Transport and geochemical			
2.3.1 Advection	•	•	all
2.3.2 Diffusion	•	•	all
2.3.3 Hydrodynamic dispersion	•	•	all
2.3.4 Solubility constraints	•	•	all
2.3.5 Sorption including ion-exchange	•	•	all
2.3.6 Changes in sorptive surfaces	•	•	all
2.3.7 Changes in groundwater chemistry & flow direction	•	•	all
2.3.8 Colloid transport	•	•	all
2.3.9 Transport of radionuclides bound to microbes	•	•	all
2.3.10 Transport of radioactive gases	•	•	0 to 10 000
2.3.11 Gas induced groundwater transport	•	•	0 to 10 000
2.3.12 Thermal effects on hydrochemistry			
2.3.13 Biogeochemical changes			
2.4 Geomorphology			
2.4.1 Generalised denudation	•	•	all
2.4.2 Localised denudation	•	•	all
3: CLIMATOLOGY			
3.1 Climate change			
3.1.1 Human induced	•	•	0 to 1 000
3.1.2 Natural	•	•	all
3.1.3 Exit from glacial/interglacial cycling	•	•	all
3.1.4 Intensification of natural climate change	•	•	all
4: BIOSPHERE			
4.1 Radionuclide entry points to the biosphere			
4.1.1 Groundwater discharge to soils & surface waters	•	•	all
4.1.2 Solid discharge via erosional processes	•	•	all
4.1.3 Gas discharge	•	•	all
4.2 Transfer (concentration/dilution) mechanisms			
4.2.1 Soil moisture and evaporation	•	•	all
4.2.2 Surface water mixing	•	•	all
4.2.3 Sediment transport including bioturbation	•	•	all
4.2.4 Sediment/water/gas interaction with the atmosphere	•	•	all
4.2.5 Bioaccumulation and translocation	•	•	all
4.2.6 Biogeochemical processes	•	•	all
4.3 Land & surface water use			
4.3.1 Terrestrial	•	•	all
4.3.2 Estuarine	•	•	all
4.3.3 Coastal waters	•	•	all
4.3.4 Seas	•	•	all

4.4 Human exposure			
4.4.1 External	•	•	all
4.4.2 Ingestion	•	•	all
4.4.3 Inhalation	•	•	all
5: SHORT-CIRCUIT PATHWAYS			
5.1 Related to repository construction			
5.1.1 Loss of integrity of borehole seals	•	•	all
5.1.2 Loss of integrity of shaft or access tunnel seals	•	•	all
5.1.3 Incomplete near-field chemical conditioning	•	•	all
5.2 Unrelated to repository construction			
5.2.1 Meteorite impact		•	
5.2.2 Deliberate intrusion			
5.2.3 Malicious intrusion			
5.2.4 Accidental intrusion	•	•	all

Table 3

Detailed Comments of the System Concept Group on the Nature and Significance of the Processes in Table 2

1	The near-field		
1.1	Chemical/physical degradation		
1.1.1	**Container metal corrosion**		
Ideal assessment: YES		Adequate assessment: YES	Time frame to assess: 0 to 10,000 yrs

Description of process:

Corrosion of steel containers. Initially aerobic to form ferric oxides during the operational phase of the repository and for a short time post-closure. Anaerobic thereafter to form ferrous oxides. Besides solid corrosion products, large volumes of hydrogen are evolved.

Discussion of process:

The design-life of the 500 litre ILW drums is apparently 50 years, and the design-life of some of the ILW containers containing more soluble radionuclides is apparently 300 years, although many may last significantly longer. Many of the containers (those containing material that degrades to evolve gas) will be vented to the vault. As such it is concluded that the level of physical containment some of these containers offer is limited. A realistic mild steel container lifetime is thought to be compatible to the operational period of the repository. As a consequence, physical containment from these containers cannot be assumed beyond closure and, from this point of view, the corrosion of certain metal containers is not thought to be a significant process. In short, the low-level waste metal containers offer no physical radiological barrier function, while the intermediate-level waste containers offer some, but it is not clear to what extent. It is possible that the degradation products from corrosion of the metal containers may sorb certain radionuclides.

However, the hydrogen gas evolved during the corrosion process may significantly influence other near-field processes (eg. microbial viability, groundwater flow and radionuclide transport) and is a key factor in controlling the near-field chemical environment. The extent to which metal corrosion may influence these processes is directly controlled by the corrosion rate. Most importantly, it is possible that a high metal corrosion rate may inhibit groundwater resaturation of the near-field due to the large volumes of gas produced (see 1.2.1). From this viewpoint, bulk metal container corrosion is a very important process and should be examined in any performance assessment. The time period over which bulk metal corrosion needs to be examined is 0 to 10,000 years after closure. After this time, virtually all of the metal should have corroded and gas production should have ceased. This needs, however, to be confirmed by supporting calculations.

Forms of metal corrosion other than 'bulk' (eg. pitting, crevice corrosion and stress cracking) are not significant for understanding gas production and, therefore, may be omitted from any assessment.

1	The near-field
1.1	Chemical/physical degradation
1.1.2	**Physico-chemical degradation of concrete**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**all**

Description of process:

There will be two primary types of cementitious material in the repository; 1) structural elements (eg. boxes and shotcreted gallery roofs), and 2) the highly porous cementitious backfill (in the intermediate-level vaults only) which allows rapid diffusion of species and formation of an alkaline (high pH) near-field chemistry. Interactions with groundwater may cause loss of strength of structural elements and changes in the physico-chemical properties of the backfill.

Discussion of process:

A principal aspect of the intermediate level waste disposal vault near-field is the development of a formation of an alkaline (high pH), chemically reducing near-field which may offer chemical containment of solubility-limited radionuclides. The physical containment of non solubility-limited radionuclides is extremely restricted, limited to offering slight resistance to groundwater flow from the structural elements.

Degradation of the physical elements will occur by cement dissolution in the groundwater, alkali-aggregate reactions, cement-groundwater reactions and corrosion of reinforcing rods. These reactions are generally expansive and result in loss of compressive strength and cracking. The effective lifetime of the structural elements is thought to be restricted to a few hundred years at most. However, as the structural elements have no extensive physical containment role, their degradation may not be important from this viewpoint. As a consequence, the physical and chemical degradation of the structural elements need be addressed only in scoping calculations in the ideal assessment to determine its importance in the first few hundred years after closure.

Physical and chemical degradation, and changes in the properties, of the porous backfill are perceived to be considerably more important than degradation of the structural elements. A particularly important process would be pore-blockage in the intermediate-level waste backfill, which is a physical effect of a chemical process. This may occur if dissolved cement species are reprecipitated in the pore spaces causing a reduction in porosity and permeability and, therefore, in the ability of the backfill to allow rapid mixing and chemical conditioning of the near-field.

1.1.2	Physico-chemical degradation of concrete continued

Discussion of process continued:

It was recognised that the continued dissolution-migration-reprecipitation process would not allow the initially homogenous backfill characteristics to be maintained for long, and the assumption that alkaline (high pH) and chemically reducing conditions would soon develop throughout the entire near-field may, therefore, be addressed.

As the structural elements will provide some of the dissolved species that may be reprecipitated in the backfill pores, modelling of changes in the chemical and physical properties of the backfill must consider the structural elements and the backfill together.

A full assessment of the behaviour of the cement must include the effect on the cement of three important factors:

1) Reaction of the cement with structural components with which it is in intimate contact, eg. aggregate and admixtures (plasticizers and fluidizers).

2) Reaction of the cement with groundwater constituents (eg. chloride) although a precise list of constituents must await comprehensive groundwater analysis but it is noted that chemistry of the groundwater may change with time (1.5.5).

3) Effects on the cement due to the thermal peak resulting from the heat-generating waste.

In summary, the physico-chemical degradation of cement requires to be included in all assessments due to the fact that a high reliance is placed on chemical (hyperalkaline) containment of radionuclides and that the large volumes of cement in the repository are the principal material controlling the pH. This assessment should be carried out for all time frames to ensure that a high pH is maintained in the repository near-field for long time periods (up to and beyond one million years). The physico-chemical degradation of the structural elements need only be considered by scoping calculations in the ideal assessment over a time period of a few hundred years.

1	The near-field
1.1	Chemical/physical degradation
1.1.3	**Waste corrosion and solubility and speciation of radionuclides**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**all**

Description of process:

Progressive physico-chemical degradation of the wastes will release radionuclides. The subsequent transport behaviour of the radionuclides will be controlled by their solubility and speciation and, therefore, by the chemical environment of the near-field. The near-field chemistry is dominated by degradation of the large volumes of cement but may be perturbed by various other near-field processes.

Discussion of process:

A number of different types of waste and waste-forms will be present in the repository and each will degrade by different mechanisms, at different rates. The important degradation processes are dissolution, metal corrosion, microbial degradation of organic wastes and microbial corrosion of inorganic wastes. The nature of the degradation processes may control the proportions of radionuclides released in solution and in the gaseous phase. It is thought likely that the proportion of radionuclides released in the gaseous phase will be low, but it is recommended that scoping calculations are performed to check this. Radionuclides released in the gas phase will not be controlled by near-field chemistry and their containment will depend on the gas permeability of the near and far-fields.

The subsequent transport behaviour of radionuclides released to solution will be controlled by their solubility and speciation. A few radionuclides, eg. 36-Cl and 129-I, are not solubility limited and these will be advectively removed by groundwater from the near-field.

The release of non-solubility limited radionuclides in solution, and radionuclides in the gaseous phase from the near-field is, therefore, dependent on the degradation rates of the waste-forms and on the diffusive escape from the nondegraded waste-form. It is recommended that in the ideal assessment the degradation rate of the waste-forms is addressed, over all time periods.

The majority of radionuclides released by waste-form degradation to the groundwater will be solubility limited. Near-field chemistry in the intermediate-level waste vaults will attain alkaline (high pH), chemically reducing conditions rapidly due to the large volumes of corroding metal, and the cement and the porous microstructure of the backfill.

1.1.3	Waste corrosion and solubility and speciation of radionuclides continued

Discussion of process continued:

This chemical environment should ensure that a large proportion of the solubility limited radionuclides do not enter solution. The small fraction that can enter solution will be advectively transported by the groundwater but migration should be limited by sorption onto the concrete or the host rock.

Transport of solubility limited radionuclides out of the repository may also be enhanced if these radionuclides form complexes or bind to colloids. Organic complexing agents will be produced in the near-field during the microbial degradation of the organic waste-forms, colloids will be formed in the near-field by the physical degradation of the waste, the rock and the structural elements in the repository. In addition, complexing agents and colloids may be introduced to the near-field by ingress of groundwater. However, it is likely that repository generated production of complexing agents and colloids in the near-field will dominate any introduced fraction.

Migration of radionuclides transported as complexes or bound to colloids will depend, in part, on the stability of the complex or colloid in question.

Transport of solubility limited radionuclides out of the near-field as complexes or bound to colloids is potentially a problem and must be addressed in all performance assessments, over all time periods.

The longevity of the chemically conditioned environment in the near-field will control the period of retention for the majority of solubility limited radionuclides. The alkalinity may be reduced by the formation of organic acids during microbial degradation of organic wastes. It is not clear that the 300 metre separation distance between organic and non-organic wastes is sufficient to prevent organic acids modifying the alkalinity in the entire near-field (see 1.4.2). It is recommended that scoping calculations are performed in the ideal assessment to address this issue.

The redox potential of the near-field could be raised as a result of oxidant production during radiolysis of the groundwater. However, the absence of high-activity wastes will maintain radiolysis at low levels, and the large volumes of iron in the near-field will buffer near-field redox conditions. It is recommended that radiolysis is omitted from all assessments.

The hyperalkaline, reducing near-field conditions will ensure that long-lived, high-activity, solubility-limited daughter radionuclides will be released very slowly from the near-field. Concentration of these radionuclides will occur due to continued production via decay chains. If the near-field chemical environment were to change (become less alkaline, or more oxidising) then these radionuclides may become considerably more soluble and migrate out to the far-field. Such an event may occur by some short-circuit (eg. intrusion) process bringing surface waters to depth. The same short-circuit may transport the radionuclides to the surface. The possibilities and consequences of this scenario need to be addressed in the ideal assessment.

1	The near-field		
1.1	Chemical/physical degradation		
1.1.4	**Electrochemical effects of metal corrosion**		
Ideal assessment: **YES**		Adequate assessment: **NO**	Time frame to assess: **0 to 10,000 yrs**

Description of process:

The corrosion of the large volumes of steel in the repository may create low voltage electrical currents in the near-field which may influence radionuclide transport.

Discussion of process:

In the present context, metal corrosion is an electrochemical process which depends on the flow of negatively charged species in the water normally on a very localised scale. However, if the metal object becomes electrically polarised, charged species may be driven in the water over longer distances to maintain the electrical cell.

In the repository near-field, if all the metal containers in one vault were in contact (eg. in the low-level waste vaults) and polarisation were induced over their entire length, then one large electrical cell may be formed with ionic species (radionuclides or colloids) being driven through the groundwater to maintain the polarisation. Although the driving forces are likely to be small (maybe 1 or 2 volts), over a long time period the flow of charged particles may be significant.

The probability of the metal containers becoming polarised in this manner is not known and scoping calculations are recommended in the ideal assessment to address this issue over the time period when the containers are corroding, ie. the first 10,000 years after closure, if this duration is confirmed. The influence of the presence of other metals (aluminium, Zircalloy etc.) on the development of an electrical field needs to be assessed.

1	The near-field	
1.2	Gas production, transport and flammability	
1.2.1	**Hydrogen by metal corrosion**	

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**0 to 10,000 yrs**

Description of process:

Production of hydrogen by the corrosion of all metals in the repository including structural and container steel, waste Magnox, aluminium and Zircalloy. This process also includes the effect of corrosion-derived hydrogen on the growth of microbes on concrete.

Discussion of process:

The evolution of hydrogen gas by the corrosion of metals in the near-field of the repository is a highly significant process. This hydrogen production may influence other near-field processes (eg. microbial viability, groundwater flow and radionuclide transport) and is a key factor in controlling the near-field chemical environment. The extent to which hydrogen production may influence these processes is directly controlled by the corrosion rate. Most importantly, it is possible that a high metal corrosion rate and, therefore, large volumes of hydrogen may inhibit groundwater resaturation of the near-field.

Hydrogen production via metal corrosion should be examined in any performance assessment. The time period over which this process needs to be examined is 0 to 10,000 years after closure. After this time, virtually all metal should have corroded and hydrogen gas production ceased, or at least be insufficient to inhibit groundwater resaturation, but this has to be confirmed by scoping calculations.

Documentation from Nirex suggests that some twenty thousand tonnes each of aluminium and Zircalloy may be emplaced in the repository. These metals were excluded from the Dry Run 3 assessment but must now be included and assessed along with steel and Magnox. All of these metals may evolve hydrogen during corrosion. No other metals were identified in the waste inventory as being important for this process, although if any other metal were to be placed in the repository in significant mass then they, too, would need to be included in the assessment.

Microbial activity may significantly enhance metal corrosion either directly or indirectly due to production of corrosive substances during microbial activity on concrete. The large volumes of hydrogen evolved may inhibit microbial activity on concrete and, therefore, limit the production of these corrosive substances. It is uncertain if this is an important process or not but, as inhibition of microbes is a conservative process, it should only be included in the ideal assessment.

1	The near-field		
1.2	Gas production, transport and flammability		
1.2.2	**Methane and carbon dioxide by microbial degradation**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **0 to 10,000 yrs**

Description of process:

Production of methane and carbon dioxide by the microbial degradation of organic wastes and waste matrices in the repository.

Discussion of process:

In the immediate post-closure period when conditions in the near-field are still oxidising, aerobic microbial degradation of organic materials will evolve carbon dioxide only. Later, when reducing conditions have been established, both carbon dioxide and methane may be evolved from anaerobic degradation. Some of the carbon dioxide may later be consumed during methanogenesis. The main controls on the viability of the microbes in the repository are the supply of nutrients (C, P, N, O, S) and the temperature. However, the conditions in the near-field are not thought to be hostile to microbes, although the microbial degradation process may be poisoned by a high hydrogen partial pressure or passivated surfaces. The hydrostatic pressure and radiation are not thought to be controlling factors.

Most of the methane and carbon dioxide will be generated from the decomposition of cellulose within the first 10,000 years, although lesser volumes of these gases will also be generated via the degradation of other organic materials such as the bitumen waste matrix, possibly over a longer time period.

Perhaps the single most important potential effect of carbon dioxide production may be carbonate/bicarbonate exchange with concrete. If the carbon dioxide partial pressure were to reach a high enough level then cement may begin to take up carbon dioxide with a consequent reduction in pH from about 12 to 8. At repository pressures it is not known what the critical carbon dioxide pressure would be, but at STP the required partial pressure is low, about 1 x E-12 atmospheres.

1.2.2	Methane and carbon dioxide by microbial degradation continued

Discussion of process continued:

The impact of carbonation on concrete depends upon the mode of interaction. Factors requiring to be assessed are the rate of decrease of alkalinity conditioned by dissolved carbon dioxide, the enhancement of corrosion rates as a consequence of loss of high pH and the increase in solubility of certain radionuclides as carbonate containing complexes. In more general terms, the addition of carbon dioxide and methane to the hydrogen from metal corrosion may further delay the resaturation of the near-field if the gas generation rate is high and the gas cannot easily migrate out to the far-field.

This process must be addressed in all assessments, over the period of gas production, ie. the first 10,000 years after closure, if this duration is confirmed.

1	The near-field		
1.2	Gas production, transport and flammability		
1.2.3	**Gas generation from concrete**		
Ideal assessment: **NO**		Adequate assessment: **NO**	Time frame to assess: **none**

Description of process:

Production of gases from the ageing and degradation of concrete.

Discussion of process:

The only likely processes that may generate gas from concrete are radiolysis of water in the cement pore spaces, and microbial growth on concrete. However, it is agreed that these methods of gas production are insignificant compared to the gas generation from metal corrosion or microbial action on organic material. No other significant deleterious affects are likely from these processes.

It is concluded that these processes do not need to be evaluated in an assessment.

1	The near-field
1.2	Gas production, transport and flammability
1.2.4	**Radioactive gases**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**0 to 10,000 yrs**

Description of process:

Production of radioactive tritium and 14-C during the biological degradation of the waste and the incorporation of these radionuclides in gases that may reach the surface.

Discussion of process:

The biological degradation of the waste will release a number of radionuclides into the near-field which, potentially, may become incorporated into gaseous or volatile hydrocarbon molecules. However, due to the dominance of hydrogen, methane and carbon dioxide in the near-field, only those radionuclides (eg. tritium and 14-C) which may become incorporated into these gases are of potential concern. Tritium may form tritiated hydrogen and methane, whilst the 14-C may form radioactive carbon dioxide and methane. Radioactive gases have no special physical properties and will be transported out of the near-field at the same rate and by the same processes as other gases in the repository.

If there is no short-circuit pathway from the repository to the biosphere, the short half-life of tritium (about 12 years) will preclude it from reaching the surface. Therefore, assessments need only include tritium in dose calculations for scenarios incorporating rapid transport pathways.

The half-life of 14-C is 5730 years, much longer than that of tritium (12.98 years) and, consequently, it is possible that 14-C may reach the surface in the form of radioactive carbon dioxide or radioactive hydrocarbons and constitute part (although probably a small part) of the total dose. It follows that all assessments need to include 14-C over a time period controlled by the degradation of the waste and the half-life of the radionuclide.

1	The near-field		
1.2	Gas production, transport and flammability		
1.2.5	**Chemotoxic gases**		
Ideal assessment: **NO**		Adequate assessment: **NO**	Time frame to assess: **none**

Description of process:

Production of chemotoxic gases that may influence other processes in the repository near-field, far-field or biosphere with radiological consequences. The health effects of chemotoxicity are not, themselves, of concern in this assessment.

Discussion of process:

The biological degradation of the waste may produce a number of chemotoxic gases. However, it is not believed that chemotoxic gases will be produced in sufficient quantities that they would be able to influence any near-field processes (eg. microbial activity).

It is recommended that chemotoxic gases are omitted from all assessments, since only the radiological consequences of the repository are considered.

1	The near-field		
1.2	Gas production, transport and flammability		
1.2.6	**Gas transport**		
Ideal assessment: YES		Adequate assessment: YES	Time frame to assess: **0 to 10,000 yrs**

Description of process:

Consideration of the way in which gas will get out of the waste containers and vaults into and through the far-field and the potential effects of this transport. Or, alternatively, the effects of gas being trapped in the repository.

Discussion of process:

Gases are produced in the containers as a consequence of degradation of the container and of the waste. The low-level waste containers have a short lifetime (about 50 years) and they are vented. Consequently, gas pressurisation of the containers is not considered a problem. Vent blockage is not a problem as the build up of gas pressure within the container is likely to open a blocked vent. The equilibrium pressure at which hydrogen production will cease is very high (about 800 atmospheres). It is recommended that gas pressurisation from containers is omitted from any assessment.

Gas transport between containers and between vaults will not be a problem if the waste mix is homogenous. In this situation, the type of gas produced and the rate of production will be the same from all containers, and no net gas transport will occur from one container to another or from one vault to another. However, if the waste mix is heterogenous between containers or vaults, then different gases may be produced at different rates and a net gas flux may occur from one part of the repository to another if the gas cannot rapidly escape from the near-field. This would be of concern for it is most likely that, in this situation, any net gas movement in the repository would tend to be from the low-level waste caverns (high gas production rates) to the intermediate-level waste caverns (lower gas production rates) particularly if there has been partial collapse of the vaults. Corrosive and complexing agents may be transported with the gas.

It is recommended that all assessments address gas movement in the near-field, between vaults and containers over the period of maximum gas production, ie. over the first 10,000 years after closure, if this duration is confirmed.

1.2.6	Gas transport continued

Discussion of process continued:

Gas pressure dissipation in the near-field is not considered a problem given the fractured nature of the host rock, unless the fractures are sealed during construction or by precipitation from cement leachates. However, early gas releases to the surface may occur if gas transport occurred in the access shafts and adits. This may occur if the shaft seals failed as a result of high gas pressures in the near-field. It is recommended that all assessments, therefore, address gas transport from the near-field and gas transport in access shafts and adits over the period of maximum gas production.

1	The near-field		
1.2	Chemical/physical degradation		
1.2.7	**Flammability**		
Ideal assessment: YES		Adequate assessment: NO	Time frame to assess: **0 to 10,000 yrs**

Description of process:

Hydrogen and methane generated in the repository could form potentially explosive mixtures with air in the operational and immediate post-closure periods. Fire and explosion in the repository could have radiological consequences if the structure of the repository were damaged or near-field processes enhanced or inhibited. The hazards of fire and explosion, themselves, are not of concern in this assessment.

Discussion of process:

The repository will contain large volumes of void space; possibly the low-level vaults will not be backfilled at all and the intermediate-level vaults may not be backfilled in the upper gantry spaces. In total up to five hundred thousand cubic metres of void space may be left in the vaults.

During the operational phase, as individual vaults are filled and sealed but the repository is still pumped, these void spaces will begin to fill with hydrogen and mix with trapped air to form potentially explosive mixtures. This condition will continue for a short period post-closure while the repository resaturates with groundwater. During these times, it is possible that the hydrogen-air mixture could be ignited by spontaneous combustion or from sparks generated from rock falls onto steel containers.

The radiological consequences of fire or explosion in the vaults may arise from damage to the containers and damage to the vaults. Explosion would create a pressure wave which would disturb the groundwater flow in the near-field, and may enlarge fracture apertures or create new fractures creating preferential pathways in the near-field for subsequent radionuclide transport.

The probability and radiological consequences of fire or explosion are not obvious. It is recommended that scoping evaluations are performed in the ideal assessment to address this issue. It is pointed out that this is an issue that falls on the boundary between operational and post-closure periods and needs to be incorporated into the assessments for both periods.

1	The near-field
1.2	Gas production, transport and flammability
1.2.8	**Thermo-chemical effects**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	NO	0 to 10,000 yrs

Description of process:

Potential effects in the near-field due to a build up of gas (predominantly hydrogen), if the gas production rate is greater than the rate at which gas may migrate out to the far-field.

Discussion of process:

The rate at which gas (mostly hydrogen) is produced in the near-field may exceed the rate at which gas may escape to the far-field if all the fractures are effectively sealed by grouting and/or shotcreting. If this were to occur then large gas bubbles could exist in the near-field, thus maintaining hydraulically unsaturated conditions.

The effect of such a bubble on the thermal regime in the near-field may be serious because the gas would act thermally to insulate the disposal caverns. The result may be that the heat generated by the intermediate-level waste could then cause the cavern temperature to rise higher and more rapidly than predicted. This would occur because the high porosity of the backfill ensures that the overall thermal conductivity of the near-field is controlled by the gas or water filling the backfill pore-spaces and not the backfill itself. If this effect were to occur, it is not expected that the condition would last long, due to the short period of the thermal peak, but it might have significance to the chemical activity of the cementitious materials.

If the hydrogen partial pressure were to rise to very high levels then the corrosion of metal may be inhibited, although this is not considered probable. However, if it did occur this would not cause a problem for conditioning the near-field redox potential for all pore-spaces would be filled with the reducing hydrogen gas.

These two processes are not thought to have high probabilities because it is thought that the gas should be able to escape easily into the far-field. Nonetheless, scoping calculations in the ideal assessment are recommended to compare the gas production and gas migration rates.

1	The near-field		
1.3	Radiation phenomena		
1.3.1	**Radioactive decay and ingrowth**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **all**

Description of process:

Calculation of the radioactive decay of radionuclides and the growth of daughter products as a consequence of that decay. The repository inventory defines initial quantities of radionuclides and standard decay chain theory and half-lives are used to calculate the radionuclide quantities at any later time.

Discussion of process:

This is clearly a very important process as it defines the nature and quantity of radionuclides derived from the initial inventory at any given time after closure.

It is essential that radioactive decay and ingrowth is included in all assessments for all time periods.

1	The near-field	
1.3	Radiation phenomena	
1.3.2	**Nuclear criticality**	

Ideal assessment:	Adequate assessment:	Time frame to assess:
NO	NO	**none**

Description of process:

The accumulation of a sufficient mass of fissile material such that a self-sustaining nuclear fission reaction can occur. Such a process would generate heat and quantities of fission products and actinide elements which would not otherwise be accounted for in the low and intermediate-level waste inventories.

Discussion of process:

It is believed that 235-U will not be emplaced in sufficient quantities for a fissile mass to accumulate. Therefore, criticality could only occur in the intermediate-level waste vaults if one large mass of plutonium formed. The total mass of plutonium in the repository will be very low because plutonium is mostly removed in reprocessing operations. Careful distribution of the small quantity of plutonium throughout the waste volume by Nirex will ensure that the initial concentration of plutonium will be many orders of magnitude below that required for criticality. Therefore, criticality could only occur in the repository if some fractionation process concentrated this plutonium. This is thought to be extremely improbable in the repository environment. No other radionuclide is likely to be present in the repository in sufficient quantities for criticality to be a possibility.

It is recommended that criticality is omitted from all assessments.

1	The near-field
1.4	Structural integrity
1.4.1	**Waste-form and backfill consolidation**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**0 to 10,000 yrs**

Description of process:

Physico-chemical degradation of the wastes and their containers, and the backfill, will cause collapse and settlement within the disposal caverns, which may affect the development of the intermediate-level waste chemical environment and, therefore, radionuclide transport out of the near-field.

Discussion of process:

Collapse and settlement of the container, waste-form and backfill materials will occur as a result of physico-chemical degradation. It should be noted that the porous backfill has no structural function (minimal strength) in the intermediate-level waste vaults. It is possible that no backfill will be included in the low-level waste vaults between containers. The resulting compaction will increase the void space already above the waste, and this void (along with all the vaults) will saturate with groundwater. If these processes of waste and containment degradation are combined with potential vault collapse (see 1.4.2), then the possibility of developing gross physico-chemical heterogeneities in the near-field needs to be evaluated.

There will be no loss in physical containment resulting from this collapse of the waste form and backfill since these materials are ascribed no physical containment function. The principal near-field barrier in the intermediate-level waste vaults is the evolution of alkaline (high pH), chemically reducing conditions which develops rapidly owing to the initially porous backfill. It is possible that the potential large scale re-ordering of the materials in the vaults, due to collapse, may affect this chemical conditioning and the evolution of the hyperalkaline environment around the waste may take longer, with 'pockets' of lower pH remaining.

It is recommended that all assessments address this issue over the time period when container and backfill collapse and evolution of the intermediate-level waste near-field chemical environment takes place, ie. over the first 10,000 years after closure.

In the low-level-waste vaults the degradation of the waste stacks is unlikely significantly to affect the source term calculations.

1	The near-field
1.4	Structural integrity
1.4.2	**Vault collapse**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**all**

Description of process:

The only means of support for the vaults (besides its natural strength given by its shape) are likely to be shotcrete/mesh and rock-bolts which prestress the roof arch. These supports have a limited lifespan, after which the cavern roof will be unsupported and may collapse creating an extensive disturbed zone. This zone of enhanced permeability may have consequences for radionuclide transport out of the near-field.

Discussion of process:

The roof-bolts have a limited lifespan of probably a few tens to hundreds of years at most. Once these roof-bolts fail the collapse of the cavern roof is dependent on the local stress field and the joint/fracture distribution and orientation. The backfill in the intermediate-level waste vaults offers no support as this porous material has no structural function and a large void is present above the ILW. It seems probable that, given the fractured nature of the rocks of the Borrowdale Volcanic Group (BVG), complete collapse of the vaults would occur in under 10,000 years.

A disturbed zone will form, mainly above each vault. Lateral migration of each vault's disturbed zone over time will tend to produce an amalgamation of zones, with the result that it could be safely assumed that a disturbed zone equal in width to the repository will eventually form. The result may be a zone of greatly enhanced permeability situated directly above and connecting all the vaults. The present repository design, in which LLW vaults are placed directly above one another, is likely to result in the connection of the vaults by roof collapse.

It is not obvious how far upwards and outwards the disturbed zone may propagate, but the nature and extent of this disturbed zone are clearly time-dependent. If the stress-field and fracture geometry were unfavourable, the disturbed zone may propagate to the BVG/Brockram contact. This is clearly a major process and, if it occurred, would dominate the effects of lesser processes such as rock creep.

It is recommended that this event should be included in all assessments for all time-frames, as it is clearly a time-dependent process. This process seems inevitable, to some extent, even if it is decided to completely backfill all vaults, since the probable backfill is significantly compressible.

1.4.2	Vault collapse continued

Discussion of process continued:

In addition to the hydraulic effects of collapse, assessments should also account for the potential heterogeneity of the near-field caused by blocks of collapsed rock and, in particular, the potential which would exist for chemical short-circuit interactions between the low-level waste and intermediate-level waste vaults. This may allow, for example, introduction of organic complexants from degrading low-level waste into the intermediate-level waste environment, and more rapid flushing of the intermediate-level waste alkaline waters by groundwaters moving more freely through the collapsed region of the rock.

1	The near-field
1.5	Hydrogeological effects
1.5.1	**Desaturation (pumping) effects**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**0 to 1 000 yrs**

Description of process:

Desaturation of the rock due to pumping during the construction and operational phases.

Discussion of process:

Dewatering of the rock will occur due to pumping in the construction and operational phases. This will result in unsaturated conditions in the near-field and a drawdown in the groundwater level above the repository. Pumping is likely to continue for between 50 and 100 years.

In the immediate post-closure phase, groundwater will flow towards the repository and the repository will resaturate. Resaturation may be complete in only a few hundred years. During this phase, all near-field processes will be occurring in an unsaturated, initially oxidising environment and, as a consequence, their rates may be different from when the repository is saturated.

It is recommended that unsaturated flow conditions are included in all assessments, over the first 1000 years after closure.

1	The near-field
1.5	Hydrogeological effects
1.5.2	**Disturbed zone (hydromechanical) effects**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**all**

Description of process:

The disturbed zone formed around the repository during construction may change the local hydrogeological system around the disposal vaults and access excavations.

Discussion of process:

The principal characteristic of the disturbed zone is a net increase in porosity and permeability due to expansion of the rock from destressing, and also due to the pressure waves created during blasting that may penetrate the rock for some distance. Locally, the permeability may be decreased, especially in the vicinity of the vault walls, and so it is not easy to predict the actual consequences of permeability and porosity changes for groundwater flow directions. However, the consequences of changes in groundwater flow directions may be considerable, since the locations and rates of groundwater ingress to and egress from the vaults are primarily controlled by the porosity and permeability of the rock close to the vaults.

The disturbed zone is a permanent feature of the repository and, thus, will control groundwater flow directions in the near-field for the lifetime of the repository.

It is recommended that disturbed zone effects on hydrogeology are included in all assessments, over all time periods.

1	The near-field		
1.5	Hydrogeological effects		
1.5.3	**Unsaturated flow due to gas production**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **0 to 10,000 yrs**

Description of process:

Hydrogen and methane gas will be produced in large volumes due to the corrosion of metal and microbiological degradation of organic waste, respectively. This gas may accumulate in the near-field and inhibit resaturation.

Discussion of process:

Gas produced by the degradation of metal containers and organic wastes may readily escape from the repository along fractures and faults. However, gas escape may be minimised if these faults and fractures are grouted, and the vault walls and roofs shotcreted, during the constructional phase. If this were to occur, then the build up of gas pressure may slow down or even halt the resaturation of the near-field, thus affecting the rate or scale of the chemical conditioning process.

It is recommended that unsaturated groundwater flow due to gas production is addressed in all assessments, over the time period when gas production occurs, ie. in the first 10,000 years after closure, if this duration is confirmed.

1	The near-field		
1.5	Hydrogeological effects		
1.5.4	**Saturated groundwater flow**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **all**

Description of process:

Saturated groundwater flow will persist over the entire lifetime of the repository subsequent to the immediate post-closure resaturation phase. As such the saturated environment is the environment where all the important radionuclide leaching and transport processes will occur.

Discussion of process:

All the important radionuclide leaching, transport, retardation and sorption process will occur within a saturated environment, after the initial resaturation phase is complete.

It is, therefore, clearly important that all assessments evaluate saturated groundwater flow conditions, over all time periods.

1	The near-field
1.5	Hydrogeological effects
1.5.5	**Transport of chemically-active substances into the near-field**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**all**

Description of process:

Groundwater flowing into the near-field may carry various species both in solution or in suspension as particulates or colloids. These species may then influence leaching and transport of radionuclides within the near-field.

Discussion of process:

Natural groundwaters carry various species in dissolved or suspended form. These species include; 1) inorganic ions, 2) organic complexing agents, 3) microbes and 4) colloids. The consequences of introducing these species into the near-field depends on the relative quantities of introduced species compared to species produced directly in the near-field.

The transport of inorganic ions into the near-field may be significant. A few kilometres to the south of the repository site is the Ravenglass sub-basin, which is likely to contain groundwaters considerably more saline than those in the repository near-field. It is possible that these saline waters may flush through the repository if they were induced to flow horizontally as a consequence of, perhaps, differential glacial loading. The consequences of introducing inorganic ions in the near-field are difficult to assess and depend on their nature and concentration. The likely times for maximum and minimum concentrations of inorganic ions in groundwaters are controlled by climate. It is likely that minimum concentrations would occur at the end of glaciations, when large volumes of fresh water flush through the rocks. Maximum concentrations may occur during extended periods of permafrost, when recharge and discharge are minimal, thus increasing the residence time of water in the rock, and freezing causes salts to accumulate at depth.

Inorganic ions may also reach the repository if the freshwater/seawater interface is moved because of sea level changes, or if waters having dissolved evaporites start to flow towards the repository.

It is possible that the quantity of organic complexing agents introduced into the near-field will be small compared to the quantities produced from degradation of the waste. However, this is not certain and traces of methane and other hydrocarbons have been recorded during drilling. It is recommended that scoping calculations are performed in the ideal assessment to address this issue.

1.5.5	Transport of chemically-active substances into the near-field continued

Discussion of process continued:

It is probable that the quantities of microbes and colloids introduced into the near-field by the groundwater will be small compared to the quantities of microbes introduced with the waste and the quantities of colloids produced in the near-field. It is recommended that the introduction of colloids and microbes into the near-field by groundwater are omitted from all assessments.

1	The near-field		
1.6	Thermal effects		
1.6.1	**Rock-mass changes**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **0 to 10,000 yrs**

Description of process:

The thermal pulse generated in the intermediate-level waste will cause the near-field rock to heat up possibly changing its physical properties, which in turn could affect radionuclide transport in the far-field.

Discussion of process:

Thermal effects on the host rock are generally considered to be of no importance: the only potentially significant effect could be a change in fracture aperture. It is not thought probable that fracture generation, or changes in fracture length will occur simply due to the relatively modest envisaged heating.

The changes in fracture aperture due to the thermal pulse are believed to be less important than changes in fracture aperture that will occur due to mechanical effects. However, it is noted that, in unusual circumstances, the thermal pulse may itself induce mechanical movement.

It is recommended that thermally induced changes in fracture aperture are addressed in the ideal assessment, over the time period when the thermal pulse occurs, ie. the first 10,000 years after closure.

1	The near-field	
1.6	Thermal effects	
1.6.2	**Hydrogeological changes**	
Ideal assessment: **YES**	Adequate assessment: **YES**	Time frame to assess: **0 to 10,000 yrs**

Description of process:

The thermal pulse generated in the intermediate-level waste may cause the groundwater flow paths to change direction due to the existence of buoyancy forces.

Discussion of process:

The thermal pulse is believed to be sufficient to perturb the groundwater flow paths in the far-field. The magnitude of the effect will depend on the scale of the natural flow cells; if these are large, then the effect of the thermal pulse will be less significant.

A number of consequences may result from the thermal perturbation of the groundwater flow-field, for example; groundwaters with different chemistries could be drawn towards the repository, groundwater velocities may be increased and radionuclides may follow faster pathways to the biosphere.

It is recommended that hydrogeological changes are included in all assessments over a time period equal to the thermal pulse, ie. the first 10,000 years after closure.

1	The near-field	
1.6	Thermal effects	
1.6.3	**Chemical and microbiological changes**	
Ideal assessment: **YES**	Adequate assessment: **YES**	Time frame to assess: **0 to 10,000 yrs**

Description of process:

The thermal pulse generated in the intermediate-level waste may cause the rate of near-field processes and microbiological activity to change. The result may be that radionuclides are released from the waste and migrate to the far-field more quickly.

Discussion of process:

The rate of all near-field processes may be changed by the thermal pulse, and in most cases the rate will be accelerated. The more important processes which may be influenced by increased temperatures are: 1) metal corrosion, 2) physico-chemical degradation of concrete, 3) physico-chemical degradation of waste-forms, 4) microbial degradation of organic wastes, 5) gas production, 6) complex formation, 7) colloid production, 8) radionuclide solubility, 9) sorption processes, and 10) speciation.

The result of the thermal peak changing the rates of near-field processes could be that radionuclides could enter the far-field and be transported towards the biosphere more rapidly than expected.

It is recommended that thermally-induced chemical changes are included in all assessments, over the time period of the thermal pulse, ie. the first 10,000 years after closure.

1	The near-field		
1.6	Thermal effects		
1.6.4	**Transport (diffusion) effects**		
Ideal assessment: **YES**		Adequate assessment: **NO**	Time frame to assess: **0 to 10,000 yrs**

Description of process:

The thermal pulse generated in the intermediate-level waste may cause diffusion rates and, consequently, radionuclide transport rates to increase. This would only be significant if a diffusive barrier were still operating in the near-field.

Discussion of process:

Diffusion rates will increase with increasing temperature as a result of the thermal peak. However, this will only be significant if a diffusive barrier (eg. the concrete) is still in operation and advective transport does not occur. Furthermore, only surface diffusion rates will be significantly increased by the thermal peak. If advective transport does occur throughout the entire near-field, then the more rapid transport due to increased diffusion rates will be insignificant.

The cement structures are not expected to operate as a diffusive barrier for the entire period of the thermal peak and, consequently, thermally enhanced diffusion rates are not expected to be significant. However, since this is not certain it is recommended that increases in diffusion rates are addressed in scoping calculations in the ideal assessment, over the period of the thermal peak, ie. the first 10,000 years after closure.

2	The far-field		
2.1	Geological		
2.1.1	**Regional tectonic**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **> 10,000 yrs**

Description of process:

Natural tectonic movements in the form of uplift, subsidence and regional warping may induce faulting and changes to the hydrogeological regime with consequent changes to the radionuclide transport pathways.

Discussion of process:

Tectonic activity is a very slow process and direct observations have only been made for a relatively short time, with the consequence that it is extremely difficult to make quantitative predictions about tectonic activity in the future. However, more qualitative predictions may be made from geological observations. The on-land Quaternary deposits of Britain show no evidence of significant movement, so it may be concluded that tectonic activity in the future will be negligible for the first 10,000 years after closure.

Over longer time scales, up to one million years or more, general denudation of the land-surface will cause isostatic adjustment and may be associated with general warping of the upper crust. The exact consequences of such activity cannot be predicted but groundwater flow directions and rates are likely to be significantly altered.

It is recommended that regional tectonism is addressed in all assessments, over long time-frames.

2	The far-field		
2.1	Geological		
2.1.2	**Magmatic activity**		
Ideal assessment: NO		Adequate assessment: NO	Time frame to assess: **none**

Description of process:

The occurrence of igneous activity in the form of volcanoes and associated intrusive magmatic activity would severely affect the behaviour and safety of a repository.

Discussion of process:

Although the consequences of magmatic activity on a repository are severe, the probability of such an event occurring in the next one million years is practically zero. The entire British Isles is located near the centre of a very stable lithospheric plate, on the edge of a passive continental margin; a location where magmatic activity is unusual. This situation is unlikely to alter in the next one hundred to two hundred million years.

It is recommended that magmatic activity is omitted from all assessments.

2	The far-field		
2.1	Geological		
2.1.3	**Regional metamorphism**		
Ideal assessment: **NO**		Adequate assessment: **NO**	Time frame to assess: **none**

Description of process:

The onset of regional metamorphism as a consequence of the deep burial of northwest England. Such an event would radically change the properties of the host rock and would effectively erase the repository.

Discussion of process:

Although the consequences of the onset of regional metamorphism on a repository are severe, the probability of such an event occurring in the next one million years are practically zero. The entire British Isles is located near the centre of a very stable lithospheric plate, on the edge of a passive continental margin; a location where regional metamorphism is extremely unusual. This situation is unlikely to alter in the next one to ten million years. Besides, as regional metamorphism can only occur as the result of deep burial, the present day land-surface would be subsumed also.

It is recommended that regional metamorphism is omitted from all assessments.

2	The far-field		
2.1	Geological		
2.1.4	**Diagenesis**		
Ideal assessment: **NO**		Adequate assessment: **NO**	Time frame to assess: **none**

Description of process:

The physicochemical alteration of a sediment during compaction and cementation as a consequence of shallow burial.

Discussion of process:

Diagenesis is an ongoing process in all buried sediments and will currently be affecting the unconsolidated Quaternary drift deposits in particular. However, the evidence of Quaternary sediments in Britain suggests that diagenetic effects will not produce major changes in hydrogeological or hydrochemical properties over a one million year timescale. Besides, over the next one million years these sediments are likely to be stripped and new deposits laid during glaciations. Diagenesis cannot affect the repository directly as, by definition, it occurs only within sediments and not basement rocks such as the BVG.

It is recommended that diagenesis is omitted from all assessments.

2	The far-field		
2.1	Geological		
2.1.5	**Diapirism**		
Ideal assessment: **NO**		Adequate assessment: **NO**	Time frame to assess: **none**

Description of process:

The process by which plastic, low density rocks (most commonly evaporites) may flow and rise upwards through more dense overlying rocks. Such a process would modify the groundwater regime and affect radionuclide transport.

Discussion of process:

Within the Sellafield region, evaporite deposits occur below the sandstones but not directly above the site of the repository. Whilst in principle these evaporites may form diapirs it is not clear if the density contrast between them and the sandstone is sufficiently great to invoke movement. In addition, the evaporites are probably too thin to cause any significant upward movement if a preferential density contrast does occur. Furthermore, the process of diapirism is so slow that no significant movement would occur in a one million year time frame.

It is recommended that diapirism is omitted from all assessments.

2	The far-field
2.1	Geological
2.1.6	**Seismicity**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	NO	all

Description of process:

Seismicity is the compressional and shear wave energy transmitted through the rock mass resulting naturally from the generation or reactivation of faults; it may also be induced due to stress-relief mechanisms in the near-field.

Discussion of process:

In general, seismicity is not a cause for concern for post-closure repository safety and the potential effects of the dissipation of seismic energy are secondary to the potential effects of the cause of the seismicity; eg. movement on a fault may affect the hydrogeology (see 2.1.7). The frequency of seismic events may be influenced by the frequency of glacial loading and unloading.

It is possible that seismic energy may be focused by the vault openings causing small rock bursts. However, this rock damage mechanism is considered to be negligible compared to the inevitable vault collapse expected due to failure of the rock-bolts. Potentially more important is the possibility that seismicity temporarily may affect groundwater flow, a mechanism termed 'seismic pumping.' The probability and likely consequences of seismic pumping are not known.

It is recommended that the effect of seismicity on the physical integrity of the repository may be omitted from all assessments, but that scoping calculations should be performed in the ideal assessment to examine the potential consequences of seismic pumping on groundwater movement.

2	The far-field
21	Geological
2.1.7	**Faulting/fracturing**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	NO	> 10,000 yrs

Description of process:

Faults and fractures are the primary pathway for groundwater movement and, hence, radionuclide transport. Generation of new faults and reactivation of pre-existing faults may significantly change the far-field transport pathways.

Discussion of process:

It is generally believed that generation of significant new faults in the Sellafield area is unlikely. However, reactivation of preexisting faults is highly probable due to changes in sea-level (in all time-frames), glacial loading and unloading (in all time-frames), and general denudation (in all time frames). It is also possible that fault reactivation may be induced during the resaturation phase as pore-pressures increase causing slippage on fault planes. Of all these possible fault reactivation mechanisms, glacial loading and unloading is probably the most significant factor, considering that it is estimated that the ice thickness at Sellafield may be up to one kilometre.

Fault reactivation may cause changes in the properties of the faults but, perhaps, most significantly the pathways along the fault plane will change. This is likely to be a beneficial process because it will expose fresh rock surfaces for sorption of radionuclides. Changes in flowpaths are possible with only small magnitude (one or two millimetres) shearing along the fault plane. Blockage of pathways along faults could be a continuous process due to precipitation and filtration of colloidal and particulate matter.

The changes in fault properties due to reactivation are, however, almost impossible to predict in any quantitative manner and the resultant changes are generally considered to be within the uncertainty in the predicted ranges of parameter values. Consequently these processes need only be dealt with by scoping evaluations in the ideal assessment over all time-frames, but particularly over the period of glaciation, ie. from 10,000 years after closure (see 3.1.4).

2	The far-field
2.1	Geological
2.1.8	**Major incision**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	> 10,000 yrs

Description of process:

Any mechanism which may cut a deep channel into surface rocks. A deep incision may effect the groundwater flow patterns and may reduce the distance from repository to biosphere for radionuclide transport.

Discussion of process:

The only mechanism likely to cause major incision is thought to be glacial erosion. Observations of glacial terrains have revealed 'tunnel valleys,' features cut into surface rocks to depths of up to 400 metres, which can be a few kilometres wide and some tens of kilometres long. The exact mode of formation of these features is not fully understood, but they are believed to be form rapidly at the edges of glaciers by meltwater, and not by direct erosion by the ice. It appears that these valleys fill with sediment as the glacier retreats; the bottom part of these valleys characteristically is filled with coarse material providing a highly permeable linear feature. Features similar to tunnel valleys, but with depths not exceeding 100 m, have been observed near to Sellafield. There is disagreement about whether such features do form in bedrock, although they certainly form in unlithified sediments.

The lack of an accepted theory of formation for tunnel valleys means that there is no means of predicting quantitatively their future distribution, but it seems very unlikely that any such feature would form close to the Lake District Massif. However, if such a feature were to form above or close to the repository during a period of glacial retreat, it would have a major impact on the hydrogeology. This feature would provide a shorter pathway to the biosphere at a time when the far-field is flushed with large volumes of glacial meltwater.

The combined impact of progressive reduction in repository cover by erosion of the surface by repeated glaciations and the possibility of single, multiple or repeated deep incision also needs to be considered.

It is recommended that the effect of major glacial incision is addressed in all assessments over a time period covering future glaciations, ie. from 10,000 years after closure (see 3.1.4).

2	The far-field		
2.1	Geological		
2.1.9	**Effects of natural gases**		
Ideal assessment: YES		Adequate assessment: NO	Time frame to assess: > 10,000 yrs

Description of process:

Natural gases may be generated in the vicinity of the repository, or may migrate towards the repository from a source elsewhere. In extreme conditions, these gases may influence groundwater flowpaths and releases to the biosphere.

Discussion of process:

Hydrocarbons have been identified during drilling of the boreholes at Sellafield, although the fluxes of these gases in boreholes are low. It is believed that the sources of these gases are offshore and that there is a net gas flux towards Sellafield. It is noted that natural gas reserves have been located in the Irish Sea and are being recovered from Morecambe Bay, some tens of kilometres to the south.

There are no obvious physicochemical effects of this natural gas on either the near-field (when compared to the amounts of repository produced hydrocarbon gases) or the far-field and, from this point of view, they may be omitted from all assessments. However, during glaciations natural gas may form clathrates (solid gas hydrates) beneath the ice which rapidly sublime when the glacier retreats. If glaciation persists, this process provides effective long-term accumulation and storage of methane with the possibility of subsequent sudden release in one large pulse, possibly explosively. Only natural gases are included in this mechanism as the repository-derived gases are mainly produced in the time-frame before the onset of glaciation.

It is not clear if clathrate formation will have any effect on radionuclide transport or release. It may be possible that a layer of clathrates would hold back radionuclide releases until glacier retreat, thus allowing a large and rapid pulse of radionuclides to reach the biosphere. The formation of clathrates needs to be considered in the context of other hydrogeological impacts of permafrost development.

Due to the uncertain consequences of clathrate formation for radionuclide releases to the biosphere, it is recommended that scoping evaluations are performed in the ideal assessment to examine this process, over a time-frame including major glaciations, ie from 10,000 years after closure (see 3.1.4).

2	The far-field
2.2	Hydrogeological
2.2.1	**Changes in geometry and driving forces of the flow system**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	**YES**	**all**

Description of process:

The geometry of the groundwater flow-field in the region around the repository will be bounded by a variety of physical features, eg. topographic highs or faults. Over the lifetime of the repository the flow-field geometry and the driving forces for flow will change as the physical boundaries are altered by processes such as glaciation, erosion or sea level change. The changes in flow-field geometry and driving forces will then control migration of dissolved radionuclides through the far-field.

Discussion of process:

The present-day geometry of the groundwater flow-field is modelled on the assumption that it is bounded by the following features; to the west by the coast and the saline interface, to the north by the flooded hematite mines, to the east by the topographic high of the Lake District and to the south by the Ravenglass sub-Basin.

Over the lifetime of the repository the geometry of the flow-field will change and other features may bound the flow-field, including major faults, groundwater density contrasts, topography and permafrost formation. It is not possible to predict quantitatively the future boundaries but it is possible to identify processes that will cause the flow geometry to change, the most obvious being the onset of glaciation and sea-level changes.

The most important driving forces are; 1) position and rate of recharge, 2) position and rate of discharge, 3) sea-level changes (causing changes to heads and to recharge), 4) groundwater salinity (controlling density contrasts, and being controlled by both climate and dissolution of evaporites), 5) glacial loading and the direction of slope of the glacier surface, 6) permafrost (limiting recharge and discharge, and increasing the areal extent of the flow-field).

Two other driving forces are thought to control the groundwater flow-field, but are second order effects, they are; 1) geothermal gradient, 2) tectonic flexing.

The heat flux at Sellafield is slightly higher than average due to the proximity of the radiogenic heat producing Eskdale Granite. The natural thermal gradient will constitute a second order driving force on the groundwater at Sellafield but, as this geothermal gradient is not expected to change over the lifetime of the repository, can be considered to be a time-independent function.

2.2.1	Changes in geometry and driving forces of the flow system continued

Discussion of process continued:

General tectonic activity over the next one million years and longer will cause warping of the crust, which may change the magnitude and orientation of the in situ stress field. Any change in the in situ stresses may be reflected in a change in groundwater flow. This could be considered, in some respects, as a slow variation of the seismic pumping observed during earthquakes which causes rapid and significant changes in groundwater flow directions and fluxes. Changes in situ stress can also influence the hydraulic properties of discontinuities, with the result that the anisotropy for flow can change with time. The influence of regional tectonic activity is a second order driving force on the groundwater at Sellafield and is time-dependent.

It is recommended that the effect of both the geothermal gradient and regional tectonic activity is assessed in the ideal assessment, over all time-periods.

2	The far-field
2.2	Hydrogeological
2.2.2	**Rock property changes**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	**YES**	**all**

Description of process:

Changes in the porosity and permeability properties of the rock due to a number of processes may alter the groundwater flow-field and, thus, radionuclide transport in the far-field.

Discussion of process:

The only rock property changes that are important to consider in the far-field are increases and decreases in permeability and porosity and a number of processes may occur that affect these properties of the rock mass.

The most important process is the interaction of the rock with the alkaline plume that will migrate out of the near-field due to the degradation of the cement. This alkaline plume may interact with the rock in a number of ways to cause a change in porosity and permeability; eg. reaction, ion exchange, precipitation or dissolution. The exact nature of the interactions will depend on the chemistry of the plume and the mineralogy of the rock. In addition to the chemical species in the plume, microbes may also be transported. It seems possible that these microbes may accumulate at the near-field/far-field interface and cause a reduction in porosity.

The extent to which the high pH plume extends into the rock may significantly affect far-field radionuclide transport, and it will be important to evaluate flux rates out of the near-field, the buffering capacity of the far-field rocks for these fluids, and the extent to which poor buffering or enhanced porosity and permeability can lead to large-scale modifications of the far-field.

A number of other processes may also affect the porosity and permeability of the far-field rock. These are: permafrost formation, closure of fractures due to ice loading, stress readjustment due to vault construction, dissolution of the evaporite sequence and precipitation elsewhere, eg in the BVG microfractures.

It is recommended that changes in porosity and permeability are addressed in all assessments, over all time-periods.

2	The far-field
2.2	Hydrogeological
2.2.3	**Groundwater flow**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**all**

Description of process:

The manner in which groundwater flows through the far-field rocks is central to understanding radionuclide transport and, consequently, for calculating fluxes to the biosphere. There are three basic conceptual flow modes, 1) matrix flow, 2) planar (fracture) flow, and 3) channelled flow, all of which may be combined. However, there are many possible approaches to modelling flow.

Discussion of process:

Groundwater flow is often represented by three types of conceptual model; 1) porous medium, 2) fractured medium, or 3) dual-porosity medium. It is likely that these models do not adequately characterise the system and, for this reasons, the basic assumptions underlying them may be wrong. Consequently, although these models may provide good correspondence with observed hydrogeological observations they may not, necessarily, be a good basis on which to base radionuclide transport calculations. Radionuclide transport is a combination of water/solute/rock interactions and is, therefore, dependent on the area of the surfaces over which the radionuclides migrate into the rock, the so called flow wetted surfaces, and residence time distributions. Radionuclide transport is not, necessarily, well supported by the assumption of constant dispersivity inherent in most groundwater flow models.

It is recommended that alternative concepts are considered to model the potential geometries of planar and fracture flow. Possible concepts are; 1) channel networks, 2) fracture networks, 3) capillary bundles, 4) idealised channelling, and 5) spatial heterogeneity, but other concepts should be developed and assessed.

The goodness of fit of a flow model should not be assessed solely by comparison of the model predictions of physical indicators, eg. heads, with measured values, but also with relevant palaeohydrogeological geochemical indicators.

It is recommended that groundwater flow is addressed in all assessments, over all time-periods, and that different assumptions of geometry are included in different flow models and each is fully evaluated, so that the most coherent may be identified for use in geochemical transport calculations.

2.2.3	Groundwater flow continued

Discussion of process continued:

Unsaturated flow also needs to be modelled. In the far-field, unsaturated flow can occur by three mechanisms; 1) migrating gas bubbles may change groundwater flow paths by blocking or opening channels, or by causing buoyancy of the water/gas mixture, 2) in the zone of aeration at the upper far-field/biosphere boundary; this zone is only a few tens of metres deep, and 3) during glaciations, when the permafrost layer may trap natural gases beneath it.

It is recommended that unsaturated flow in the far-field is addressed in the ideal assessment during the period when gas production in the repository will occur, ie. the first 10,000 years after closure.

2	The far-field		
2.3	Transport and geochemical		
2.3.1	**Advection**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **all**

Description of process:

Advection will be the principal mechanism for radionuclide transport in the far-field.

Discussion of process:

Advection will dominate radionuclide transport within the majority of the far-field rocks, with the possible exception of any sedimentary sequences with very low permeabilities and it is essential that advection is included in all assessments, over all time periods.

2	The far-field		
2.3	Transport and geochemical		
2.3.2	**Diffusion**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **all**

Description of process:

Bulk, matrix and surface diffusion may be significant transport processes, depending on the nature of the far-field rock and the transported species. Diffusion may, therefore, be important in controlling radionuclide transfers to the biosphere.

Discussion of process:

Three diffusion mechanisms will operate in the far-field; bulk, matrix and surface. Each diffusion mechanism is potentially important for controlling different processes.

Bulk diffusion is the dominant transport mechanism in very slow moving groundwaters, ie. when advection is operating only very slowly. When rapid advection occurs, bulk diffusion still operates but becomes a very minor component of transport and provides just a small effect on the advection front. In sequences of shales or evaporites transport may become bulk diffusion controlled and this transport mechanism may need to be considered.

Matrix diffusion will occur perpendicular to the general flow direction in fractures, and will transport species into pores containing water with no (or very small) advective velocity, where they may be effectively removed from the flow-field, and where certain species may sorb to the walls. The matrix porosity is believed to be high in the BVG (around 2%) and in the overlying sandstones (10 to 20%), consequently, it is believed that matrix diffusion will be the dominant retardation process operating in the far-field.

It is, therefore, recommended that matrix diffusion is included in all assessments, over all time-periods.

Surface diffusion occurs when certain species preferentially adsorb onto the surfaces of solid phases and diffuse along them, rather than remain in the main body of water. Surface diffusion is thought to be significant only for caesium and strontium, although it is recommended that surface diffusion is included in the ideal assessment, for all appropriate time-periods.

2	The far-field		
2.3	Transport and geochemical		
2.3.3	**Hydrodynamic dispersion**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **all**

Description of process:

Hydrodynamic dispersion is the mechanism whereby concentrations of radionuclides are diluted as they are mixed with greater volumes of groundwater during transport through the far-field.

Discussion of process:

Hydrodynamic dispersion is a poorly understood process. High dispersivities are often attributed to the rock mass in tracer tests, where it is common to find early tracer arrivals which indicate much faster transport for a small fraction of tracer, than for the bulk of tracer which arrives later. High dispersivities may be caused by two factors; first, there is a large difference in flow velocity between the different flow channels followed by the groundwater; second, there is a large uncertainty regarding the centre of mass of the transported tracer, ie. it is not known which flow channel is preferentially followed.

Models often assume that a high dispersivity implies high bulk mixing (ie. the models assume that the different flow channels eventually mix before the release boundary is reached) but this is not, necessarily, the case because a dispersivity value does not provide any information on the dispersion that occurs within each individual channel. It is possible that dispersion within a single, or a few, fast-flow channels is very low and, consequently, the original concentration of radionuclides is not diluted within such channels. However, this system may still be assigned a high dispersivity because of the uncertainty in which of the many possible channels is the fast-flowing route. In the case of the far-field, this may be translated into a situation where apparently high dispersivities occur in the rock, but where undiluted radionuclide concentrations may reach the biosphere quite quickly.

Additionally, the effect of scale on dispersivities needs to be taken into account; the greater the scale of the flow-transport system, the higher the dispersivity value tends to be.

It is recommended that, because hydraulic conductivity and the significance of dispersivity values are poorly understood, this issue should be addressed in all assessments, over all time-periods.

2	The far-field		
2.3	Transport and geochemical		
2.3.4	**Solubility constraints**		
Ideal assessment: YES		Adequate assessment: YES	Time frame to assess: **all**

Description of process:

The solubility of radionuclides is controlled by a number of factors, notably pH and Eh. The far-field chemistry is less perturbed by the presence of the repository than the near-field chemistry and, consequently, solubility constraints in the far-field can be less significant. However, the alkaline plume migrating from the near-field may cause a significant perturbation in far-field chemistry and control radionuclide solubilities there.

Discussion of process:

It has been assumed in the past that solubility constraints in the far-field are not important because the far-field chemistry is not significantly perturbed by the presence of the repository and individual trace element concentrations in far-field waters are very unlikely to approach solubility limits.

However, a significant feature of the repository design is the leaching of cementitious material in the near-field and the migration of an alkaline (high pH) plume into the far-field. This plume may have a high ionic strength and may carry with it colloids, complexing agents and microbes. In addition, the natural deep groundwaters may, themselves, have a high ionic strength. The important factors which control solubility are; 1) changes in Eh and pH, 2) changes in ionic strength, 3) naturally occurring complexing agents, and complexing agents formed in the near-field, 4) naturally occurring colloids, and colloids formed in the near-field, 5) major ions migrating from the near-field, 6) the common ion effect, and 7) microbes migrating from the near-field.

It is recommended, therefore, that solubility constraints in the far-field due to the alkaline (high pH) plume and high ionic strength groundwater are addressed in all assessments over all time-periods.

The migration of a radiolytic redox front out of the near-field would also cause solubility constraints to be important in the far-field, but radiolysis is not believed to be an important process as radiation fluxes are considerably lower than for high-level waste. Furthermore, the near-field also has a very high iron content which will buffer any oxidants produced by the limited radiolysis. It is recommended that radiolysis controlling far-field solubility may be omitted from all assessments.

2.3.4	Solubility constraints continued

Discussion of process continued:

It is possible (but maybe not probable) that if far-field solubility constraints are important, then reconcentration may occur at a chemical front and that if the chemical front later moves a 'pulse' of radionuclides could be released. The most likely situations favouring reconcentration need to be assessed, and include regions of sharp geothermal gradients such as where rock types change abruptly or where dissimilar groundwaters mingle or at the far-field/biosphere interface. From this perspective far-field solubility constraints may increase releases to the surface and this possibility should be examined in the ideal assessment, over all time-periods.

2	The far-field		
2.3	Transport and geochemical		
2.3.5	**Sorption including ion-exchange**		
Ideal assessment: YES		Adequate assessment: YES	Time frame to assess: **all**

Description of process:

Sorption is a general term to describe the retardation of radionuclides when they bind directly to solid surfaces. This may occur in a dynamic system, eg. during advection along fractures, or in a static system, eg. in immobile water in secondary porosity. Many sorption processes may operate to restrict radionuclide transport in the far-field and, consequently, releases to the biosphere.

Discussion of process:

Sorption is clearly a very important factor in far-field retardation. However, an adequate understanding of radionuclide migration requires the impact of various sorption processes to be assessed.

The important factors or assumptions controlling sorption are:-

1) Linear-reversible sorption. This is the normal approach used to model sorption which can be conservatively taken to occur in all cases and should be included in all assessments.

2) Nonlinear-irreversible sorption. This is known to take place and may be significant but is difficult to measure quantitatively or to prove. Irreversibility is a non-conservative process which should be addressed only in the ideal assessment. Nonlinearity may decrease sorption for high concentrations (saturation effects) and should be considered for all radionuclides which may be present in relatively high concentrations.

3) Effects of pH and Eh. These are very important factors for controlling sorption behaviour and should be included in all assessments.

4) Effects of ionic strength. These may be important in influencing the radionuclide distribution coefficients between solid and solution. This factor should be addressed in the ideal assessment.

5) Naturally occurring organic complexing agents. Potentially important if high concentrations of humic and fulvic substances occur in the far-field because they may reduce sorption onto solid surfaces. Should be included in the ideal assessment.

2.3.5	Sorption including ion-exchange continued

Discussion of process continued:

6) Naturally occurring inorganic complexing agents. Potentially important if high concentrations of carbonates and phosphates occur in the far-field because they may reduce sorption onto solid surfaces. Should be included in the ideal assessment.

7) Organic and inorganic complexing agents formed in the near-field. Very important because complexing agents formed in the near-field which migrate to the far-field are expected to dominate over naturally occurring complexing agents. Should be included in all assessments.

8) Naturally occurring colloids and colloids formed in the near-field. It is not clear how significant colloid transport may be and, consequently, it should be addressed in all assessments.

9) Major ions migrating from the near-field. Very important as this may change the ionic strength of the groundwaters and affect sorption behaviour. Also, there is a possibility that some major ions may sorb to the solid surfaces filling a considerable fraction of the sorption sites.

10) The effect of microbial activity is not thought to be very significant and should be considered only in the ideal assessment.

11) Isotopic exchange. Possibly a very important retardation process where radionuclides in solution exchange with stable nuclides in mineral structures. Should be included in the ideal assessment.

12) Surface precipitation and other reactions. A number of other processes may occur which are not strictly termed sorption but which may retard radionuclides. These should be addressed in the ideal assessment.

It is recommended that all assessments of sorption processes should be performed over all time-periods.

2	The far-field		
2.3	Transport and geochemical		
2.3.6	**Changes in sorptive surfaces**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **all**

Description of process:

Sorption to solid surfaces (in fractures and secondary porosity) will be controlled by the accessibility of those surfaces and their mineralogy (chemistry, structure). Over the lifetime of the repository, both the available area and mineralogy of solid surfaces may change and, hence, the potential for sorption in the far-field will be time-dependent.

Discussion of process:

Sorption will occur on fracture surfaces and on the surfaces of secondary porosity. The accessibility of surfaces for sorption is likely to change over the lifetime of the repository as old flow-paths become blocked and new flow-paths are formed. These changes may occur due to movement on faults, changes in the stress field, or chemical reactions within the fractures, eg. precipitation/dissolution reactions. The most important aspect of changes to surface area will be the opening up of new surfaces for sorption.

The mineralogy (chemistry, structure) of sorption surfaces will change as the surface mineralogy evolves, due to saturation of sorption sites, precipitation of new minerals, dissolution of existing minerals. These processes are especially likely to occur in the far-field as a result of the migration of the alkaline (high pH) plume from the near-field.

The most important consequence of changes in both the available surface area and the mineralogy of those surfaces will be a change in the sorption capacity.

It is recommended that changes in both the available surface area and the mineralogy (chemistry) of those surface are addressed in all assessments, over all time-periods.

2	The far-field		
2.3	Transport and geochemical		
2.3.7	**Changes in groundwater chemistry and flow direction**		
Ideal assessment: YES		Adequate assessment: YES	Time frame to assess: **all**

Description of process:

It is inevitable that over the lifetime of the repository the groundwater chemistry and flow direction will change, eg. due to changing recharge during glacial conditions. These changes may alter the sorption and desorption processes that occur on solid surfaces and may increase or decrease the sorptive capacity of the far-field rocks.

Discussion of process:

Changes in the chemistry of groundwaters are likely to occur when the flow direction changes, and different groundwaters arrive at the far-field from new sources or when recharge rates change significantly. Changes to flow direction may occur as a result of many processes, including changes in the stress field or changes to the climate. Glacial conditions, for instance, may cause large volumes of oxidising fresh waters to flush through the far-field rocks.

Any change in groundwater chemistry is likely to cause a change in precipitation/ dissolution reactions and, as a consequence, more sites for sorption may be made available. Alternatively, previously sorbed radionuclides may be released back to the groundwater through dissolution.

The introduction of groundwaters with higher ionic strength will cause a drop in the sorption capacity as ion-exchange reactions are inhibited. An increase in ionic strength would be likely if dissolution products from the evaporites migrated into the far-field.

It is clear that the interfaces between the different groundwaters existing today (and also between different groundwaters that are likely to exist in the future), are in a state of temporal instability, and these interfaces are likely to move to and fro. This means that the changes in sorption behaviour will be important to evaluate.

It is recommended that changes in groundwater chemistry and flow direction are addressed in all assessments, over all time-periods.

2	The far-field
2.3	Transport and geochemical
2.3.8	**Colloid transport**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**all**

Description of process:

Radionuclide transport may be enhanced by organic and inorganic colloids in the far-field, when poorly soluble radionuclides sorb onto the colloids and are subsequently transported by advection along fractures. Colloids may form in the far-field or may migrate into the far-field from the near-field or the biosphere.

Discussion of process:

Colloidal transport of radionuclides is potentially significant in the far-field, particularly for those actinides which are poorly soluble in deep groundwater environments. The actual significance of colloid transport depends on the abundance of colloids, their stability, the stability of the inclusion or sorption of radionuclides on the colloid and the ability of the rock to filter out colloids. Both organic and inorganic colloids may be significant.

Colloids may be introduced into the far-field from the near-field and also from the biosphere. However, colloids may also be generated in the far-field itself. Colloids are frequently generated at chemical interfaces (changes in Eh, pH or ionic strength) and, consequently, their significance is likely to be greater where chemical interfaces or chemical gradients occur in the far-field.

Chemical gradients and interfaces will occur at the edges of, and within, the alkaline (high pH) plume which will migrate from the near-field. As this plume migrates through the far-field, its chemistry will change as major ions continuously interact with the far-field rock. The consequence of this is that colloids may be continuously generated along the flow-path as the plume creates its own chemical gradient.

It is recommended that the generation of colloids and colloidal transport of radionuclides in the far-field is included in all assessments, over all time-periods.

2	The far-field
2.3	Transport and geochemical
2.3.9	**Transport of radionuclides bound to microbes**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	NO	**all**

Description of process:

Microbes can be considered as colloids, as they are similar in size and radionuclides may sorb to them and be advectively transported along fractures in the same manner as colloids. Microbes may, however, through biological processes, enhance the transport of radionuclides through the far-field over and above that expected by colloids.

Discussion of process:

Microbes can be considered as just another type of colloidal material unless biological processes cause some change to the transport properties of radionuclides sorbed onto them, eg. some microbes are capable of self-propulsion.

Microbial sizes are similar to those of colloids, and the potential size of the near-field population is large. In addition, the mobility of some species may be a factor in their migration rate. Changes in the hydrochemical environment of the near-field, particularly in terms of nutrient levels, may mean that mobility is very limited, but this needs to be evaluated in an ideal assessment.

2	The far-field		
2.3	Transport and geochemical		
2.3.10	**Transport of radioactive gases**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **0 to 10,000 yrs**

Description of process:

Certain gaseous or volatile radionuclides may be able to migrate through the far-field faster than the groundwater advection rate.

Discussion of process:

Radioactive gases may occur dissolved in the groundwater or in a gaseous phase. Those in the gaseous phase may migrate through the far-field at a much faster rate than the groundwater is advecting. The likely transport rates of gases in the far-field is not known.

The concentration of certain radionuclides in gases may be attenuated during transport through the far-field if these radionuclides are involved in reactions with the rock, or if precipitation occurs. This is not likely to be significant for tritium in hydrogen, or tritium and 14-C in methane but may be significant for 14-C in carbon dioxide if it becomes involved in ion-exchange reactions with, or precipitation of, carbonates. The significance of these attenuation processes is not known.

During permafrost conditions, radioactive gases may become trapped in the far-field or be involved in clathrate formation (see 2.1.9). This may also require evaluation in the ideal assessment.

It is recommended that transport of radioactive gases, and attenuation processes in the far-field are addressed in all assessments, over all time-periods of major gas production, ie. the first 10,000 years after closure, if this duration is confirmed.

2	The far-field		
2.3	Transport and geochemical		
2.3.11	**Gas induced groundwater transport**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **0 to 10,000 yrs**

Description of process:

Two phase flow (gas and groundwater) occurring in the far-field may affect the rate and direction of the groundwater flow by a number of processes. The consequences of these processes could be that contaminated groundwaters follow different far-field pathways and reach the biosphere earlier than predicted.

Discussion of process:

A gaseous phase in the far-field is likely to have a number of effects on the groundwater flow and dissolved radionuclide transport; 1) mobile bubbles may change the apparent viscosity and density of groundwater and induce or accelerate movement, 2) bubbles may push groundwater in front of them along preferred pathways, ie. fingering, 3) immobile bubbles may change the direction of groundwater flow by effectively sealing certain pathways, 4) bubbles may scavenge radionuclides from the groundwater which then bind to the gas/water interface and move with the bubble, ie. gas flotation, and 5) gas bubbles coming out of solution due to a drop in confining pressures as groundwater rises may change the water chemistry, notably altering the pH as gaseous carbon dioxide is evolved.

The significance of these processes clearly depends on the rate of bubble formation, the size of the bubbles, and the rate of bubble movement through the far-field and, consequently, the rate of gas production in the repository is important to determine.

It is recommended that gas induced groundwater transport is addressed in all assessments, over the time period of gas production, ie. the first 10,000 years after closure.

2	The far-field		
2.3	Transport and geochemical		
2.3.12	**Thermal effects on hydrochemistry**		
Ideal assessment: NO		Adequate assessment: NO	Time frame to assess: **none**

Description of process:

Changes in the groundwater temperature in the far-field, if significant, may change the solubility and speciation of certain radionuclides. This would have the effect of altering radionuclide transport processes operating in the far-field.

Discussion of process:

The thermal effect due to heat-producing intermediate-level waste will be insignificant in the far-field and, consequently, only the normal geothermal gradient need be considered.

The possible changes to groundwater temperatures in the far-field, due to the geothermal gradient, are believed to be too low to cause significant changes in radionuclide solubility or speciation. Radionuclide transport processes operating in the far-field will not, therefore, be affected.

It is recommended that thermal effects on hydrochemistry are omitted from all assessments.

2	The far-field		
2.3	Transport and geochemical		
2.3.13	**Biogeochemical changes**		
Ideal assessment: **NO**		Adequate assessment: **NO**	Time frame to assess: **none**

Description of process:

The surface environment will change over the lifetime of the repository due to changes in climate. The biological (microbial) load of recharge water may also change and this could affect the transport of radionuclides in the far-field.

Discussion of process:

The quantity of microbes introduced into the far-field from the biosphere is likely to be low and the nature of these microbes is not likely to be significantly different from those occurring at the present. It is unlikely, therefore, that any change in radionuclide transport processes in the far-field may result.

It is recommended that such biogeochemical changes are omitted from all assessments.

2	The far-field		
2.4	Geomorphology		
2.4.1	**Generalised denudation**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **all**

Description of process:

The erosion of the land-surface on a regional scale due to glacial, fluvial and aeolian processes.

Discussion of process:

Denudation of the land surface on a regional scale will have three principal consequences, 1) the groundwater flow system will be changed, 2) the repository progressively will be brought closer to the surface, and 3) the sediment produced by erosion will form the substrate for biosphere development.

The most important erosional mechanisms will be glacial and fluvial, often as a combined fluvio-glacial system. Fluvio-glacial erosion will become progressively more important on longer timescales. Under glacial conditions, the Quaternary sediments will be removed very quickly and other fluvio-glacial sediments are likely to be laid down. The groundwater flow system will be changed significantly in response to this sediment redistribution bringing about a change in the groundwater recharge and discharge points.

The rocks of the Sherwood Sandstone Group will be removed by fluvio-glacial erosion at a rate in the order of 100 metres per million years and, as the glaciers retreat ,the land surface will rise due to isostatic compensation. The net effect could be to bring the repository significantly closer to the land surface over a period in excess of one million years.

During interglacial periods and after the exit from glacial/interglacial cycling aeolian denudation may occur. However, in comparison to fluvio-glacial erosion rates, aeolian erosion is insignificant.

It is recommended that fluvial and glacial denudation on a regional scale is included in all assessments over all time periods. In contrast aeolian denudation is slow and can be omitted from all assessments.

2	The far-field
2.4	Geomorphology
2.4.2	**Localised denudation**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	**YES**	**all**

Description of process:

The erosion of the land-surface on a local scale due to glacial, fluvial and coastal erosion processes.

Discussion of process:

Denudation of the land surface on a local scale will occur by fluvial processes (valley erosion), coastal erosion and glacial action. River down-cutting to form valleys is controlled by the rate of uplift, ie. the rate of general denudation. If uplift is rapid then localised valleys of some depth may be formed. It follows that valley erosion is most significant when glaciers retreat and when sea-level drops due to onset of glacial conditions, when there are large volumes of surface water and the land-surface is rising.

Coastal erosion is a general horizontal denudation, moving inland and is controlled by the sea-level. If the sea-level is low then coastal erosion in the area of the repository is not significant but becomes more important in this respect as sea-levels rise. It follows that coastal erosion may be most significant in the short term if the greenhouse effect causes melting of the icecaps and sea-level rise.

Localised glacial erosion will occur by general scouring of the land-surface and by fluvio-glacial erosion when glaciers retreat; 'tunnel valley' formation (see 2.1.8).

Localised denudation will be superimposed on the general denudation processes and may be significant, but will possibly be a second order effect. However, it is recommended that localised denudation is addressed in all assessments over all time-frames. Certain localised denudation effects (eg. tunnel valleys) are so significant as to require separate treatment.

3	Climatology		
3.1	Climate change		
3.1.1	**Human induced**		
Ideal assessment: YES		Adequate assessment: YES	Time frame to assess: **0 to 1,000 yrs**

Description of process:

Changes to the climate due to human activities, eg. release of greenhouse gases to the atmosphere. It is normally considered that the consequences of human activity will be to warm the atmosphere but this is not certain, especially in the long-term, and cooling may occur. Climate change will have a direct effect on the biosphere in terms of ecology, and will indirectly affect the far-field by changing hydrogeological boundary conditions.

Discussion of process:

The principal effect of human induced climate change will be either to delay the onset of glaciation if anthropopogenic influences warm the climate, or to accelerate the onset of glaciation if anthropogenic influences cool the climate. Human induced changes in the climate may have more profound consequences than simple temperature changes. For example, during warming melting of continental ice-sheets could raise sea-levels with the consequence that fundamental changes to the Earth's climate patterns and cycles could occur.

It is not possible to predict in a quantitative fashion the consequences of human induced climate change. However, a number of factors will need to be considered in any climate change model. Some of these factors relate directly to the biosphere through ecological changes; other factors relate indirectly to the far-field as hydrogeological boundary conditions become altered. The important factors are: 1) changes in precipitation which will have ecological consequences and will change erosion and recharge to groundwater, 2) changes in temperature which only have ecological consequences, 3) sea-level changes which may have ecological consequences and will change the boundary conditions for groundwater flow, 4) potential for storm surges which may have ecological consequences, and 5) changes to potential evaporation which will change recharge to groundwater.

In a full assessment, it is important that these linkages are considered to ensure that models are not constructed where incompatible states for the biosphere and far-field are superimposed.

It is recommended that human induced climate change is included in all assessments over a period of 1000 years after closure. Beyond this time it is thought likely that natural climate changes will dominate.

3	Climatology		
3.1	Climate change		
3.1.2	**Natural**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **all**

Description of process:

Natural climate changes associated with Milankovitch cycles (external forcing processes) and leading to glacial/interglacial cycling. Natural climate change will have a direct effect on the biosphere in terms of ecology, and will indirectly affect the far-field by changing hydrogeological boundary conditions and, thus, influencing radionuclide transport.

Discussion of process:

Climate changes involved with glacial/interglacial cycling will have a profound impact on both the biosphere and groundwater flow in the far-field. A number of factors are important, including 1) changes in precipitation, 2) changes in temperature, 3) sea-level changes, 4) seasonally frozen ground, 5) permanently frozen ground and, 6) potential evaporation. All of these factors will effect groundwater flow by producing possible changes in the recharge and discharge volumes and fluxes, the groundwater flow directions and the length of flow paths. In particular, it should be noted that the formation of a large ice sheet will cause a change in groundwater flow from small topographically driven cells, to cells as extensive as the ice sheet itself.

It is recommended that natural climate change is included in all assessments over all time-frames.

3	Climatology		
3.1	Climate change		
3.1.3	**Exit from glacial/interglacial cycling**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **all**

Description of process:

It is expected that a succession of glacial and interglacial periods may continue for the feasible future and possibly well beyond HMIP's quantitative assessment phase (see 3.1.4).

Discussion of process:

Exit from individual glacial periods will cause large volumes of surface water to accumulate as some glaciers melt. Meltwater, and its rate of production, have an important effect on surface environments, groundwater fluxes and flow directions. However, exit from the whole period of glacial/interglacial cycling will create maximum volumes of surface water as glaciers and icecaps melt. This will have an even greater effect on surface environments, and groundwaters.

The times of exits from individual glaciations and from the whole period of glacial/interglacial cycling are not well defined (see 3.1.4).

It is recommended that the exit from glacial/interglacial cycling is included in all assessments over all time frames.

3	Climatology
3.1	Climate change
3.1.4	**Intensification of natural climate change**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**all**

Description of process:

The frequency and amplitude of glaciations seems to be controlled by the Milankovitch periodicities. The current dominant periodicity of glacial events is approximately 100,000 years. This periodicity could change at any time to a shorter, or possibly a longer time interval.

Discussion of process:

Many periodicities can be inferred from fossilised glacial features observed within the geological record and it is seen that changes occur in the dominant periodicity at discrete 'change points'. It is not yet understood what basic mechanisms control these change points.

Although it is not thought likely, it is possible that the current dominant periodicity could be superseded by another, possibly with a longer frequency of 400,000 years. In addition, the amplitude of glaciations could increase, with the glaciations becoming more intense. Such intensification in glaciations would affect the biosphere and produce more extensive periods of permafrost which would affect groundwater flow in the far-field due to changes in the pattern of recharge and discharge.

A lengthening of individual glaciations or repeated glaciations may more rapidly exhume the repository.

It is recommended that glacial intensification is included in all assessments over all time-frames.

4	Biosphere
4.1	Radionuclide entry points to the biosphere
4.1.1	**Groundwater discharge to soils and surface waters**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	**YES**	**all**

Description of process:

Radionuclides transported in groundwater as solutes or solid material (suspended particulates) from the far-field to the biosphere will occur at specific 'entry' points in the biosphere.

Discussion of process:

Groundwater will be the principal carrier of released radionuclides, and the locations at which groundwater leaves the far-field and enters the biosphere ('entry' points) need to be identified and their importance assessed.

These groundwater entry points include soils, sediments and all surface waters, eg. springs, rivers, lakes, estuaries, coastal waters and seas. For the sake of clarity, we include wells in the latter category. Once radionuclides have arrived at a groundwater entry point they are available for transfer within the biosphere and subsequent contact with the human population.

It is recommended that all entry points for groundwater are examined in all assessments over all time frames.

4	Biosphere	
4.1	Radionuclide entry points to the biosphere	
4.1.2	**Solid discharge via erosional processes**	
Ideal assessment: **YES**	Adequate assessment: **YES**	Time frame to assess: **all**

Description of process:

Dissolved radionuclides migrating in the far-field will contaminate the far-field rock by sorptive and retardation processes. At some later time, this contaminated far-field rock may be exposed to the biosphere by general and localised denudation. As the rock further weathers and erodes, the radionuclides will enter the biosphere.

Discussion of process:

Contaminated far-field rocks will be exhumed by normal denudation processes and the rock's radionuclide load will enter the biosphere.

It is recommended that radionuclide entry to the biosphere by erosional processes is included in all assessments over all time frames.

4	Biosphere
4.1	Radionuclide entry points to the biosphere
4.1.3	**Gas discharge**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**all**

Description of process:

Some radionuclides migrating through the far-field may do so in the gas phase, eg. tritium, or C-14 in carbon dioxide or methane. Transfer of gaseous radionuclides from the far-field to the biosphere is likely to occur at specific 'entry' points to the biosphere controlled by faults and fractures.

Discussion of process:

Locations at which gases may enter the biosphere from the far-field include the soils and surface waters, eg. wells, springs, rivers, lakes, estuaries, coastal waters and seas.

It is necessary to identify those radionuclides which may be released and transported in the gaseous phase, and to identify the critical exposure routes and, hence, entry points to the biosphere.

It is recommended that all entry points for gaseous radionuclides are examined in all assessments over all time frames.

4	Biosphere
4.2	Transfer (concentration/dilution) mechanisms
4.2.1	**Soil moisture and evaporation**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**all**

Description of process:

Radionuclides contained in near-surface waters and in soil water may become concentrated in the soil, as water is evaporated from it. The concentrated radionuclides are then available for further transfer processes within the biosphere and, possibly, increased exposure to the human population.

Discussion of process:

Soils form an entry point to the biosphere for radionuclides associated with groundwater, radionuclides deposited in soils due to erosional processes and gaseous radionuclides passing through which become fixed on route. Those radionuclides that remain or become incorporated in the near-surface and soil waters may be concentrated in the soil as evaporation proceeds.

If the supply of contaminated groundwater to the soil is continuous, the quantity of concentrated radionuclides in the soil could continue to grow. This supply of concentrated radionuclides will be available for transfer within the biosphere and may cause increased exposure to the human population. However, other processes also may proceed (such as flushing by rainwater) which will serve to dilute radionuclides.

The consequences of radionuclide concentration by soil-water evaporation depend, in part, on the time since closure, the radionuclide flux to the soil, the soil use and the climate.

It is recommended that radionuclide concentration by soil water evaporation is addressed in all assessments over all time frames.

4	Biosphere
4.2	Transfer (concentration/dilution) mechanisms
4.2.2	**Surface water mixing**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**all**

Description of process:

Dissolved radionuclides contained in surface waters will be transported and transferred around the biosphere by mixing of the surface waters. This mixing may serve to concentrate or dilute the radionuclide load of any particular surface water body.

Discussion of process:

Surface waters form an entry point to the biosphere for radionuclides associated with discharging groundwater and entrained gaseous radionuclides. Radionuclides associated with solid material from erosion of contaminated rocks may become incorporated into the water body. However, due to the dynamic state of surface waters, mixing between surface water bodies is inevitable, and radionuclides may become diluted as a consequence.

Mixing will occur between springs and rivers, rivers and lakes, rivers and estuaries, estuaries and coastal waters, coastal waters and seas.

The consequences of surface water mixing depend, in part, on the time since closure and the relative volumes of the surface water bodies involved and their turnover rates.

It is recommended that surface water mixing is addressed in all performance assessments over all time-periods.

4	Biosphere
4.2	Transfer (concentration/dilution) mechanisms
4.2.3	**Sediment transport including bioturbation**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**all**

Description of process:

Contaminated sediments will be transported in the biosphere by fluvial, glacial and, to a lesser extent, aeolian processes. In addition, sediment transport may occur through the actions of living organisms, ie. by bioturbation. Sediment transport and redistribution may cause concentration or dilution of radionuclides.

Discussion of process:

Sediments will act as a temporary sink for radionuclides entering the biosphere via erosion, and other radionuclides may be transferred to sediments by other processes, eg. sorption and deposition. Apart from those in the deep oceans and on stable land masses, most sediments are continuously being redistributed, and this movement may cause concentration or dilution of radionuclides.

Sediment transport and redistribution may occur via fluvial, glacial and aeolian processes, with aeolian being least important. Sediment transport may also occur through the actions of living organisms, that is by bioturbation and by human activities such as dredging and ploughing the sediment on land.

The consequences of sediment transport depend, in part, on the transport mechanism and the time since closure.

It is recommended that sediment transport is addressed in all performance assessments, over all time-periods.

4	Biosphere
4.2	Transfer (concentration/dilution) mechanisms
4.2.4	**Sediment/water/gas interaction with the atmosphere**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**all**

Description of process:

Radionuclides contained in sediments and surface water bodies, and in the gaseous phase may be transferred to the atmosphere by a variety of processes. Once in the atmosphere, radionuclides are readily available for exposure to the human population.

Discussion of process:

Radionuclides contained in soils, sediments and surface water bodies may be transferred to the atmosphere by a variety of processes, as either vapour, aerosols, gases or as particulates.

Radionuclides entering the biosphere from the far-field as gases can directly enter the atmosphere by advective mixing. Transfer to the atmosphere is most likely to cause dilution, but some processes may cause concentration, ie. by entry into a confined space such as a house.

The rate of transfer to the atmosphere will be controlled by the nature of the release from the geosphere and by the climate, ie temperature, wind speeds and patterns. Once in the atmosphere, radionuclides are readily available for exposure to the human population through inhalation, although they may be subject to considerable dilution.

The consequences of radionuclide transfer to the atmosphere depend, in part, on the time since closure, the climate and the local environment where the release occurs.

It is recommended that radionuclide transfer to the atmosphere is addressed in all performance assessments, over all time-periods.

4	Biosphere
4.2	Transfer (concentration/dilution) mechanisms
4.2.5	**Bioaccumulation and translocation**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**all**

Description of process:

Radionuclides may be incorporated and concentrated in plants, animals and birds and may then be transferred to sediments or to man via the food chain. Long-lived animals, birds and plants may also act as temporary storage locations.

Discussion of process:

Radionuclides contained in soils, water and the atmosphere may become associated with plants as a result of direct uptake through roots and leaves or deposition onto external surfaces, and may be taken up by animals and birds by ingestion and inhalation.

Within the animals and plants, internal translocation mechanisms may distribute the radionuclides to various parts of the organic structure and, in so doing, may concentrate radionuclides, ie. bioconcentration. Radionuclides may be recycled back to soils and water bodies from plants and animals as they die and decay. Radionuclides may be passed to the human population via the food chain, and may be further concentrated in the process, ie. bioaccumulation. However, processing of foodstuffs prior to human consumption may decrease the radionuclide content.

Transport of radionuclides may occur through relocation or migration of animals and birds.

It is recommended that bioaccumulation and translocation are included in all performance assessments, over all time-periods.

4	Biosphere
4.2	Transfer (concentration/dilution) mechanisms
4.2.6	**Biogeochemical processes**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**all**

Description of process:

The transportation and transfer, through and between different compartments of the biosphere is controlled by the biochemical environment. Time-dependent chemical environments in the biosphere may promote or retard certain transport and transfer processes, and consequently control exposure to the human population.

Discussion of process:

Changes in the biochemical environment will influence the movement of radionuclides throughout the biosphere by, for example, changing the speciation or complexation of the radionuclides and, therefore, the transport properties.

The two most important factors are pH and Eh which, on a short timescale, may vary seasonally due to changes in the rate of organic degradation in certain biosphere locations, such as estuaries. On a longer timescale, these factors could be influenced by climate change.

Biogeochemical processes may be very important at the geosphere/biosphere interface as there could be significant changes in the oxygen status and pH which could directly affect radionuclide speciation and, hence, mobility. Besides evaporation as a concentration mechanism in soils (4.2.1), biogeochemical processes such as Eh changes may also cause radionuclides to precipitate from solution in soils.

It is recommended that biogeochemical processes are addressed in all performance assessments, over all time-periods.

4	Biosphere
4.3	Land and surface water use
4.3.1	**Terrestrial**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**all**

Description of process:

Transfer of radionuclides from the entry points to the biosphere, to the human population depend on future land use and ecological development. Terrestrial land use will be primarily controlled by both natural factors, eg. topography, climate etc. and human factors, eg. economics, population density etc.

Discussion of process:

Future terrestrial land use cannot be predicted in a quantitative manner. However, all types of terrestrial land use can be classified into four groups. Assessments would need to look at each land use classification.

The four land use classifications are: 1) agricultural systems; intensive use of the land for food production, both crops and livestock, 2) semi-natural systems; low intensity use of the land for food production or land previously used for food production left fallow, eg. upland grazing and set aside, 3) natural systems; land not changed by human activities, eg. remnants of ancient forests, 4) urban systems, land used for building construction, including homes, work places, roads and recreational facilities.

The land use will strongly control radionuclide pathways in the biosphere to the human population and is, itself, controlled by topography, economics and climate.

It is recommended that land use is included in all assessments, over all time-periods.

4	Biosphere		
4.3	Land and surface water use		
4.3.2	**Estuarine**		
Ideal assessment: YES		Adequate assessment: YES	Time frame to assess: **all**

Description of process:

Transfer of radionuclides from the entry points to the biosphere to people depends on future land use and ecological development. Estuarine land use will be primarily for recreation and food production.

Discussion of process:

Current estuarine land use can be classified into two groups. Assessments would need to look at each land use classification.

Estuaries are associated with active deposition of sediment and materials transported downstream with the flowing waters. The estuarine region could, therefore, act as a sink for radionuclides associated with depositing materials.

The two land use classifications are: 1) food production; estuaries are a rich source of many seafoods, both fish and shellfish. Other food production could be anticipated in estuaries, eg. saltpans, or seaweed harvesting. 2) recreation; estuaries may be continuously used for a variety of recreational pursuits, eg. sailing and swimming.

It is recommended that estuarine land use is included in all performance assessments, over all time-periods.

4	Biosphere		
4.3	Land and surface water use		
4.3.3	**Coastal waters**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **all**

Description of process:

Transfer of radionuclides from the entry points to the biosphere, to people depends on future land use and ecological development. Coastal waters will be primarily used for recreation, food production and industrial purposes.

Discussion of process:

The three commonly used coastal water classifications are: 1) food production; coastal waters are intensively fished, 2) recreation; coastal waters may be continuously used for a variety of recreational pursuits, eg. sailing and swimming, 3) industrial uses; near-shore oil and gas reservoirs and potential tidal power schemes.

It is recommended that coastal water use is included in all performance assessments, over all time-periods.

4	Biosphere		
4.3	Land and surface water use		
4.3.4	**Seas**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **all**

Description of process:

Transfer of radionuclides from the entry points to the biosphere to people depends on future land and surface water use and ecological development. Seas will be primarily used for food production, transportation and recreation purposes.

Discussion of process:

The three commonly used sea usage classifications are: 1) food production; seas are intensively fished, 2) recreation; seas may be continuously used for a variety of recreational pursuits, eg. sailing, 3) shipping.

It is recommended that the use of seas is included in all performance assessments, over all time-periods.

4	Biosphere
4.4	Human exposure
4.4.1	**External**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**all**

Description of process:

Human exposure to repository-derived radionuclides passively by contact with contaminated materials or actively by use of contaminated materials.

Discussion of process:

Releases to the biosphere will cause contamination of the land, sediments and surface waters bodies. Human exposure can occur passively in many ways, for example; standing, sitting or lying on contaminated land or sediment, eg. a beach, or swimming in contaminated water.

Greater human exposure can occur by the active use of contaminated land, sediment or water, for example; cutting of peat or use of contaminated materials in building and construction.

It is recommended that external exposure is included in all assessments over all time frames.

4	Biosphere		
4.4	Human exposure		
4.4.2	**Ingestion**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **all**

Description of process:

Human exposure to repository-derived radionuclides through eating contaminated foodstuffs or drinking contaminated water.

Discussion of process:

Human exposure via contaminated foodstuffs and contaminated water would clearly be a major component of total doses if significant releases to the biosphere occurred. Most of the possible ingestion pathways are covered by the following factors; 1) drinking water from wells, surface water bodies or desalinated estuarine/seawaters, 2) agricultural crops, 3) domestic animals and animal products, 4) wild animals, 5) wild plants, 6) wild and farmed, fresh and marine fish and seafood, 7) evaporative seasalt from saltpans, and 8) direct ingestion of soils and sediments.

It is recommended that ingestion is included in all assessments, over all time frames.

4	Biosphere		
4.4	Human exposure		
4.4.3	**Inhalation**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **all**

Description of process:

Human exposure through inhalation of air and vapour contaminated with repository-derived radioactive gases, or inhalation of suspended solid particulate matter contaminated with repository-derived radionuclides.

Discussion of process:

Human exposure via contaminated foodstuffs and contaminated water could clearly be a major component of total doses if significant releases to the biosphere occurred. Two major ingestion pathways are likely, the first is inhalation of gases and vapours emanating directly from the ground after transportation through the far-field, the second is inhalation of suspended, contaminated particulate matter, eg. daughter products of radon (210-Pb, 210-Po), dust, smoke, pollen, soil and salt particles.

Inhalation of vapours and gases is most likely to be of concern indoors, when a gas exit point from the far-field to the biosphere lies beneath a building, eg where a house has been built astride a high-permeability zone. In this situation, high ambient concentrations may be achieved because rapid accumulation predominates over dilution and dispersion processes. Inhalation may also need to be considered in scenarios for intrusion into a repository.

Outdoors, gases and vapours emanating from the ground will normally be greatly diluted by the wind, and are not of concern. However, one situation when outdoor exposure could be high is where a gas exit point to the biosphere is via a spring or well. In this situation, people regularly using the well or spring for water are at risk from the localised radioactive gas and contaminated suspended particulates (eg. 210-Pb deposits at the wellhead).

Inhalation of contaminated suspended solid particulates needs to be considered outdoors, eg. in recreational areas or roads built with contaminated materials.

It is recommended that inhalation is included in all assessments, over all time frames.

5	Short-circuit pathways		
5.1	Related to repository construction		
5.1.1	**Loss of integrity of borehole seals**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **all**

Description of process:

A number of boreholes will be drilled from the surface in and around the repository footprint during the exploration and site characterisation phase. These boreholes will be sealed after use. If the seals degrade the boreholes may offer a short-circuit route to the biosphere.

Discussion of process:

It is noted that a number of site characterisation boreholes have already been drilled very close to the repository footprint and that if these are not adequately sealed, or the seals fail, they offer an obvious short-circuit route for radionuclides to reach the biosphere. In addition, failure of borehole seals may provide a rapid pathway for short-lived tritium to reach the surface.

Adequate sealing of boreholes is a significant problem in the oil industry where experience has shown that it is difficult to guarantee that the annulus between the steel casing and the rock has been completely filled with sealant. Over long time-periods both the steel casing and the sealant is expected to degrade by reaction with groundwater and possibly also by microbial action. Most of the boreholes at Sellafield will not be cased within basement rocks and later sealing of these sections of the boreholes is likely, but their degradation will also take place.

Due to the possibility of inadequate or failed borehole seals, it is recommended that this issue is examined in all assessments over all time-frames.

5	Short-circuit pathways
5.1	Related to repository construction
5.1.2	**Loss of integrity of shaft or access tunnel seals**

Ideal assessment:	Adequate assessment:	Time frame to assess:
YES	YES	**all**

Description of process:

Access to the repository during the operational phase will be via two parallel long (several kilometres) spiral tunnel from the surface which are likely to be lined with concrete. Ventilation of the repository during the operational phase will be via two vertical shafts from the surface to one corner of the repository footprint. The access tunnels and ventilation shafts will be backfilled and sealed at closure. If the seals fail, the tunnel and shafts will provide short-circuit pathways to the surface.

Discussion of process:

Short-circuit pathways from the repository to the surface created by seal failure will allow more rapid transport of radionuclides dissolved in groundwater and in the gas phase. If seal failure occurs soon after closure, then both groundwater and gas transport may be thermally driven due to the heat output of the waste. In addition, failure of tunnel seals may provide a rapid pathway for short-lived tritium to reach the surface.

During construction of the access tunnels, numerous small boreholes will have to be drilled in its vicinity to perform the necessary support to and barrier for the permeable sandstones by freezing and/or grouting. This means that an extensive disturbed zone will surround the access tunnel making adequate sealing difficult.

It is not known what the nature of the seals in the access tunnels and ventilation shafts will be and, consequently, it is not possible to be specific about the degradation processes or rates. However, chemical and microbiological degradation of the seals may be exacerbated by cracking of the monolithic concrete liner due to movement on faults which intersect the tunnels or shafts.

It is recommended that radionuclide transport to the surface as a consequence of the failure of seals in the access tunnels and ventilation shafts is addressed in all assessments over all time-frames.

In addition to providing a rapid pathway from the repository to the surface, the access tunnels and ventilation shafts may provide a route for oxidising surface waters to reach the repository. This issue also should be addressed in all assessments over all time-periods.

5	Short-circuit pathways		
5.1	Related to repository		
5.1.3	**Incomplete near-field chemical conditioning**		
Ideal assessment: **YES**		Adequate assessment: **YES**	Time frame to assess: **all**

Description of process:

In the near-field the metal and concrete containers offer limited physical containment. The principal near-field barrier for the intermediate-level waste is chemical: the development of hyperalkaline, reducing conditions. If this chemical conditioning were incomplete or were lost, the only barrier to radionuclides would be the far-field. It is conceivable that rapid fracture flow could prematurely allow releases to the surface.

Discussion of process:

The rapid chemical conditioning of the intermediate-level waste near-field is dependent on the porous backfill allowing rapid mixing. If this backfill were to collapse prematurely, be fractured, behave heterogeneously or if vault collapse occurred, chemical conditioning of the near-field could be a much slower, or even incomplete process. If this were to occur, it is possible that groundwater may flow into a poorly chemically conditioned region of a vault, dissolve radionuclides and pass out of the near-field without having to migrate through the backfill. If the groundwater were less strongly reducing and flowing faster than expected, then it is possible that releases to the far-field would be higher.

The likelihood of incomplete chemical conditioning of the near-field is not known but depends on difference between the rate of backfill degradation and the rate of groundwater ingress to the vaults and radionuclide dissolution.

An alternative scenario is where the near-field is chemically conditioned but that groundwater flux through the repository is greater than expected, which would lower the pH.

It is recommended that the potentials for incomplete chemical conditioning of the near-field or rapid lowering of the pH due to fast groundwater fluxes are examined in all assessments over all time-frames.

5	Short-circuit pathways		
5.2	Unrelated to repository construction		
5.2.1	**Meteorite impact**		
Ideal assessment: **NO**		Adequate assessment: **NO**	Time frame to assess: **none**

Description of process:

The impact of a meteorite large enough to disturb or remove rock in the far-field so that radionuclide transport to the surface is accelerated via newly formed fissures.

Discussion of process:

The probability of a meteorite large enough to disturb the far-field impacting at any given point on Earth has been calculated to be about one in one thousand million per year. This probability is so low that it may be ignored. Besides, the direct consequences of such a collision are far greater than the radiological risks associated with enhanced releases from the repository.

It is recommended that meteorite impact is omitted from all assessments.

5	Short-circuit pathways		
5.2	Unrelated to repository construction		
5.2.2	**Deliberate intrusion**		
Ideal assessment: **NO**		Adequate assessment: **NO**	Time frame to assess: **none**

Description of process:

Purposeful drilling or tunnelling into the repository with full knowledge of its nature and subsequent consequences.

Discussion of process:

It is conceivable that at some time after closure of the repository deliberate intrusion into the repository may occur. A number of possible reasons for this can be considered but the two that appear most likely are: 1) to recover materials emplaced in the repository that have attained commercial value since the repository was closed, or 2) for scientific research, to determine if actual repository performance matches that predicted.

However, as such intrusion is deliberate and done with full knowledge of the consequences and cannot be prevented, it is recommended that this issue is omitted from all assessments.

5	Short-circuit pathways	
5.2	Unrelated to repository construction	
5.2.3	**Malicious intrusion**	
Ideal assessment: **NO**	Adequate assessment: **NO**	Time frame to assess: **none**

Description of process:

Purposeful drilling or tunnelling into the repository with the intent of releasing harmful radionuclides to the surface.

Discussion of process:

While obviously undesirable, it is conceivable that at some time in the future the repository may be drilled into or excavated with the sole intent of releasing harmful radionuclides to the surface. Such an event may occur as the result of an act of war, or terrorist or other activities.

However, as such intrusion is deliberate and done with full knowledge of the consequences and cannot be prevented, it is recommended that this issue is omitted from all assessments.

5	Short-circuit pathways		
5.2	Unrelated to repository construction		
5.2.4	**Accidental intrusion**		
Ideal assessment: YES		Adequate assessment: YES	Time frame to assess: **all**

Description of process:

Drilling, tunnelling or mining into the repository without knowledge of its existence.

Discussion of process:

While obviously undesirable, it is conceivable that at some time in the future the repository may be drilled, tunnelled or mined into by accident, or without knowledge of the consequences. There are countless possible reasons why this may occur, eg. exploratory drilling, exploitation drilling, archaeological excavations, injection of liquid wastes etc.

Despite the large number of possible accidental intrusion scenarios the range of outcomes of all of them is thought to be quite similar and, as a consequence, only three need to be considered:-

1) The repository is drilled into, the nature of the repository is soon recognised and the borehole sealed. The drillers and the nearby biosphere are contaminated to a level primarily dependent on the time of intrusion after closure.

2) The repository is drilled into, the nature of the repository is not recognised and large volumes of organic or corrosive liquid wastes are injected into the highly porous or collapsed near-field. The consequences are primarily dependent on the nature of the waste injected and the time of intrusion after closure.

3) The repository or a zone of contaminated far-field rock is drilled into, the nature of the repository is not recognised and water is extracted from the borehole for drinking. The local population and the nearby biosphere are contaminated to a level primarily dependent on the time of intrusion after closure. It is realised that repository intrusion is unlikely because boreholes sunk for drinking water would not penetrate the BVG but would stop in the sandstones. However, drilling into a contaminated major fracture zone is considerably more likely, and this does represent a worst case scenario for comparison purposes.

It is recommended that these three scenarios are included in all assessments for all time-frames and are used to represent the entire spectrum of all other possible intrusion scenarios.

Appendix 1

Guidance Notes for the System Concept Group

IZ3185-TN1
Version 2

Her Majesty's Inspectorate of Pollution Assessment of UK Nirex Ltd Proposals

Guidance Notes and Instructions for Members of the

SYSTEM CONCEPT GROUP

April 1992

Study Leader: Neil A. Chapman

Neil Chapman ..... Date: 8/5/92

Project Manager: Trevor J. Sumerling

Trevor Sumerling ..... Date: 11/5/92

INTERA

1. Background

During the course of 1992 UK Nirex Ltd, the company with responsibility for the disposal of Britain's low and intermediate level radioactive wastes, will submit a planning application to allow them to begin the construction of a deep repository at Sellafield, on the north-east coast of England. This application will lead to a Public Inquiry, probably to be held in late 1993. It is anticipated that the Nirex application will be for approval to excavate a shaft and underground workings at the proposed repository site, and continue with surface exploration. Although the application will contain a description of how the site was selected, and how it is expected to perform in terms of long-term radiological safety, it will not constitute a formal submission for approval to dispose of wastes. Consequently, the safety case will be preliminary, and somewhat peripheral to the main intent of the application, which is concerned with permission to carry out development. Indeed, the safety case contained in the Public Inquiry documents will be based on only a limited amount of the information which is actually available from the current investigations at the site, which have been under way for three years. It is anticipated that, having explored the site in detail via underground activities, Nirex will submit a full safety case in some years time when they seek formal approval to operate a repository and bury wastes. At that time they must satisfy the requirements of the regulatory agencies, which include Her Majesty's Inspectorate of Pollution (HMIP), part of UK Department of the Environment. However, HMIP will be expected to present an interim view on the proposed development at the current stage, and will be called upon to give this view at the 1993 Public Inquiry.

In order to fulfil its regulatory role, HMIP has, for the last decade, been developing an assessment capability independent of that within the nuclear industry. This recently culminated in the partial testing of components of their methodology in the 'Dry Run 3' exercise (DR3), a trial assessment of a hypothetical L/ILW repository sited beneath the Harwell site in Oxfordshire. Combined with earlier studies, DR3 has provided HMIP with a comprehensive capacity to assess Nirex proposals.

In order to be able to respond to the upcoming inquiry, HMIP has commissioned Intera to co-ordinate an assessment of the Nirex proposals for Sellafield using, in part, the methodology of DR3.

2. Approach to the HMIP assessment

The approach Intera will adopt, in outline, is:

- First, we shall 'track' the safety assessment that Nirex will present, using the same conceptual models and data, but alternative computer codes which may handle the information in a different way. This will provide a check and comparison of Nirex calculations and codes.

- Second, we shall examine, and carry out calculations for, alternative conceptual models and data interpretations. We shall also exercise the capability for long-term environmental modelling developed by HMIP/DoE to investigate the radiological impacts under changing environmental conditions and associated temporal uncertainty.

- Third, an uncertainty and bias audit will be carried out for both Nirex and HMIP assessments in order to analyse the various phenomenological scopes, and data and modelling choices made, and to map the treatment of uncertainty in each case. This will provide a basis for the comparison of results from both assessments, identify key uncertainties that Nirex must seek to quantify or reduce by further site investigation or design, and to enable quantitative statements to be made about the level of confidence that can be attached to the various results.

In the present piece of work we are concerned with developing a basis for the second and third tasks described above. Essentially this will involve a thorough analysis of all aspects of the site and repository, the identification of any gaps present in the Nirex assessment, the development, if

necessary, of alternative conceptual models of critical processes, and the quantitative evaluation of their impacts. These evaluations, together with the definition of how they are to be carried out, will be performed by several specialist Assessment Groups looking, for example, at near-field processes, hydrogeology, repository design issues, and the biosphere. These groups will, however, need to be 'primed' with a comprehensive list of all the factors and phenomena which could be important in an assessment, together with an expert view on the relative significance of each of these phenomena and whether they should be included in a full system assessment, or their impacts evaluated by separate scoping calculations.

The primary task of the System Concept group is to elicit this comprehensive list of phenomena and factors and related information for use by the various Assessment Groups. The list will also be used as the basis of a phenomenological audit to be carried out as part of the Uncertainty and Bias Audit.

3. The System Concept Group.

The Assessment Groups need to be provided with as comprehensive a list of potentially significant factors as possible. The specification for what needs to be delivered to them is as follows:

Deliverables

1. A comprehensive list of all the phenomena which could occur and which could influence the behaviour of the repository after closure, with some consideration of when they might occur.

2. An expert opinion on whether and when these phenomena are likely to be of significance to the behaviour of the repository system; i.e. some expert estimate of likelihood and consequence (NB: here, consequence does not mean radiological consequence, merely impact on system behaviour).

3. Abstracted from this list, an outline of the phenomenological contents of what ought to constitute the minimum acceptable level of a full system safety assessment (the 'minimal assessment'), together with some comments on the potential interactions of phenomena that need to be accounted for in such an assessment.

4. A further list of other significant phenomena whose impacts need not necessarily be evaluated in a full system assessment, but which may be more amenable to separate scoping calculations, together with a commentary on their relative importance.

5. Adequate documentation of the decisions taken.

The best way to achieve such objectives is by means of an Expert Group, with members whose expertise covers the scientific and technical range of a safety assessment, with adequate overlap of interest and experience. This is the 'System Concept Group', of which you are a member. The *outline* tasks of the SCG are as follows:

Outline Tasks of SCG

1. Each expert begins by applying their own knowledge **independently** and, thinking laterally, considers all phenomena and factors which might occur, regardless of apparent significance.

2. Individual experts then attach a significance, in terms of how they believe each phenomenon on which they feel competent to comment will influence the behaviour and evolution of the system, and also make a preliminary division of phenomena that need

to be in the minimal assessment, treated separately, or neglected entirely.

3. Experts then discuss together the working list of phenomena and significances, looking for interactions between phenomena which they might not have perceived individually.

4. From the final agreed list of phenomena and significances, the SCG constructs the contents of what they jointly regard as being a minimal assessment, and decides how to treat all the remaining phenomena.

In order to perform this work the SCG members will clearly require the basic information on the nature of the site and the wastes, and the proposed repository design, see below.

In the course of this work the SCG should take no account of how the assessment groups might handle the evaluation of any of the phenomena identified as significant; this is not their problem, and the SCG should not allow perceived practical limitations to influence their thinking. Similarly, the SCG should take no account of how Nirex has addressed issues in their safety assessment, either in terms of which phenomena they considered, or how they were modelled. Equally, they should not examine documentation describing either the HMIP modelling capabilities, or the Nirex safety case for Sellafield.

Thus, the Group is intended to provide a neutral, unbiased evaluation of important factors in the future behaviour of a repository by means of expert opinion. It is the task of the Intera secretariat to provide the Group with the relevant supporting information, and a forum in which the information can be elicited from each member, again without directing the thinking of the group in any way that could cause bias. It is important that the discussions of the Group are managed in such a way that no particular view or expert should dominate the outcome. To this end it is probable that an observer will be present to detect any areas where bias may have been inadvertently introduced.

Fortunately, this process has already being carried through once before, as part of DR3. Consequently a methodology already exists, as does a very comprehensive list of phenomena and factors relevant to a L/ILW repository at Harwell. The task of the SCG is thus made easier, in that we simply have to review this list in the light of what is known about the Sellafield site, in order to ensure that it is complete and applicable, and to add any new phenomena that may be required, and remove any that are not. The significance of the factors can then be re-evaluated by the SCG for the Sellafield case.

4. Baseline Information

Each expert will be provided with these briefing notes, plus a set of reports covering what is known about the Sellafield site (geology, surface environment, repository design, etc) derived from the Nirex site investigation programme. In addition, copies of relevant papers from the parallel DR3 exercise will be provided, principal among these being the final list of phenomena derived, which will form the basis for the SCG work. All experts will receive all the information, and a list of documents is appended to this note.

5. Work Programme

The SCG will carry out its work over a period of a few weeks only. The task will be broken into three phases:

1. *Individual review*. Each expert is provided with the complete set of supporting literature and these briefing notes. Each expert will then spend a period of up to three days reviewing this information, at the end of which they should send a revised list of phenomena, plus information on significances, etc (as outlined below) to Intera, and prepare notes to support their contributions to

subsequent discussions, which they will use in the next phase.

2. *A meeting* will be held at which the list of phenomena is discussed. Intera will lead this discussion, and, being in receipt of each experts revisions and comments, will elicit their views for general discussion. At the start of the meeting each expert will be asked to describe how their own experience may lead to bias and, as a group, we will discuss how potential biases could arise. Attention will be paid to any unforseen coupling of phenomena that may arise. A record will be kept of the reasons for treating each phenomenon in the way decided. It is hoped that in many cases this will be a relatively simple task, as no change from the DR3 analysis may be required. This discussion should lead to a joint view of the significance of phenomena, and the manner in which they should be treated by the Assessment Groups.

3. *Final review.* Following the meeting the secretariat will write-up the deliberations and provide each expert with a document comprising

a) the final list of phenomena,
b) comments on the significance of each,
c) the contents of the minimal assessment,
d) proposals on how to treat the remaining phenomena.

Each expert will then spend a day reviewing this report and send back written comments to be included in a final version which will be presented to the Assessment Groups.

6. Detailed Guidance to the Experts.

The following notes define specifically what is expected of each expert, and provide further information on how to evaluate the documentation provided.

6.1. Several documents describing various aspects of the Sellafield site and the design and waste inventory of the repository are provided (see Bibliography). You should first familiarise yourself with these in order to build up a picture of the full system we are to consider.

6.2. A list of phenomena is provided. We hope that the phenomena will be self-explanatory and no definitions are provided. In this manner the list should spur individual experts thinking, and any potential for different interpretations will widen the net usefully, and can be brought out at the meeting. If, however, you have any problems please contact the secretariat. This is the initial list provided to the DR3 Expert Group and revised and upgraded by them to be comprehensive of all items that might be influential in a safety assessment. Bear in mind that this list was prepared for the same wastes and a generically similar repository, but situated in clay formations at an inland site in southern England. The list contains crosses against phenomena which, in the view of the previous group, could be ignored, even in a comprehensive assessment. The list has been formatted by us to allow you to use it as a worksheet. You are requested to review the list in the light of what you have learned about the 'Sellafield system' and:

a) ensure that it is complete,

b) specify in which future time period each phenomenon ought to be accounted for, using three time frames; 0-10ka, 10ka-1Ma, beyond 1Ma. You will note that the list of phenomena is tabulated to allow you to check items against timeframes. You may wish to comment on the choice of these timeframes.

c) decide whether the phenomena are of major or minor importance in influencing the behaviour of the system, again within each timeframe. This will help us in the next step of deciding how to treat each phenomenon.

b) decide which items can be omitted from an assessment on the grounds of negligible impact, again accounting for the three time frames if a different answer would be appropriate for different times.

Each time frame column should thus be marked with:

M = major importance
o = minor importance
x = negligible impact; neglect

In doing this you should be aware that:

1. the period over which HMIP intends to attempt quantitative assessment is 1 million years; beyond this only qualitative evaluations will be made

2. the safety assessment will not concern itself with the operational period of the repository, only the post-closure period

3. negligible impact means that the phenomenon will not affect the behaviour of the system in any way, either alone or in conjunction with other phenomena, that would require its effects on radionuclide release/radiological safety to be evaluated

4. the safety assessment, will not concern itself with non-radiological hazards (e.g. flammable gases, toxic but non-radioactive materials), provided these phenomena do not affect radionuclide releases.

6.3. The minimal assessment that we shall be aiming to construct can be defined as that with *the lowest level of complexity which would not exhibit gross bias as a result of excluded phenomena*. The minimal assessment will comprise a full system analysis which takes account of all the linkages and influences between the phenomena which it is modelling. It will not be our concern to consider how this will be done. In addition to the minimal assessment, we shall provide suggestions for phenomena or groups of phenomena where we believe that separate scoping calculations need to be made, but not necessarily a full assessment.

6.4. The minimal assessment will be constructed principally from those items you have assigned with 'M' marking on the list. However, we will need to bear in mind influences and interactions which may mean that a phenomenon marked with an 'o' actually becomes of major importance when associated with another phenomenon. A further column has been provided on the list for you to make your preliminary suggestions of how each phenomenon should be handled in the subsequent assessment:

A = component of minimal assessment
S = evaluate by separate scoping calculations
X = no assessment required

To assist in your deliberations on what should be in the minimal assessment we also enclose a tabulated list of the conclusions of the DR3 expert group. In addition, the DR3 minimal assessment 'influence diagram' is attached.

As preparation for the discussion on the minimal assessment and topics for separate analysis we would thus request that you:

a) complete the 'How to Evaluate' column on the master list

PROCESSES CONSIDERED IN DRY RUN 3	Excluded from DR3	SIGNIFICANCE 0-10 ka	10 ka-1 Ma	1 Ma plus	How to evaluate
		Mox	Mox	Mox	ASx
1: NEAR-FIELD					
1.1 Chemical/physical degradation		1, 0, 0	0, 1, 0	0, 0, 1	0, 1, 0
1.1.1 Structural and container metal corrosion		1, 3, 0	0, 3, 1	0, 1, 3	2, 0, 1
1.1.1.1 Localised pitting	x	1, 0, 3	0, 0, 4	0, 0, 4	0, 1, 3
1.1.1.2 Bulk		4, 1, 0	1, 2, 1	0, 1, 3	2, 1, 1
1.1.1.3 Crevice	x	0, 1, 2	0, 0, 3	0, 0, 3	0, 0, 3
1.1.1.4 Stress corrosion cracking	x	1, 0, 3	0, 0, 3	0, 0, 3	0, 0, 3
1.1.2 Physical degradation of concrete		4, 1, 0	2, 2, 1	1, 1, 3	2, 1, 1
1.1.2.1 Cracking		2, 2, 0	1, 0, 2	1, 1, 2	2, 1, 1
1.1.2.2 Sealing of cracks		2, 2, 0	1, 1, 1	1, 1, 2	2, 1, 1
1.1.2.3 Pore blockage		3, 1, 0	2, 1, 1	1, 1, 2	2, 1, 1
1.1.2.4 Alkali-aggregate reaction		2, 2, 0	1, 0, 2	1, 1, 2	2, 2, 0
1.1.2.5 Cement-sulphate reaction		3, 1, 0	2, 0, 2	1, 1, 2	2, 2, 0
1.1.3 Chemical degradation of concrete		4, 1, 0	3, 1, 1	1, 2, 2	3, 0, 1
1.1.3.1 Changes in pore water composition, pH, Eh		4, 0, 0	3, 1, 0 •	2, 1, 1	3, 1, 0
1.1.3.2 Exchange capacity exceeded		2, 1, 0	2, 0, 1	1, 1, 1	1, 1, 1
1.1.3.3 Alkali-aggregate reaction		2, 2, 0	1, 0, 2	1, 1, 2	1, 3, 0
1.1.3.4 Cement-sulphate reaction		3, 1, 0	2, 1, 1	1, 1, 2	2, 2, 0
1.1.4 Degradation of wastes		5, 0, 0	3, 1, 1	0, 2, 3	3, 1, 0
1.1.4.1 Metal corrosion		2, 2, 0	1, 1, 2	0, 1, 3	2, 1, 1
1.1.4.2 Leaching		4, 0, 0	2, 1, 1	2, 0, 2	3, 0, 1
1.1.4.3 Complex formation		4, 0, 0	2, 1, 1	0, 2, 2	2, 1, 1
1.1.4.4 Colloid formation		3, 1, 0	1, 2, 1	0, 2, 2	1, 3, 0
1.1.4.5 Microbial degradation of organic wastes		4, 0, 0	0, 2, 2	0, 1, 3	2, 2, 0
1.1.4.6 Microbial corrosion		1, 2, 1	0, 1, 3	0, 0, 4	0, 2, 2
1.1.4.7 Radiolysis		1, 2, 1	1, 0, 3	0, 1, 3	1, 1, 2
1.2 Gas Production, Transport and Flammability		1, 1, 0	0, 1, 1	0, 0, 2	1, 0, 1
1.2.1 Hydrogen by metal corrosion		5, 0, 0	1, 3, 1	0, 0, 5	3, 0, 1
1.2.1.1 Structural steel		3, 1, 0	1, 1, 2	0, 1, 3	2, 1, 1
1.2.1.2 Container steel		3, 1, 0	1, 1, 2	0, 1, 3	2, 1, 1
1.2.1.3 Waste steel		4, 0, 0	1, 1, 2	0, 1, 3	2, 2, 0
1.2.1.4 Waste Magnox		1, 3, 0	1, 1, 2	0, 1, 3	1, 2, 1
1.2.1.5 Waste aluminium	x	1, 0, 3	1, 0, 3	0, 1, 3	1, 0, 3
1.2.1.6 Waste Zircaloy	x	1, 0, 3	1, 0, 3	0, 1, 3	1, 0, 3
1.2.1.7 Waste other metals	x	0, 0, 3	0, 0, 3	0, 1, 3	0, 0, 3
1.2.1.8 Effects of microbial growth on concrete		1, 3, 0	0, 2, 2	0, 0, 4	0, 2, 1
1.2.2 Methane and carbon dioxide by microbial degradation		5, 0, 0	1, 4, 0	0, 1, 4	3, 1, 0
1.2.2.1 Cellulosics		4, 0, 0	0, 2, 2	0, 0, 4	2, 1, 1
1.2.2.2 Other susceptible organic materials	x	0, 1, 2	0, 1, 2	0, 0, 3	0, 1, 2
1.2.2.3 Aerobic degradation		0, 2, 2	0, 1, 3	0, 0, 4	0, 2, 2
1.2.2.4 Anaerobic degradation		3, 1, 0	1, 3, 1	1, 0, 4	1, 4, 0
1.2.2.5 Effects of temperature		3, 0, 1	0, 2, 2	0, 0, 4	1, 1, 2
1.2.2.6 Effects of lithostatic pressure	x	1, 0, 2	1, 1, 2	1, 0, 3	1, 1, 2
1.2.2.7 Effects of microbial growth	x				
on properties of concrete		1, 2, 1	0, 1, 3	0, 0, 4	1, 2, 1
1.2.2.8 Effects of biofilms	x	1, 0, 2	0, 1, 2	0, 0, 3	0, 1, 2
1.2.2.9 Effects of hydrogen from metal corrosion		1, 3, 0	0, 1, 3	0, 0, 4	0, 3, 1
1.2.2.10 Inhibition due to the presence of					
toxic materials		1, 2, 1	0, 2, 2	0, 0, 4	0, 2, 2
1.2.2.11 Carbonate/bicarbonate exchange	x				
with concrete		1, 0, 2	1, 0, 2	0, 0, 3	0, 1, 2
1.2.2.12 Energy and nutrient control of metabolism		1, 2, 0	0, 2, 1	0, 0, 3	0, 3, 0
1.2.2.13 Effects of radiation on microbial populations	x	0, 1, 2	0, 1, 2	0, 0, 3	0, 0, 2

1.2.3 Gas generation from concrete	x	0, 3, 1	0, 0, 4	0, 0, 4	0, 3, 1
1.2.4 Active gases		2, 0, 0	2, 0, 0	0, 1, 0	1, 0, 0
1.2.4.1 Tritiated hydrogen		1, 3, 0	0, 2, 2	0, 0, 4	0, 3, 1
1.2.4.2 Active methane and carbon dioxide		1, 3, 0	0, 2, 2	0, 0, 4	0, 3, 1
1.2.4.3 Other active gases	x	0, 0, 3	0, 0, 3	0, 0, 3	0, 0, 3
1.2.5 Toxic gases	x	0, 0, 3	0, 0, 3	0, 0, 3	0, 0, 3
1.2.6 Transport		4, 0, 0	2, 1, 1	1, 1, 2	1, 1, 1
1.2.6.1 In the waste container	x	1, 1, 2	1, 0, 3	1, 0, 3	0, 0, 3
1.2.6.2 In the vault between containers		2, 2, 1	1, 2, 2	1, 1, 3	0, 3, 1
1.2.6.3 Between vaults		2, 2, 1	1, 2, 2	1, 1, 3	0, 3, 1
1.2.6.4 In the near-field, including up and around access shafts and adits		5, 1, 0	2, 3, 1	1, 1, 4	3, 1, 1
1.2.6.5 Into and through the far-field		4, 1, 1	2, 2, 2	2, 0, 4	3, 1, 1
1.2.7 Flammability	x	0, 1, 2	0, 0, 3	0, 0, 3	0, 2, 2
1.2.7.1 Fires	x	1, 1, 2	0, 1, 3	0, 0, 4	0, 2, 2
1.2.7.2 Explosions	x	1, 0, 3	0, 1, 3	0, 0, 4	0, 1, 3
1.3 Radiation Phenomena					
1.3.1 Radioactive decay and ingrowth		6, 0, 1	6, 1, 0	6, 0, 1	5, 0, 1
1.3.2 Nuclear criticality	x	0, 1, 3	0, 0, 4	0, 0, 4	0, 2, 2
1.4 Mechanical Effects					
1.4.1 Canister or container movement		2, 3, 1	1, 4, 1	0, 2, 4	0, 3, 2
1.4.2 Changes in situ stress field		3, 3, 0	4, 3, 0	2, 3, 2	2, 3, 1
1.4.3 Embrittlement		2, 3, 0	2, 2, 1	1, 2, 2	1, 1, 2
1.4.4 Subsidence/collapse		3, 2, 1	2, 3, 0	2, 2, 1	1, 1, 2
1.4.4.1 Repository induced		3, 2, 1	2, 2, 1	2, 1, 2	1, 1, 2
1.4.4.2 Natural		1, 2, 2	3, 3, 1	3, 1, 2	0, 2, 3
1.4.5 Rock creep		3, 3, 0	2, 4, 0	2, 3, 1	1, 3, 2
1.4.6 Fracturing		4, 2, 0	4, 2, 0	3, 2, 1	3, 2, 1
1.5 Hydrological Effects		2, 0, 0	1, 1, 0	1, 0, 1	2, 0, 0
1.5.1 Changes in moisture content		4, 2, 0	1, 3, 2	1, 1, 4	2, 2, 1
1.5.1.1 Due to dewatering		2, 2, 0	2, 1, 2	1, 1, 3	1, 2, 1
1.5.1.2 Due to stress relief		2, 1, 1	2, 1, 2	1, 1, 3	0, 2, 2
1.5.2 Groundwater flow (unsaturated conditions)		3, 2, 0	1, 0, 4	0, 1, 4	1, 2, 1
1.5.2.1 Initial		4, 1, 0	0, 3, 2	0, 0, 5	2, 1, 1
1.5.2.2 Due to gas production		4, 0, 1	0, 3, 2	0, 0, 4	3. 0, 1
1.5.3 Groundwater flow (saturated conditions)		6, 0, 0	7, 0, 0	5, 2, 0	5, 0, 1
1.5.4 Transport of chemically active substances into the near-field		6, 0, 0	5, 1, 0	5, 0, 1	4, 1, 0
1.5.4.1 Inorganic ions		6, 0, 0	5, 1, 0	4, 1, 1	4, 0, 1
1.5.4.2 Humic and fulvic acids		2, 3, 1	2, 3, 1	2, 2, 2	2, 2, 1
1.5.4.3 Microbes		3, 2, 1	2, 2, 2	1, 2, 3	2, 1, 2
1.5.4.4 Organic complexes		4, 2, 0	3, 2, 1	3, 0, 3	3, 1, 1
1.5.4.5 Colloids		3, 3, 0	2, 3, 1	2, 3, 1	1, 3, 1
1.6 Thermal Effects		1, 2, 0	0, 1, 2	0, 0, 3	1, 1, 1
1.6.1 Differential elastic response		1, 2, 1	0, 0, 4	0, 0, 4	0, 2, 1
1.6.2 Non-elastic response		2, 2, 0	0, 1, 3	0, 0, 4	0, 3, 0
1.6.3 Fracture changes		3, 3, 0	1, 1, 4	1, 0, 5	1, 3, 1
1.6.3.1 Aperture		2, 2, 0	0, 1, 3	0, 0, 4	0, 3, 0
1.6.3.2 Length		1, 2, 1	0, 1, 3	0, 0, 4	0, 2, 1
1.6.4 Hydrological changes		5, 1, 0	1, 3, 2	0, 1, 4	0, 4, 0
1.6.4.1 Fluid pressure		2, 2, 1	0, 1, 4	0, 0, 5	0, 2, 2
1.6.4.2 Density		1, 4, 0	0, 1, 4	0, 0, 5	0, 3, 1
1.6.4.3 Viscosity		1, 2, 2	0, 1, 4	0, 0, 5	0, 1, 3

2.3.3.3 Microbial pore blocking		1, 4, 1	0, 3, 3	2, 4, 0	0, 3, 2
2.3.3.4 Channel formation/closure		3, 0, 1	2, 1, 1	2, 0, 2	2, 1, 1
2.3.4 Groundwater flow		2, 0, 1	3, 0, 0	3, 0, 0	3, 0, 0
2.3.4.1 Darcy		4, 1, 1	6, 0, 0	5, 0, 1	3, 1, 0
2.3.4.2 Non-Darcy		3, 2, 1	3, 3, 0	3, 2, 1	1, 3, 0
2.3.4.3 Intergranular (matrix)		4, 0, 2	5, 0, 1	4, 0, 2	3, 0, 1
2.3.4.4 Fracture		5, 0, 1	6, 1, 0	5, 0, 1	4, 0, 0
2.3.4.5 Effects of solution channels		3, 2, 0	3, 2, 0	3, 1, 1	1, 2, 1
2.3.4.6 Unsaturated		2, 3, 0	0, 3, 2	0, 1, 4	0, 3, 1
2.3.5 Salinity	x	3, 3, 0	2, 1, 0	2, 0, 1	1, 1, 0
2.3.5.1 Effects of differences in salinity	x	4, 1, 1	5, 0, 1	5, 0, 1	3, 1, 1
2.3.5.2 Effects at the saline-freshwater interface	x	5, 1, 0	5, 1, 0	5, 0, 1	5, 0, 0
2.3.5.3 Implications of evaporite deposits/minerals	x	4, 0, 1	3, 1, 1	3, 0, 2	2, 1, 1
2.3.6 Variations in groundwater temperature	x	1, 2, 3	1, 3, 2	1, 3, 2	1, 2, 2
2.4 Transport and geochemical		1, 0, 0	1, 0, 0	1, 0, 0	1, 0, 0
2.4.1 Advection		5, 1, 0	6, 1, 0	6, 0, 1	5, 0, 1
2.4.2 Diffusion		3, 1, 1	4, 1, 1	4, 1, 1	4, 0, 1
2.4.2.1 Bulk		2, 2, 1	2, 1, 2*	2, 1, 2	1, 0, 2
2.4.2.2 Matrix		4, 1, 0	4, 0, 1	4, 0, 1	3, 0, 1
2.4.2.3 Surface	x	1, 2, 1	0, 2, 2	0, 1, 3	0, 2, 2
2.4.3 Hydrodynamic dispersion		3, 2, 0	2, 2, 1	2, 2, 1	2, 2, 0
2.4.4 Solubility constraints	x	3, 0, 1	3, 0, 1	3, 0, 1	2, 0, 1
2.4.4.1 Effects of pH and Eh	x	2, 0, 1	2, 0, 1	2, 0, 1	2, 0, 1
2.4.4.2 Effects of ionic strength	x	1, 0, 2	1, 0, 2	1, 0, 2	1, 0, 2
2.4.4.3 Naturally-occurring complexing agents	x	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1
2.4.4.4 Complexing agents formed in the near-field	x	2, 1, 0	2, 0, 1	0, 0, 3	2, 1, 0
2.4.4.5 Naturally-occurring colloids	x	1, 2, 0	0, 2, 1	0, 2, 1	0, 2, 1
2.4.4.6 Colloids formed in the near-field	x	1, 2, 0	1, 1, 1	0, 1, 2	0, 2, 1
2.4.4.7 Major ions migrating from the near-field	x	1, 2, 0	2, 1, 1	2, 1, 1	2, 1, 1
2.4.4.8 Effects of microbial activity	x	1, 1, 1	0, 2, 1	0, 1, 2	0, 2, 1
2.4.5 Sorption		5, 0, 0	4, 1, 0	4, 0, 1	3, 1, 0
2.4.5.1 Linear		3, 0, 0	3, 0, 0	3, 0, 0	3, 1, 0
2.4.5.2 Non-linear		2, 1, 0	2, 1, 0	2, 1, 0	2, 2, 0
2.4.5.3 Reversible		3, 0, 0	3, 0, 0	3, 0, 0	3, 1, 0
2.4.5.4 Irreversible		3, 0, 0	3, 0, 0	3, 0, 0	3, 1, 0
2.4.5.5 Effects of pH and Eh		3, 1, 0	3, 0, 1	3, 0, 1	3, 0, 1
2.4.5.6 Effects of ionic strength		2, 2, 0	2, 2, 0	2, 1, 1	1, 1, 1
2.4.5.7 Effects of naturally-occurring organic complexing agents		1, 3, 0	1, 2, 1	1, 2, 1	2, 1, 1
2.4.5.8 Effects of naturally-occurring inorganic complexing agents		2, 2, 0	2, 1, 1	2, 1, 1	2, 1, 1
2.4.5.9 Effects of complexing agents formed in the near-field		3, 1, 0	2, 1, 1	2, 0, 2	3, 0, 1
2.4.5.10 Effects of naturally-occurring colloids		1, 3, 0	1, 1, 2	1, 1, 2	1, 2, 1
2.4.5.11 Effects of colloids formed in the near-field		1, 3, 0	1, 2, 1	1, 1, 2	1, 2, 1
2.4.5.12 Effects of major ions migrating from the near-field		2, 2, 0	2, 1, 1	1, 1, 2	1, 2, 1
2.4.5.13 Effects of microbial activity		1, 3, 0	1, 1, 2	1, 1, 2	1, 2, 1
2.4.6 Fracture surface changes		3, 2, 0	2, 3, 0	2, 2, 1	2, 2, 0
2.4.7 Organic colloid transport		3, 1, 0	2, 1, 1	2, 1, 1	1, 1, 1
2.4.7.1 Porous media		1, 2, 1	1, 2, 1	1, 2, 1	1, 2, 1
2.4.7.2 Fractured media		2, 2, 0	1, 3, 0	1, 3, 0	1, 3, 0
2.4.7.3 Effects of pH and Eh		2, 2, 0	2, 1, 1	2, 1, 1	1, 2, 1
2.4.7.4 Effects of ionic strength	–	1, 3, 0	1, 2, 1	1, 2, 1	1, 2, 1
2.4.8 Inorganic colloid transport		2, 1, 0	1, 2, 0	1, 1, 1	1, 2, 0
2.4.8.1 Porous media		2, 2, 0	1, 3, 0	1, 2, 1	1, 3, 0
2.4.8.2 Fractured media		2, 2, 0	1, 3, 0	1, 2, 1	1, 3, 0

2.4.8.3 Effects of pH and Eh		2, 2, 0	2, 2, 0	2, 1, 1	1, 2, 1
2.4.8.4 Effects of ionic strength		1, 2, 0	1, 2, 0	1, 2, 0	1, 2, 0
2.4.9 Transport of radionuclides bound to microbes		2, 2, 2	2, 2, 2	2, 2, 2	0, 3, 2
2.4.10 Isotopic exchange		0, 3, 0	1, 3, 0	1, 3, 0	1, 3, 0
2.4.11 Gas transport		3, 0, 0	0, 1, 2	0, 1, 2	2, 0, 0
2.4.11.1 Solution		2, 1, 0	1, 2, 1	1, 2, 1	2, 2, 0
2.4.11.2 Gas phase		3, 0, 0	1, 2, 1	1, 2, 1	2, 2, 0
2.4.12 Gas-induced groundwater transport		4, 1, 1	2, 2, 3	1, 3, 3	3, 2, 1
2.4.13 Thermally-induced groundwater transport		2, 3, 0	0, 3, 2	0, 1, 4	2, 1, 1
2.4.13.1 Repository-induced		1, 4, 0	0, 2, 3	0, 1, 4	0, 3, 1
2.4.13.2 Naturally-induced	x	1, 1, 3	1, 2, 3	1, 1, 4	1, 0, 4
2.4.14 Biogeochemical changes	x	0, 1, 4	1, 0, 5	1, 0, 5	0, 1, 5
3: BIOSPHERE					
3.1 Climatology					
3.1.1 Transient greenhouse gas induced warming		4, 2, 0	0, 2, 4	0, 1, 5	2, 1, 1
3.1.1.1 Precipitation		3, 1, 0	1, 2, 1	0, 0, 3	2, 1, 0
3.1.1.2 Temperature		3, 1, 0	1, 2, 1	0, 0, 3	1, 2, 0
3.1.1.3 Sea level rise	x	2, 4, 0	1, 2, 2	0, 0, 4	4, 0, 1
3.1.1.4 Storm surges	x	0, 3, 1	1, 1, 1	0, 1, 2	0, 1, 2
3.1.1.5 Ecological effects		1, 3, 0	2, 0, 1	1, 0, 2	1, 1, 1
3.1.1.6 Potential evaporation		1, 3, 0	1, 2, 1	0, 0, 3	1, 1, 1
3.1.2 Glacial/interglacial cycling		0, 3, 2	6, 0, 0	5, 1, 0	3, 2, 0
3.1.2.1 Precipitation		0, 3, 0	3, 1, 0	2, 1, 1	2, 1, 0
3.1.2.2 Temperature		3, 1, 0	3, 1, 0	2, 2, 0	1, 2, 0
3.1.2.3 Sea level fall		2, 2, 1	3, 1, 1	2, 2, 1	3, 1, 0
3.1.2.4 Storm surges	x	0, 3, 1	1, 1, 1	0, 2, 1	0, 1, 2
3.1.2.5 Ecological effects		3, 0, 1	2, 2, 0	1, 2, 1	1, 1, 1
3.1.2.6 Seasonally frozen ground		2, 0, 2	2, 1, 1	1, 1, 2	1, 1, 1
3.1.2.7 Permanently frozen ground		0, 2, 2	2, 0, 2	1, 1, 2	1, 1, 1
3.1.2.8 Glaciation		0, 3, 2	4, 1, 0	3, 1, 1	3, 0, 1
3.1.2.9 Deglaciation		0, 2, 2	4, 1, 0	3, 1, 1	3, 1, 0
3.1.2.10 Potential evaporation		1, 2, 0	2, 0, 1	1, 1, 1	1, 1, 0
3.1.3 Exit from glacial/interglacial cycling		0, 2, 3	0, 4, 1	0, 3, 2	0, 3, 0
3.1.3.1 Greenhouse gas induced		1, 1, 3	1, 3, 1	1, 3, 1	1, 2, 1
3.1.3.2 Other causes		0, 1, 3	0, 4, 0	1, 3, 0	0, 3, 0
3.2 Geomorphology					
3.2.1 Generalised denudation		1, 4, 2	4, 3, 0	4, 2, 1	2, 3, 1
3.2.1.1 Fluvial		2, 2, 2	1, 5, 0	2, 3, 1	0, 3, 1
3.2.1.2 Aeolian		1, 3, 2	1, 4, 1	2, 3, 1	0, 2, 2
3.2.1.3 Glacial		0, 2, 4	2, 4, 0	3, 2, 1	2, 2, 1
3.2.2 Localised denudation		1, 3, 1	5, 0, 0	4, 1, 0	3, 1, 0
3.2.2.1 Fluvial (valley incision)		2, 2, 2	3, 3, 0	3, 2, 1	1, 4, 0
3.2.2.2 Fluvial (weathering/mass movement)		1, 3, 2	4, 2, 0	2, 2, 2	0, 3, 2
3.2.2.3 Glacial		0, 2, 4	5, 1, 0	4, 1, 1	3, 1, 1
3.2.2.4 Coastal	x	3, 3, 0	5, 1, 0	4, 1, 1	2, 2, 1
3.2.3 Sediment redistribution		3, 1, 2	2, 4, 0	1, 4, 1	1, 4, 0
3.2.3.1 Fluvial		3, 2, 1	3, 3, 0	2, 3, 1	1, 4, 0
3.2.3.2 Aeolian		0, 5, 1	2, 3, 1	1, 4, 1	0, 4, 1
3.2.3.3 Glacial		0, 2, 4	3, 3, 0	2, 3, 1	2, 2, 1
3.2.4 Effects of sea level change		2, 2, 1	4, 1, 0	3, 2, 0	3, 1, 0
3.2.4.1 River incision/sedimentation	–	3, 3, 0	5, 1, 0	4, 1, 1	4, 1, 0
3.2.4.2 Coastal erosion	x	5, 1, 0	5, 1, 0	4, 1, 1	4, 1, 0

3.5.7.4 Biogeochemical cycling		1, 2, 0	1, 2, 0	1, 1, 1	1, 1, 1
3.5.7.5 Effects of fluvial system development		2, 1, 0	1, 2, 0	1, 1, 1	1, 1, 1
3.5.8 Estuaries		2, 0, 0	2, 0, 0	2, 0, 0	1, 0, 0
3.5.8.1 Water flow		2, 0, 1	2, 0, 1	2, 0, 1	2, 0, 1
3.5.8.2 Suspended sediments		1, 2, 0	1, 1, 1	1, 1, 1	1, 1, 1
3.5.8.3 Bottom sediments		2, 1, 0	1, 2, 0	1, 1, 1	1, 2, 0
3.5.8.4 Effects of salinity and pH variation		2, 1, 0	1, 2, 0	1, 1, 1	1, 2, 0
3.5.8.5 Biogeochemical cycling		1, 2, 0	1, 2, 0	1, 1, 1	1, 1, 1
3.5.8.6 Effects of estuarine development		3, 1, 0	2, 2, 0	1, 1, 1	1, 1, 1
3.5.8.7 Effects of sea level change		3, 1, 0	2, 2, 0	1, 1, 1	2, 0, 1
3.5.9 Coastal waters		3, 0, 0	3, 0, 0	2, 1, 0	2, 0, 0
3.5.9.1 Water transport		2, 1, 0	2, 1, 0	2, 0, 1	2, 0, 1
3.5.9.2 Suspended sediment transport		3, 0, 0	2, 1, 0	2, 0, 1	2, 0, 1
3.5.9.3 Bottom sediment transport		1, 2, 0	1, 2, 0	1, 1, 1	1, 1, 1
3.5.9.4 Effects of sea level change		1, 2, 0	1, 2, 0	1, 1, 1	1, 1, 1
3.5.9.5 Effects of estuarine development		1, 2, 0	1, 1, 1	1, 1, 1	1, 1, 1
3.5.9.6 Effects of coastal erosion		2, 1, 0	1, 2, 0	1, 1, 1	1, 2, 0
3.5.9.7 Effects of sea level change		2, 1, 0	1, 1, 1	1, 1, 1	2, 0, 1
3.5.10 Plants		2, 0, 0	2, 0, 0*	2, 0, 0	1, 0, 0
3.5.10.1 Root uptake		3, 0, 0	2, 0, 0	2, 0, 0	2, 0, 0
3.5.10.2 Deposition on surfaces		1, 1, 0	1, 1, 0	1, 1, 0	1, 1, 0
3.5.10.3 Vapour uptake		0, 2, 0	0, 2, 0	0, 2, 0	0, 2, 0
3.5.10.4 Internal translocation and retention		0, 2, 0	0, 2, 0	0, 2, 0	0, 2, 0
3.5.10.5 Washoff and leaching by rainfall		1, 2, 0	0, 2, 0	0, 2, 0	0, 2, 0
3.5.10.6 Leaf-fall and senescence		1, 2, 0	0, 3, 0	0, 2, 1	0, 3, 0
3.5.10.7 Cycling processes		1, 2, 0	1, 1, 1	1, 1, 1	0, 2, 1
3.5.11 Animals		1, 0, 0	1, 0, 0	1, 0, 0	0, 0, 0
3.5.11.1 Uptake by ingestion		4, 0, 0	3, 0, 0	3, 0, 0	3, 0, 0
3.5.11.2 Uptake by inhalation		1, 3, 0	1, 2, 0	1, 2, 0	1, 2, 0
3.5.11.3 Internal translocation and retention		0, 3, 0	0, 2, 0	0, 2, 0	0, 2, 0
3.5.11.4 Cycling processes		0, 2, 0	0, 1, 0	0, 1, 0	0, 1, 0
3.5.11.5 Effects of relocation and migration		0, 2, 0	0, 2, 0	0, 2, 0	1, 1, 0
3.6 Planning considerations		0, 1, 0	0, 1, 0	0, 1, 0	0, 1, 0
3.6.1 Urbanisation		4, 1, 0	1, 2, 2	1, 2, 2	2, 2, 0
3.6.2 Management of water resources		5, 0, 0	4, 0, 1	2, 1, 2	3, 1, 0
3.6.2.1 Lake formation		4, 1, 0	3, 1, 1	1, 2, 2	2, 1, 1
3.6.3 Agricultural policy		4, 1, 0	2, 1, 2	1, 2, 2	2, 1, 1
3.6.4 Recreation policy		3, 2, 0	1, 3, 1	1, 2, 2	2, 2, 0
3.7 Human exposure		0, 1, 0	1, 0, 0	1, 0, 0	1, 0, 0
3.7.1 External		2, 2, 0	2, 1, 1	2, 1, 1	1, 1, 1
3.7.1.1 Land		0, 4, 0	0, 4, 0	0, 3, 1	0, 3, 1
3.7.1.2 Sediments		0, 4, 0	0, 4, 0	0, 3, 1	0, 3, 1
3.7.1.3 Water bodies		1, 2, 1	1, 2, 1	1, 2, 1	1, 2, 1
3.7.2 Ingestion		3, 0, 0	3, 0, 0	3, 0, 0	2, 0, 0
3.7.2.1 Drinking water		3, 1, 0	3, 0, 1	3, 0, 1	3, 0, 1
3.7.2.2 Agricultural crops		3, 0, 0	3, 0, 0	3, 0, 0	3, 0, 0
3.7.2.3 Domestic animal products		3, 0, 0	3, 0, 0	3, 0, 0	3, 0, 0
3.7.2.4 Wild plants		1, 2, 1	1, 2, 1	1, 2, 1	1, 2, 1
3.7.2.5 Wild animals		2, 1, 0	2, 1, 0	2, 1, 0	2, 1, 0
3.7.2.6 Soils and sediments		1, 3, 0	1, 2, 1	1, 2, 1	1, 2, 1
3.7.3 Inhalation		3, 0, 0	3, 0, 0	3, 0, 0	2, 0, 0
3.7.3.1 Soils and sediments		2, 1, 0	2, 1, 0	2, 1, 0	2, 1, 0
3.7.3.2 Gases and vapours (indoor)	-	1, 3, 0	1, 2, 1	1, 2, 1	1, 2, 1
3.7.3.3 Gases and vapours (outdoor)	x	0, 1, 4	0, 1, 4	0, 1, 4	0, 1, 4
3.7.3.4 Biotic material		0, 2, 1	0, 2, 1	0, 2, 1	0, 2, 1
3.7.3.5 Salt particles	x	0, 3, 0	0, 2, 1	0, 2, 1	0, 2, 1

4: SHORT CIRCUIT PATHWAYS RELATED TO HUMAN ACTIVITIES					
4.1 Related to repository construction		1, 0, 0	1, 0, 0	1, 0, 0	1, 0, 0
4.1.1 Loss of integrity of borehole seals		4, 1, 0	4, 0, 1	3, 1, 1	3, 0, 1
4.1.1.1 Failure		4, 2, 0	4, 1, 1	3, 2, 1	3, 1, 1
4.1.1.2 Degradation		4, 1, 1	4, 1, 1	3, 2, 1	3, 1, 1
4.1.2 Loss of integrity of shaft or access tunnel seals		5, 0, 0	4, 1, 0	3, 1, 1	3, 1, 0
4.1.2.1 Failure		6, 0, 0	5, 1, 0	4, 1, 1	3, 2, 0
4.1.2.2 Degradation		5, 1, 0	5, 0, 1	4, 1, 1	3, 1, 1
4.1.3 Damage of host rock through subsidence		3, 2, 1	2, 4, 0	2, 2, 2	2, 1, 1
4.2 Post-closure					
4.2.1 Deliberate recovery of wastes or associated materials	x	1, 0, 3	0, 1, 3	1, 0, 3	0, 0, 3
4.2.2 Malicious intrusion	x	1, 0, 3	0, 0, 4	0, 0, 4	0, 0, 3
4.2.3 Exploratory drilling		2, 3, 0	2, 2, 1	1, 2, 2	2, 1, 1
4.2.4 Exploitation drilling		2, 3, 0	2, 3, 0	1, 2, 2	2, 1, 1
4.2.5 Geothermal energy production	x	0, 4, 0	0, 3, 1	0, 3, 1	1, 1, 1
4.2.6 Resource mining		3, 2, 0	2, 3, 0	1, 2, 1	2, 1, 1
4.2.7 Tunnelling		1, 3, 1	0, 4, 1	0, 3, 2	1, 1, 2
4.2.8 Construction of underground storage/					
disposal facilities		3, 2, 0	1, 4, 0	0, 3, 2	2, 1, 1
4.2.9 Construction of underground dwellings/shelters		0, 3, 2	0, 3, 2	0, 2, 3	1, 1, 2
4.2.10 Archaeological investigations		0, 3, 2	0, 3, 2	0, 2, 3	0, 2, 2
4.2.11 Injection of liquid wastes		2, 2, 1	2, 1, 2	1, 2, 2	1, 1, 2
4.2.12 Groundwater abstraction		4, 0, 1	3, 1, 1	2, 1, 2	2, 0, 2
4.2.13 Underground weapons testing	x	0, 1, 3	0, 1, 3	0, 1, 3	0, 1, 2

Appendix 3

Correlation Table Showing Relationships between the Final Process List of the System Concept Group and the Process List from the Uncertainty and Bias Audit of Dry Run 3

Initial numbers	New numbers	Comment (numbers in this column refer to initial process numbers)
1	1	Unchanged
1.1	1.1	Unchanged
1.1.1	1.1.1	Renamed "Container metal corrosion"
1.1.2	1:1.2	Combined with 1.1.3 and renamed "Physico-chemical degradation of concrete"
1.1.3	1.1.2	Combined with 1.1.2 and renamed "Physico-chemical degradation of concrete"
1.1.4	1.1.3	Moved to new subsubsection, named "Waste corrosion and solubility and speciation of radionuclides"
**	1.1.4	New subsubsection, named "Electrochemical effects of metal corrosion"
1.2	1.2	Unchanged
1.2.1	1.2.1	Unchanged
1.2.2	1.2.2	Unchanged
1.2.3	1.2.3	Unchanged
1.2.4	1.2.4	Renamed "Radioactive gases"
1.2.5	1.2.5	Renamed "Chemotoxic gases"
1.2.6	1.2.6	Renamed "Gas transport"
1.2.7	1.2.7	Unchanged
**	1.2.8	New subsubsection, named "Thermo-chemical effects"
1.3	1.3	Unchanged
1.3.1	1.3.1	Unchanged
1.3.2	1.3.2	Unchanged
1.4	1.4	Renamed "Structural integrity"
1.4.1	1.4.1	Moved to new subsubsection, named "Waste-form and backfill consolidation"
1.4.2	1.4.2	Combined with 1.4.3, 1.4.4, 1.4.5, 1.4.6 and renamed "Vault collapse"
1.4.3	1.4.2	Combined with 1.4.2, 1.4.4, 1.4.5, 1.4.6 and renamed "Vault collapse"
1.4.4	1.4.2	Combined with 1.4.2, 1.4.3, 1.4.5, 1.4.6 and renamed "Vault collapse"
1.4.5	1.4.2	Combined with 1.4.2, 1.4.3, 1.4.4, 1.4.6 and renamed "Vault collapse"
1.4.6	1.4.2	Combined with 1.4.2, 1.4.3, 1.4.4, 1.4.5 and renamed "Vault collapse"

Initial numbers	New numbers	Comment (numbers in this column refer to initial process numbers)
1.5	1.5	Renamed "Hydrogeological effects"
1.5.1	1.5.1	Renamed "Desaturation (pumping) effects"
**	1.5.2	New subsubsection, named "Disturbed zone (hydromechanical) effects"
1.5.2	1.5.3	Renumbered
1.5.3	1.5.4	Renumbered and renamed "Saturated groundwater flow"
1.5.4	1.5.5	Renumbered
1.6	1.6	Unchanged
1.6.1	1.6.1	Combined with 1.6.2, 1.6.3 and renamed "Rock-mass changes"
1.6.2	1.6.1	Combined with 1.6.1, 1.6.3 and renamed "Rock-mass changes"
1.6.3	1.6.1	Combined with 1.6.1, 1.6.2 and renamed "Rock-mass changes"
1.6.4	1.6.2	Renumbered and renamed "Hydrogeological changes"
1.6.5	1.6.3	Combined with 1.6.6
1.6.6	1.6.3	Combined with 1.6.5
**	1.6.4	New subsubsection, named "Transport (diffusion) effects"
2	2	Unchanged
2.1	5.2	Combined with 4.2 and renamed "Unrelated to repository construction"
2.1.1	5.2.1	Renumbered
2.2	2.1	Renumbered
2.2.1	2.1.1	Renumbered
2.2.2	2.1.2	Renumbered and renamed "Magmatic activity"
2.2.3	2.1.3	Renumbered and renamed "Regional metamorphism"
2.2.4	2.1.4	Renumbered
2.2.5	2.1.5	Renumbered
2.2.6	2.1.6	Renumbered

Initial numbers	New numbers	Comment (numbers in this column refer to initial process numbers)
2.4.14	2.3.13	Renumbered
3	4	Renumbered
**	3	Moved to new section, named "Climatology"
3.1	3.1	Moved to new subsection and renamed "Climate change"
3.1.1	3.1.1	Moved to new subsubsection and renamed "Human induced"
3.1.2	3.1.2	Moved to new subsubsection and renamed "Natural"
3.1.3	3.1.3	Unchanged
**	3.1.4	New subsubsection, named "Intensification of natural climate change"
3.2	2.4	Moved to section on "Far-field" and renumbered
3.2.1	2.4.1	Combined with 2.2.9, 3.2.3, and renumbered
3.2.2	2.4.2	Combined with 3.2.4 and renumbered
3.2.3	2.4.1	Combined with 2.2.9, 3.2.1 and renumbered
3.2.4	2.4.2	Combined with 3.2.2 and renumbered
3.3	4.2	Moved to new subsection, named "Transfer (concentration/dilution) mechanisms"
3.3.1	4.2.1	Moved to new subsubsection and renumbered
3.3.2	4.2.2	Moved to new subsubsection, renumbered and renamed "Surface water mixing"
3.3.3	2.3.7	New subsubsection, named "Changes in groundwater chemistry and flow direction"
3.3.4	4.2.2 / 4.2.3	Considered in two new subsubsections "Surface water mixing" and "Sediment transport including bioturbation"
3.3.5	4.2.2 / 4.2.3	Considered in two new subsubsections "Surface water mixing" and "Sediment transport including bioturbation"
3.3.6	4.2.2	Moved to new subsubsection, renumbered and renamed "Surface water mixing"
3.3.7	4.2.2	Moved to new subsubsection, renumbered and renamed "Surface water mixing"
3.4	4.3	Combined with 3.6, renumbered and renamed "Land and surface water use"
3.4.1	4.3.1	Combined with 3.6.1, 3.6.2, 3.6.3, 3.6.4 and renumbered
3.4.2	4.3.2	Renumbered

Initial numbers	New numbers	Comment (numbers in this column refer to initial process numbers)
3.4.3	4.3.3	Renumbered
3.4.4	4.3.4	Renumbered and renamed "Seas"
3.5	**4.1**	Moved to new subsection, named "Radionuclide entry points to the biosphere"
3.5.1	4.1.2	Moved to new subsubsection, named "Solid discharge via erosional processes"
3.5.2	4.1.1	Moved to new subsubsection, named "Groundwater discharge to soils and surface waters"
3.5.3	4.1.1	Moved to new subsubsection, named "Groundwater discharge to soils and surface waters"
3.5.4	4.1.1	Moved to new subsubsection, named "Groundwater discharge to soils and surface waters"
3.5.5	4.1.1	Moved to new subsubsection, named "Groundwater discharge to soils and surface waters"
3.5.6	4.1.1	Moved to new subsubsection, named "Groundwater discharge to soils and surface waters"
3.5.7	4.1.1	Moved to new subsubsection, named "Groundwater discharge to soils and surface waters"
**	4.1.3	New subsubsection, named "Gas discharge"
3.5.8	4.2.2 / 4.2.3	Considered in two new subsubsections "Surface water mixing" and "Sediment transport including bioturbation"
3.5.9	4.2.2 / 4.2.3	Considered in two new subsubsections "Surface water mixing" and "Sediment transport including bioturbation"
**	4.2.4	New subsubsection, named "Sediment / gas / water interaction with the atmosphere"
3.5.10	4.2.5	Moved to new subsubsection, named "Bioaccumulation and translocation"
3.5.11	4.2.5	Moved to new subsubsection, named "Bioaccumulation and translocation"
**	4.2.6	New subsubsection, named "Biogeochemical processes"
3.6	**4.3**	Combined with 3.4, renumbered and renamed "Land and surface water use"
3.6.1	4.3.1	Combined with 3.4.1, 3.6.2, 3.6.3, 3.6.4 and renumbered
3.6.2	4.3.1	Combined with 3.4.1, 3.6.1, 3.6.3, 3.6.4 and renumbered
3.6.3	4.3.1	Combined with 3.4.1, 3.6.1, 3.6.2, 3.6.4 and renumbered
3.6.4	4.3.1	Combined with 3.4.1, 3.6.1, 3.6.2, 3.6.3 and renumbered
3.7	**4.4**	Renumbered
3.7.1	4.4.1	Renumbered
3.7.2	4.4.2	Renumbered
3.7.3	4.4.3	Renumbered

Initial numbers	New numbers	Comment (numbers in this column refer to initial process numbers)
4	5	Renumbered and renamed "Short-circuit pathways"
4.1	5.1	Renumbered
4.1.1	5.1.1	Renumbered
4.1.2	5.1.2	Renumbered
4.1.3	5.1.3	Moved to new subsubsection, named "Incomplete near-field chemical conditioning"
4.2	5.2	Renumbered and renamed "Unrelated to repository construction"
4.2.1	5.2.2	Moved to new subsubsection, named "Deliberate intrusion"
4.2.2	5.2.3	Renumbered
4.2.3	5.2.2	Moved to new subsubsection, named "Deliberate intrusion"
4.2.4	5.2.2	Moved to new subsubsection, named "Deliberate intrusion"
4.2.5	5.2.4	Moved to new subsubsection, named "Accidental intrusion"
4.2.6	5.2.4	Moved to new subsubsection, named "Accidental intrusion"
4.2.7	5.2.4	Moved to new subsubsection, named "Accidental intrusion"
4.2.8	5.2.4	Moved to new subsubsection, named "Accidental intrusion"
4.2.9	5.2.4	Moved to new subsubsection, named "Accidental intrusion"
4.2.10	5.2.4	Moved to new subsubsection, named "Accidental intrusion"
4.2.11	5.2.4	Moved to new subsubsection, named "Accidental intrusion"
4.2.12	5.2.4	Moved to new subsubsection, named "Accidental intrusion"
4.2.13	5.2.4	Moved to new subsubsection, named "Accidental intrusion"

Appendix 4

Report by Stephen Watson (Cambridge University) on the System Concept Group Meeting

Notes on a meeting organised by INTERA, on 27.6.92, to discuss effects that need to be included in an assessment of the proposed NIREX Radioactive Waste Repository at Sellafield (The System Concept Group)

Stephen Watson was asked by Brian Thompson to attend one day of the two-day meeting of the System Concept Group for the discussion of the effects that need to be included in the safety assessment of the proposed NIREX ILW and LLW repository at Sellafield. This was held on 26 and 27 June 1992. This note reports on the methodology used at that meeting.

Considerable preparatory work had been carried out by INTERA, and experts had been given much material in advance. The meeting was well organised. Experts were given a suggested list of Features, Effects and Processes (FEPs) drawn from work on Dry Run 3, with some amendments, and were asked, prior to the meeting, to indicate which effects they would think necessary for inclusion in the assessment, for each of three future time periods.

The following points were noted:

1. Sending out a list of FEPs in advance was intended to save time, since, it was argued, similar work had already been done for Dry Run 3. This may have led to the well-known anchoring bias, of experts locking on to somebody else's statement of the processes that matter. On the other hand, most of the experts had been involved in thinking about this problem before, and so might have anchored on to their previous thinking. They might have found the list provided by INTERA suggested some topics that would otherwise not have occurred to them. No expert felt that this was the case, however.

2. Some felt that the effects might have been better categorised, since some of the effects seemed to be better considered along with others in a different category.

3. The suggestion that it might have been better not to have a potential list of FEPs at all to begin with, but rather to build one up by thinking through the possible pathways to release of radionuclides, was considered. This was seen to have the advantage of focussing thinking on what was important, namely the potential future release, rather than on the details of the repository structure etc., but it was felt by some members of the group that going through a pre-prepared list did allow a free-ranging discussion, which did show up some properties which might otherwise not have been thought of.

4. It was realised that whether or not to include some FEPs in the assessment depended on whether some key events did or did not happen in the future. For example, in a scenario that does not consider human intrusion at, or near to the repository, certain details of the near-field are not necessary. Participants felt that the choice of FEPs was scenario-dependent.

5. There was some concern whether it made sense to try to determine what FEPs should be included without some consideration of the models that might be constructed; the process of modelling so that

the overall assessment was satisfactory involved both selection of the FEPs, and how they are related. There was therefore concern that the process of divorcing the System Concept Group from the rest of the Assessment process might have introduced a bias, caused by the modellers having to stick to what the System Concept Group had to say. For getting the job done, however, there may be no alternative to this mode of action.

S R Watson
June 28, 1992

Appendix 5

Résumés of the Experts on the System Concept Group

Geoffrey Boulton.
Regius Professor of Geology and Head of the Department of Geology and Geophysics, University of Edinburgh.

Research centres on glacial sedimentation and erosion, dynamics and stability of ice-sheets, climate change and it's modulation by the interaction between solar radiation and the oceans, atmosphere and ice-sheets. Radioactive waste studies have been funded by CEC (DG XII) and SKB and relate to modelling of geological processes important to disposal and the consequences of climate change on waste disposal concepts. Author of a number of research papers on these topics.

Fred Glasser.
Professor in the Department of Chemistry, University of Aberdeen.

Research related to radioactive waste disposal has focussed on waste immobilisation matrices, particularly cement, glass and ceramics. He has acted as an advisor to UK AEA (Harwell and Winfrith), UK DoE, CEC (DG XII), Nagra and SKB. Author of numerous research papers and reports related to immobilisation matrices and author of the recent (1991) European Material Research Society Proceedings 'Cementitious Systems for Waste Immobilisation.'

Helen Grogan.
Senior Staff Consultant at Intera Information Technologies Ltd., Henley-on-Thames.

Research related to radioactive waste disposal has included botany and radioecology, particularly radionuclide uptake into crops. She worked for five years in the Swiss nuclear waste mangement programme (Nagra) where she managed a group concerned with geosphere and biosphere modelling for repository safety assessments. She has also acted as a technical advisor to the Nagra microbiology programme and helped develop the conceptual design for a major radionuclide migration study. Author of numerous research papers and reports concerned with microbiology populations in the repository and radionuclide transfer to and in the biosphere.

Eric Hamilton.
Consultant-director to the Pheonix Research Laboratory, Plymouth. Previously Head of the Environmental Radioactivity Department, Institute of Marine Environment Research (Plymouth Marine Laboratory).

Research topics related to radioactive waste disposal have included evaluation

of seabed disposal concepts, studies of the distribution of radionuclides in the Irish Sea discharged from the British Nuclear Fuels' Sellafield plant, evaluation of the significance of the source term in discharges of radionuclides. He has acted as an advisor to several organisations including the IAEA and WHO. Author of a number of books on environmental geochemistry and biochemistry and numerous research papers on analytical geochemistry, biochemistry and radiological protection.

Steve Horseman.
Principal Staff Consultant at Intera Information Technologies Ltd., Melton Mowbray.

Research topics related to radioactive waste disposal are concerned with the geotechnical aspects of underground storage and disposal with particular emphasis on rock mechanics and groundwater flow in low permeability media and on the rheological, thermo-mechanical and coupled transport properties of salt, mudrocks and fractured crystalline rocks. He has acted as an advisor to nuclear, oil and gas Industry clients on site investigation methodologies and techniques of rock property evaluation. Author of numerous research papers and reports on these subjects.

Ghislain de Marsily.
Professor of Geology and Director of the Laboratoire de Géologie Appliquée, Université Pierre et Marie Curie, Paris. Professor and scientific advisor to the Director of the Paris School of Mines.

Research topics related to radiactive waste disposal centre on development of numerical models of groundwater flow and radionuclide transport in porous and fractured media. He has acted as an advisor on radioactive waste issues to a number of organisations including the French Government (Groupe Permanant Déchet), PSI, CEC (DG XII), Sandia National Laboratory (on the WIPP programme), US National Academy of Science and OECD NEA. Author of many research papers and reports related to radionuclide migration in the geosphere.

Tim McEwen.
Principal Staff Consultant at Intera Information Technologies Ltd., Melton Mowbray.

Research related to radioactive waste disposal has centred on rock deformation mechanisms. He has extensive experience with all geological aspects of radioactive waste disposal both in the field and in the laboratory. In particular, he has been closely involved with the selection of potential sites, in the UK,

for near-surface and deep disposal of radioactive waste, and with the planning and design of site investigation programmes. He has acted as an advisor to several national and international agencies including Nagra, SKB and the IAEA. Author of a number of reports related to the geological aspects of site selection and repository construction.

Ivars Neretnieks.
Professor, Head of Department and Dean of the School of Chemical Engineering, KTH (Royal Institute of Technology), Stockholm.

Research related to radioactive waste disposal includes development of models of groundwater flow and radionuclide transport, in particular the development of the concept of matrix diffusion in crystalline rocks. He has acted as an advisor to Nagra, SKB and to the IAEA on development of mathematical models for the interpretation of tracer data in groundwater hydrology. He was also a Principle Investigator for *in situ* migration experiments at the Stripa underground research station. Author of many research papers and reports related to radionuclide migration in the geosphere.

HMIP ASSESSMENT OF NIREX PROPOSALS

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