Waste Isolation Pilot Plant

Compliance Certification Application

Reference 626

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. DOE/HMIP/RR/92.040. UKDoE/HMIP, London.

Submitted in accordance with 40 CFR §194.13, Submission of Reference Materials.

HER MAJESTY'S
INSPECTORATE
OF POLLUTION

Dry Run 3
A Trial Assessment of Underground Disposal of Radioactive Wastes Based on Probabilistic Risk Analysis
Volume 8:
Uncertainty and Bias Audit

DOE Report No: DoE/HMIP/RR/92.040

Research commissioned by
HER MAJESTY'S INSPECTORATE OF POLLUTION
Department of the Environment

Department of the Environment:
HMIP-Commissioned Research

Report Title:

Dry Run 3
A Trial Assessment of Underground Disposal of Radioactive Wastes Based on Probabilistic Risk Analysis
Volume 8:
Uncertainty and Bias Audit

DOE Report No: DoE/HMIP/RR/92.040

Contract Title: Analysis of Uncertainties in Risk Estimation

DOE Reference: PECD 7/9/445 **Sector No:** 3.4

Contractor's Reference: Electrowatt Project 2636

Author/Affiliations etc: M C Thorne
Electrowatt Engineering Services (UK) Ltd

Date of submission to DOE: February 1992

Period covered by the report 1989-1991

Abstract (100-200 words as desired):

Development of an overall procedure for incorporating an uncertainty and bias audit into post-closure radiological assessments is an on-going component of the UK DoE programme. Dry Run 3 has provided a convenient opportunity to test certain aspects of the methodology. In particular:

- an Expert Group has been utilised to advise on factors/phenomena that should be included in a comprehensive assessment and to determine priorities for modelling;
- scoping calculations have been carried out to provide illustrative results, which have been used to demonstrate the potential biases inherent in the trial assessment;
- expert judgements have been used to assess the status of Dry Run 3 relative to a minimal assessment.

DoE

Disposal Assessments

Dry Run 3

A Trial Assessment of Underground Disposal of Radioactive Wastes Based on Probabilistic Risk Analysis

Volume 8: Uncertainty and Bias Audit

DA Ref: TR-DR3-8

Summary: Development of an overall procedure for incorporating an uncertainty and bias audit into post-closure radiological assessments is an on-going component of the UK DoE programme. Dry Run 3 has provided a convenient opportunity to test certain aspects of the methodology. In particular:

- an Expert Group has been utilised to advise on factors/phenomena that should be included in a comprehensive assessment and to determine priorities for modelling;
- scoping calculations have been carried out to provide illustrative results, which have been used to demonstrate the potential biases inherent in the trial assessment;
- expert judgements have been used to assess the status of Dry Run 3 relative to a minimal assessment.

Edition: 1 **Date:** February 1992

Authors: M C Thorne

TR-DR3-8
Edition 1

Dry Run 3

A Trial Assessment of Underground Disposal of Radioactive Wastes Based on Probabilistic Risk Analysis

Volume 8: Uncertainty and Bias Audit

This Report has been prepared at Electrowatt Engineering Services (UK) Ltd for Her Majesty's Inspectorate of Pollution (HMIP) of the Department of the Environment (DoE) under the terms of DoE Contract Reference PECD 7/9/445. Final editing and type-setting of the report has been carried out by Intera Information Technologies under the terms of DoE Contract Reference PECD 7/9/497.

Electrowatt Engineering Services (UK) Ltd
Grandford House
16 Carfax
Horsham
West Sussex
RH12 1UP

February 1992

Preface to Volume 8

Since 1982, the United Kingdom Department of the Environment (UK DoE) has funded the development of a procedure for the post-closure assessment of underground disposal of radioactive wastes, based on probabilistic risk analysis (pra). The present methodology is able to take explicit account of changes in the environment, over a post-closure period of about one million years, by use of Monte Carlo simulation:

- to generate samples of possible future evolutions of the natural environmental system using the TIME4 model; and
- to analyse the effect of these temporal changes and their associated uncertainties on estimates of the repository release, groundwater transport, environmental distribution of radionuclides and consequent radiological risk, using the VANDAL model.

Earlier developments of the procedure have been tested by means of trial assessments, Dry Runs 1 and 2, which considered a hypothetical repository for low- and intermediate-level wastes at Harwell, Oxfordshire. In preparation for the radiological assessment of the safety case for deep disposal of low- and intermediate-level radioactive wastes expected from UK Nirex Ltd, it is necessary to rehearse the latest assessment procedure and the use of related computer-based tools. This rehearsal has been carried out by means of a further trial assessment, called Dry Run 3, of a hypothetical repository for low- and intermediate-level wastes at the Harwell site.

The objectives of Dry Run 3 are:

- to demonstrate a time-dependent pra procedure that accounts for uncertainties associated with the possible future evolutions of the natural environmental system;
- to demonstrate systematic, traceable methods of handling information used during an assessment and to provide comprehensive structured documentation acting as a template for future assessments;
- to provide a basis for estimating the timescale and resources required for a real assessment.

The trial takes the form of a demonstration of the various assessment activities, computer calculations and of an approach to documentation, in the context of an examination of hypothetical repositories for radioactive wastes beneath the Harwell site; a full implementation of the methodology, as would be required to assess the long-term radiological risks of actual or proposed repositories in the UK, was not intended.

The Dry Run 3 trial assessment is reported in an Overview Report, plus nine volumes covering the detailed technical work thus:

1. The Factual Database
2. The Modelling Basis
3. Development of Conceptual Models
4. Elicitation of Subjective Data
5. Development of Numerical Models
6. System Calculations and PRA
7. High-risk Re-analysis
8. Uncertainty and Bias Audit
9. Quality Assurance

This volume – *Uncertainty and Bias Audit* – describes a possible procedure for carrying out a post-closure radiological safety assessment incorporating an audit of uncertainties and biases. This procedure has not been applied in Dry Run 3 since the methodology was under development in parallel with Dry Run 3. However, Dry Run 3 has provided a convenient opportunity to test certain aspects of the methodology. In particular:

- an Expert Group has been utilised to advise on factors/phenomena that should be included in a comprehensive assessment and to determine priorities for modelling;
- scoping calculations have been carried out to provide illustrative results, which have been used to demonstrate the potential biases inherent in the trial assessment;
- expert judgements have been used to assess the status of Dry Run 3 relative to a minimal assessment, as defined below.

Following a brief introduction (Chapter 1), Chapter 2 of the report summarises the overall procedure for a post-closure radiological assessment incorporating an uncertainty and bias audit which was developed prior to the start of Dry Run 3. This procedure relies to a significant extent on the use of expert judgements. Such judgements have to be elicited in an appropriately structured manner, so that the judgements made, their bases, and their applications in the assessment, can be suitably documented. The use of expert judgements in the quantification of uncertainty, by the elicitation of parameter value distributions, is the subject of Volume 4. Expert judgement in relation to factors/phenomena that should be included in an assessment is the topic of Chapter 3 of this volume. This includes discussion of a formal procedure selecting the expert group (often the least well-documented part of the process), a description of the various phases of work involved in deriving groups of factors/phenomena for modelling, and assignment of levels of confidence in the results that would be obtained from assessments of different degrees of complexity.

Overall, it proved possible for the expert group to define a *minimal assessment* that they estimated would not exhibit gross bias because of excluded factors/phenomena. Small deletions from this minimal assessment could be tolerated with only a limited to moderate (less than a factor of 10) estimated effect on peak individual risks. More extensive deletions resulted in the expert group judging that too much of substance had been deleted and that the degree of bias would be unquantifiable without modelling studies, which effectively corresponds to reintroducing the factors/phenomena into the assessment.

The material included in Chapter 3 provides a justification for the various modelling studies described in Chapter 4. These include both scoping calculations and deterministic calculations related to the pra studies undertaken as part of the main Dry Run 3 exercise and reported in Volume 6. In this section, reference is also made to the component model investigations reported in Volume 5.

The deliberations of the expert group, and the various calculations undertaken, lead to a variety of results. The individual results are summarised in Chapter 5, where approaches to their presentation and aggregation are explored, in so far as the limited material available allows.

Chapter 6 provides a discussion of the work undertaken. In particular, the Dry Run 3 experience is used to estimate resource requirements for those parts of the uncertainty and bias component of a comprehensive post-closure radiological assessment of a site, which have been exercised. Limitations and deficiencies of the methodology are also discussed and areas requiring further development are highlighted.

Acknowledgements

The Dry Run 3 trial assessment has been performed by the HMIP Team of Disposal Assessment Contractors and the Building Research Establishment, under the charge of Dr B G J Thompson of HMIP. Technical coordination of the project and editing of the final reports has been undertaken by Intera Information Technologies Limited.

The work reported in this volume has been carried out by Electrowatt Engineering Services Ltd, but has relied heavily on the enthusiastic co-operation of the Expert Group:

K M Clayton,	University of East Anglia;
T D Davies,	University of East Anglia;
F P Glasser,	University of Aberdeen;
J Higgo,	British Geological Survey;
A D Horrill,	Institute of Terrestrial Ecology;
J Knill,	Natural Environment Research Council;
C C Naish,	AEA Harwell Laboratory;
M L Parry,	University of Birmingham;
J H Rees,	AEA Culham Laboratory;
E Tufton,	Ove Arup and Partners;
J West,	British Geological Society;
H S Wheater,	Imperial College.

Thanks are also due to J Taylor (Yard Ltd.), T J Sumerling (Intera Information Technologies), B G J Thompson (HMIP) and J A G Temple (AEA Technology), for discussions on the topics considered herein, also to J-M Laurens and I Teasdale (Electrowatt) both for discussions and for active help in the preparation of this volume.

Special thanks are due to technical staff at Electrowatt and Intera for the organisation, typesetting and figure reproduction in this volume.

Contents

List of Tables

List of Figures

1 Introduction

1.1 Background to Uncertainty and Bias Studies

In 1987, a NEA/OECD Workshop (NEA, 1987) highlighted the importance of uncertainty analyses for performance assessments of radioactive waste disposal systems. At that meeting, Thompson (1987a) drew attention to the various types of uncertainty that are associated with attempting to assess the post-closure radiological performance of repositories for low- and intermediate-level radioactive wastes. At that time (Hofer and Hoffman, 1987) and subsequently (IAEA, 1989), others have also made distinctions between the different types of uncertainty involved in radiological assessments.

Recognising the complexities of the issues raised in relation to incorporation of a proper treatment of uncertainties in assessment studies, in 1988 the UK DoE initiated a programme of work to develop a general procedure for incorporating an uncertainty and bias audit into an assessment. **In this programme, explicit distinction is made between uncertainties, which can generally be incorporated into an assessment through the use of parameter value distributions, and biases, which arise from limitations in the conceptualisation of the assessment system or in the tools available for its analysis.** While the TIME4/VANDAL 1.3 system (see Dry Run 3 Volume 2) is well-structured to handle uncertainties as defined above, the treatment of biases requires a broader approach, as described herein.

Initial work in this area led to the development of an overall methodology (see Thorne and Laurens, 1989), but the validity of the approach adopted and the resource implications could not be readily evaluated without some attempt at implementation. For this reason, it was decided that the next stage of the programme should parallel the Dry Run 3 exercise, drawing on it for basic data and results from pra studies and providing guidance on the interpretation of those results.

1.2 Scope of the Report

Following this introduction, Chapter 2 of the report summarises the overall procedure which was developed prior to the start of Dry Run 3. This procedure relies to a significant extent on the use of expert judgements. Such judgements have to be elicited in an appropriately structured manner, so that the judgements made, their bases, and their applications in the assessment can be suitably documented. The use of expert judgements in the quantification of uncertainty, by the elicitation of parameter value distributions, is the subject of Volume 4. Expert judgement in relation to factors/phenomena that should be included in an assessment is the topic of Chapter 3. This includes discussion of the formal procedure for selecting the expert group, a description of the various phases of work involved in deriving groups of factors/phenomena for modelling, and assignment of levels of confidence in the results obtained from the various modelling approaches proposed.

The material included in Chapter 3 provides a justification for the various modelling studies described in Chapter 4. These constitute both scoping calculations and deterministic calculations related to the pra studies undertaken as part of the main Dry Run 3 exercise and reported in Volume 6. In this Chapter, reference is also made to the component model investigations reported in Volume 5.

The deliberations of the expert group, and the various calculations undertaken, lead to a variety of results. The individual results are summarised in Chapter 5, where alternative approaches to their presentation and aggregation are explored.

Chapter 6 provides a discussion of the work undertaken. In particular, the Dry Run 3 experience is used to estimate resource requirements for the uncertainty and bias component of a comprehensive post-closure radiological assessment of a site. Limitations and deficiencies of the methodology are also discussed and areas requiring further development are highlighted.

The report is completed by appendices detailing the guidance provided to members of the selected group and the various calculations undertaken, the results of which are reported in Chapter 5.

2 Overall Procedure

Before describing in detail the overall procedure adopted, it is proper to note some limitations that were accepted as a priori constraints. In particular:

(a) The procedure is that appropriate to an assessment of a particular repository/site combination. While uncertainty and bias audits are of relevance in the site selection process, this wider issue is not addressed herein.

(b) Uncertainties and biases in metabolic, dosimetric and health effects models applicable to man are not addressed. Supplementary studies to investigate such uncertainties and biases could be appropriate and some work on this topic has been undertaken for UK Nirex Ltd (Bull, 1990).

(c) It was assumed that the assessment should be undertaken using the mathematical and computational models available at the time and should be based on the then current understanding of the relevant processes. Thus, research and model development programmes designed to reduce uncertainties and biases are not included in the procedure.

(d) The procedure relates primarily to individual risk, as defined previously (Thorne, 1988) and not to collective measures of repository impact (eg. total detriment to health over specified intervals post-closure) which might be used in optimisation studies or evaluation of the Best Practicable Environmental Option (BPEO).

2.1 Outline of the Assessment Procedure

The main features of the assessment procedure are illustrated in Figure 1 (Thorne and Laurens, 1989).

The first step is to collect factual information relating to the system to be assessed and to document this information. As far as possible, interpretative judgements should be excluded from this compilation. Thus, borehole and seismic data may be included, but speculative geological cross-sections based on these data should be excluded. Matters outside the remit of the assessment, e.g. operational procedures and contingency plans, should be treated as factual information. Contingency plans are included because post-closure assessments should take account of the possibility that accidents or other factors may result in non-standard closure of all, or part, of a repository.

Identification of phenomena which should be represented relates closely to the procedures typically adopted in the early stages of scenario development (Hodgkinson, 1988).

Various system states may be postulated at closure. This is due in part to human factors (eg. whether contingency plans have had to be invoked), but also results from limitations in the factual database (e.g. alternative geological and hydrogeological interpretations are possible). Each such system state has to be assigned a likelihood of occurrence and its post-closure implications explored.

For each system state, there will be various views as to the phenomena that will determine system behaviour post-closure and the way in which these phenomena should be represented in consequence assessment. By the use of behavioral science techniques, involving one or more expert groups, it is proposed that a 'degree of belief' should be assigned to each view. It is emphasised that 'degree of belief' values are not probabilities, being more closely related to the concept of utilities, as used in multi-attribute analysis (ICRP, 1989). Thus, a variety of approaches may be advocated, with each alternative incorporating a different subset of relevant phenomena. In this case, the degree of belief in the adequacy of the approach will depend upon the overall scope of the approach. Since the approaches are not independent, the degree of belief values will not, in general, sum to unity over alternatives.

Given that an initial system state has been defined and a representation of a particular set of phenomena selected, it is necessary to compute the associated radiological consequences. This can be done using an overall systems model, e.g. TIME4/VANDAL, or by the use of ad hoc procedures. **Ideally, in an assessment procedure based on a systems model all the phenomena of relevance would be incorporated in the overall systems model and the use of ad hoc procedures would be redundant.** In practice, systems model implementation necessarily lags behind scientific developments, so that such models are always incomplete. Furthermore, to include an adequate representation of all phenomena of potential relevance would make such a model impossibly complex. Thus, in any actual assessment, various procedures will be used including:

- direct representation of the phenomena in the systems model;
- representation of the effects of the phenomena in the systems model by modifications to parameter values or ranges;
- representation of the effects of the phenomena by post-processing systems model results obtained neglecting the effects of those phenomena;
- calculations using supplementary special-purpose models.

2.2 Detailed Specification of the Assessment Procedure

In developing the detailed assessment procedure, the following principles were applied (Thorne and Laurens, 1989).

(a) Relevant data should be collected and documented prior to exercise of expert judgement.

(b) Probabilities or degrees of belief should be fixed prior to the calculation of consequences.

(c) Expert judgements and their justification should be fully documented.

(d) Both consensus and variant judgements should be solicited in a structured framework.

(e) The implications of consensus and variant judgements should be appropriately explored.

(f) There should be an attempt to demonstrate that all relevant initial conditions and processes have been considered.

The validity of these principles is relatively self-evident. Item (a) ensures that expert judgements are made in full cognizance of the relevant information. Item (b) ensures that there can be no accusation that probabilities have been adjusted retrospectively to obtain the desired result. Items (c) and (d) ensure that expert judgements are justified and can be revisited subsequent to the assessment. Item (e) is fundamental to quantitative bias assessment, since it ensures that the implications of alternative viewpoints are propagated through the assessment. Finally, item (f) is a completeness requirement designed to ensure that no major contributions to consequences are neglected and that the adequacy of the scope of the assessment can be demonstrated to interested parties.

It is recognised that a sequence of assessments may be required for a particular site as investigation of its characteristics proceeds. Thus, there will necessarily be some knowledge of likely consequences within the assessment team. For this reason, **it is desirable to separate, as far as possible, the group making expert judgements from the group undertaking assessments.** This is not always possible, because some of the judgements relate to assessment modelling approaches. In these cases, the best that can be done is to ensure that the judgements are subject to scrutiny by experts from outside the assessment team.

The detailed procedure is set out in Figure 2. This figure is complemented by Table 1, which defines the activity associated with each step of the process. Where judgements are involved, the group making the judgement is identified in Table 1. The major distinction is between the assessment team and an external expert group, or groups. In the remainder of this Chapter, the overall structure of the procedure is outlined. Several of the items involve expert judgement and these are discussed in detail in Section 2.3. Matters relating to consequence calculations are discussed in Section 2.4, while the combination of results from the various calculations is discussed in Section 2.5.

Boxes 1 to 18 are directed to producing a set of alternative descriptions of the repository and its environment at the time of closure. These variant descriptions take into account any lack of knowledge concerning the geology and hydrogeology, as well as the possibility that specific sequences of events during repository operations may result in the invocation of contingency plans and in abnormal closure of the repository. Variability in the physical, chemical and radiochemical characteristics of the wastes is also addressed at this stage.

Boxes 19 to 26 are directed to identifying the phenomena that need to be included in the assessment. This matter is discussed further in Section 3. The aim is to provide a check list of phenomena that should be included explicitly in the modelling stages of the assessment.

For each variant and each coherent set of phenomena, it is necessary to undertake a quantitative assessment procedure (boxes 27 and 28). Coherent sets of phenomena are those considered potentially sufficient to describe the evolution of the repository and its environs over the period of the assessment. Each such set is associated with a degree of belief (or alternative degrees of belief, if no consensus is reached) that the set is sufficient to described the evolution of the repository and its environs, without the introduction of significant bias.

procedure. It has been demonstrated that it is not possible to select an aggregation procedure which is neutral and judgement free. Indeed, "there is no consensus that the suggested procedures make sense, even at the theoretical level" (Watson and Buede, 1987). Thus, while the quality of decision making can be improved, it will never be possible to demonstrate that the best approach has been adopted.

For eliciting judgements, decision conferencing (Watson and Buede, 1987) is the preferred approach. This is because decision conferencing allows for the possibility of failure to reach a consensus, but does not contain an implicit assumption of conflict, as is the case with a Games Theory approach. Undertaken with a facilitator, well-versed in the concepts of decision theory, it helps to ensure that the widest range of possibilities is explored and that the various viewpoints in the group are fully documented. It is, however, dependent on being able to gather the relevant individuals at one time and on isolating them from other activities. As the individuals involved are typically busy senior staff, this is not readily achieved. Furthermore, care must be taken to ensure that the decision conferences are not dominated by one, or a few, experts with forceful personalities.

The elicitation of expert judgements in the context of defining parameter values and ranges is discussed in Volume 4.

2.4 Handling Data Uncertainties

In general, whenever the available systems model is applicable, data uncertainties can be handled by an appropriate data elicitation exercise (Volume 4) and associated pra calculations (Volume 6). Where the systems model is not applicable, the implications of data uncertainties have to be investigated in a variety of scoping and sensitivity calculations. Such calculations are also relevant when pra results have to be modified to apply to conditions other than those originally specified (c.f. Section 4.2).

2.5 Inclusion of Uncertainty and Bias into Measures of Consequence

An assessment incorporating an uncertainty and bias audit will necessarily lead to several different consequence estimates C_{ijk} each associated with a degree of belief B_{ijk}. In this nomenclature, an unspecified number of suffixes is used to illustrate the fact that a hierarchy of conditional judgements is made. While each of the results may be presented separately, it is also useful to present aggregated results. In performing such aggregations, it is relevant to recall that belief judgements at successively lower levels of the hierarchy are solicited conditionally. Thus:

$$B_{ijk} = \phi_i \phi_{ij} \phi_{ijk}$$

where ϕ_{ijk} is the degree of belief in option k, given that option i, j occurs. Aggregation must, therefore, be undertaken in reverse index order.

The aggregation procedure adopted will depend upon the type of system under study and the requirements of decision makers. It is not a self-evident or unambiguous procedure. Some examples are given below.

Degree of belief weighted mean

$$\overline{C}_{ij} = \frac{\sum_k B_{ijk} \cdot C_{ijk}}{\sum_k B_{ijk}}$$

This is associated with a degree of belief no larger than $\min_k B_{ijk}$, since each component of the sum must be believed.

At worst if all the components of the sum are independent, the degree of belief could be as low as $\prod_k B_{ijk}$.

Consequence maximising

$$\overline{C}_{ij} = C_{ijK}$$

where K is such that $C_{ijK} \geq C_{ijk}$ for all k.

This is associated with a degree of belief B_{ijK}.

Acceptable degree of belief

$$C_{ij} = C_{ijK}$$

where K is such that either B_{ijK} is the smallest value of B_{ijk} (over k) that exceeds some threshold B_{acc}, or B_{ijK} is the maximum value of B_{ijk} (over k), if none of the values exceeds B_{acc}.

The aggregations performed over index k can be repeated sequentially over i and j, but it is not necessary to use the same type of aggregation procedure at each stage.

3 Use of an Expert Group

In the assessment procedure described in Chapter 2, various requirements for expert judgements are identified. Some of these relate to data elicitation and are discussed in detail elsewhere (Volume 4). Others relate primarily to modelling considerations and are, therefore, mainly taken by the assessment team as a whole or by specialist groups within that team (c.f. Volumes 5 and 6). However, a broad class of judgements relating to the scope of the assessment, e.g. the factors/phenomena to be included and the relative weights to be given to different conceptualisations of the disposal system, are best made by a group independent of the assessment team, since they are not conditioned by a knowledge of the limitations of the modelling procedures available or a knowledge of any resource limitations. **Thus, the view is taken that independent experts should define the broad framework of what requires to be considered and that the assessment team should deploy the various tools available to meet these requirements to the best of their ability and within the resources available.** Of course, the independent experts must have a good grounding in the requirements and possibilities relating to disposal of radioactive wastes, and will, therefore, be drawn mainly from senior research and development staff working in the area. In addition, though not covered in this study, the group of independent experts would be available to provide guidance on decisions which have to be taken on model selection and application. However, this would occur at a later stage and would not prejudice their prior views on absolute requirements.

In this Chapter, the procedures followed in selection of the Expert Group are described and results of their deliberations are presented. This provides a basis and justification for the modelling studies presented in Chapter 4.

3.1 Selection of the Group

From previous experience, it was recognised that the initial stage of defining an expert group and justifying the choice of experts is the one which tends to be least well recorded. For this reason, particular attention was given to documentation of this stage of the work. First, a list of factors/phenomena which might be of relevance to post-closure radiological assessment was drawn up by the author in the form of a structured list. (Further uses of this structured list are described in Sections 3.2 and 3.3.) It was found that all the items identified could be classified under the following headings.

1.1 Near-field : chemical/physical degradation
1.2 Near-field : gas production and transport
1.3 Near-field : radiation phenomena
1.4 Near-field : mechanical effects
1.5 Near-field : hydrological effects
1.6 Near-field : thermal effects

2.1 Far-field : extra-terrestrial
2.2 Far-field : geological
2.3 Far-field : hydrological
2.4 Far-field : transport and geochemical

3.1 Biosphere : climatology
3.2 Biosphere : geomorphology
3.3 Biosphere : hydrology
3.4 Biosphere : ecological development
3.5 Biosphere : radionuclide transport
3.6 Biosphere : human exposure

4.1 Short-circuit pathways : related to repository construction
4.2 Short-circuit pathways : related to post-closure human actions

It was, therefore, decided that, as a minimum, the expert group should include individuals with a detailed knowledge of each of these areas. From knowledge within the assessment team, and by consultation with other individuals in the various contractor organisations and in HMIP, a list of 59 potential expert group members was drawn up from a longer list of proposed candidates according to the following criteria:

(a) Expertise in one or more of the listed areas;

(b) Preferably, some knowledge of the background to radioactive waste disposal in the UK;

(c) Resident in the UK and available for consultation;

(d) Not a member of the DoE or UK Nirex Ltd disposal safety assessment teams (this did not exclude individuals involved in research relating to radioactive waste disposal funded in whole, or in part, by either the DoE or UK Nirex Ltd).

A matrix of potential group members and their areas of expertise was then drawn up to provide a basis for the final stages of the selection procedure. On the basis of this matrix, and taking into account the need to keep the group to a reasonable size, individuals were selected with competence in several of the major areas of interest, with the secondary criterion of selecting individuals from different organisations, as far as this was consistent with maintaining the high overall level of expertise of the group. By this method, the final group contained two or more individuals with expertise in each main area and provided access to a much wider range of expertise in the organisations from which the group members were drawn.

The final composition of the expert group, and the modifications to its membership which occurred as the study progressed, are included in Appendix A.

It is emphasised that the above headings do not constitute a unique classification and that an early stage of the procedure included a review of the scope and structure of the list by the Expert Group (Section 3.2). However, it provided a broad basis for generating a list of potential Expert Group members, classifying the breadth of their expertise, and defining omissions and overlaps.

3.2 Development of a Comprehensive List of Factors/Phenomena

The first task of the expert group was to develop a comprehensive list of factors/phenomena that might be of relevance to post-closure radiological assessment. To this end, they were supplied with the initial structured list that had been drawn up previously and used to assist in the selection of the expert group (see Section 3.1) plus background information on the hypothetical repository and its environs (essentially early drafts of Chapters 1, 2, 3, 4 and 6 of Volume 1). The structured list is provided as Table 1 of document EG(90)P1 in Appendix A. This document also contains the detailed instructions issued to the expert group. Briefly, each expert was requested:

- To review the general headings to see if any item had been omitted, then repeat the procedure at each lower level of indexing;
- Where specific factors/phenomena were not listed at the lowest order, to give consideration to the specific factors/phenomena that should be listed;
- To identify factors/phenomena that should be considered, but which did not fall naturally within the framework provided;
- To prepare a brief note listing the additional factors/phenomena to be included, their position in the table (if appropriate) and a comment as to why each factor or phenomenon requires consideration.

It was stressed that at this stage factors/phenomena should not be excluded on the grounds of negligible impact or low probability.

A variety of detailed responses to EG(90)P1 were received and used to expand the original structured list. This provided the basis for the second stage of the exercise, described below.

3.3 Elimination of Factors/Phenomena from Consideration

Following receipt of replies to EG(90)P1 (see Appendix A), the secretariat produced a new, comprehensive list of factors/phenomena to provide a basis for the rest of the procedure. This was issued to the expert group incorporated in document EG(90)P2 (see Appendix A), as a basis for Stage 2 of the exercise. The objectives of Phase 2 were defined as follows.

(a) To identify those factors/phenomena that should be excluded from consideration on the grounds of negligible impact.

(b) To identify those factors/phenomena which will undoubtedly be of significance in post-closure radiological assessments, or which have to be included in order to evaluate their significance.

(c) To identify groups of factors/phenomena that could be considered together in the assessment process, because of similarities in their implications.

and its depleted variants, members of the Expert Group received a questionnaire asking them to evaluate its adequacy. This questionnaire is exhibited as Table 7, while the responses are recorded and analysed in EG(90)P8.

The main conclusions from this analysis can be summarised as follows.

(a) There was general agreement that Figure 3 is a suitable representation of the minimal assessment, with the following caveats.

- Thermal effects on groundwater transport are an outstanding concern and may require reconsideration.
- Glaciation at the site was considered to be a catastrophic event. If considered likely to occur, it should be the subject of a separate study. The judgements made as to the adequacy of the minimal assessment are taken to be conditional on major glaciation not reaching the site.
  This judgement calls into serious question the validity of those few simulations in the pra studies undertaken for Dry Run 3 which involve full glaciation of the site. This limitation of Dry Run 3 is independent of other considerations discussed below.
- Subsidence/collapse of ungrouted LLW is a residual concern which might require reconsideration.

The first reduced assessment (Figure 4) excluded:

Item	**Description**
1.6.4	Thermally induced hydrological changes in the near-field
1.6.5	Thermally induced chemical changes in the near-field
3.2.2	Localised denudation
3.6.4	Recreation policy developments

With some caveats as to the need for modelling, there was a broad agreement on the following judgements.

Item	**Effect (c.f. Table 7)**
1.6.4	Limited/Moderate
1.6.5	Limited/Moderate
1.6.4/1.6.5	Limited/Moderate
3.2.2	Limited
3.6.4	Limited
1.6.4/1.6.5/3.2.2/3.6.4	Limited/Moderate

These judgements form a coherent set and indicate a general view of the group that this reduced assessment would yield results within an order of magnitude of those obtained from the minimal assessment.

The second reduced assessment (Figure 5) excluded:

Item	**Description**
1.1.2	Physical degradation of concrete
1.4.6	Fracturing in the near field
1.6.4	Thermally induced hydrological changes in the near-field
1.6.5	Thermally induced chemical changes in the near-field
2.3.3	Modification to far-field hydrology due to rock property changes
2.4.6	Fracture surface changes in the far-field, notably demineralisation
2.4.7	Organic colloid transport
2.4.9	Transport of radionuclides bound to microbes
3.1.1	Transient greenhouse gas induced warming
3.2.2	Localised denudation
3.6.4	Recreation policy developments
4.1.1	Short-circuit pathways relating to loss of integrity of borehole seals
4.1.2	Short-circuit pathways relating to loss of integrity of shaft or access tunnel seals

In respect of the timescales for these various factors/phenomena and their probability of occurrence, it was possible to draw the following conclusions from the responses of the members of the group.

(a) Physical degradation of concrete (1.1.2) is expected to occur over a timescale of $<10^4$ years. The early phase ($<10^3$ years) is expected to be cracking, with leach-associated degradation occurring on the longer timescale.

(b) Fracturing in the near-field (1.4.6) is seen as likely to occur on a timescale of $<10^2$ years and almost certain on a timescale of $<10^4$ years.

(c) Thermally induced hydrological changes in the near field (1.6.4) are expected on a timescale of $<10^2$ years and may persist for up to $10^5 - 10^6$ years.

(d) Thermally induced chemical changes in the near field (1.6.5) are expected on a timescale of $10^2 - 10^3$ years and may persist for up to $10^5 - 10^6$ years.

(e) Modification to far-field hydrology due to rock property changes (2.3.3) is expected on a timescale of $10^4 - 10^6$ years, though some effects on the flow field local to the repository could occur on a timescale of $<10^2$ years.

(f) Fracture surface changes in the far field, notably demineralisation (2.4.6) are moderately likely to occur on a timescale of $10^4 - 10^6$ years.

(g) Organic colloid transport (2.4.7) is moderately likely to occur and may well persist for $10^5 - 10^6$ years post closure.

(h) Transport of radionuclides bound to microbes (2.4.9) is moderately likely to occur and may well persist for $10^5 - 10^6$ years post closure.

(i) Transient greenhouse gas warming (3.1.1) is expected to occur, with its environmental effects persisting for $\sim 10^4$ years.

(j) Localised denudation (3.2.2) may begin to be of significance on a timescale of 10^3 years and will become of increasing importance over the interval $10^3 - 10^6$ years.

(k) Recreation policy developments (3.6.4) are anticipated on the timescale $0 - 10^3$ years.

(l) Members of the group with near-field or engineering expertise anticipated a moderate to high probability of short-circuit pathways relating to loss of integrity of borehole, shaft or access tunnel seals (4.1.1/4.1.2) on a timescale of $< 10^3$ years.

It is notable that all the above are at least moderately likely to occur (probability ≥ 0.1) within the assessment period and that most have effects persisting for periods of $10^4 - 10^6$ years. These considerations are an indication of why these various factors and phenomena were included in the minimal assessment.

In respect of the potential implications of excluding these various factors/phenomena, the general response of the group was that these implications are not quantifiable without modelling studies.

Thus, overall, the response to the questionnaire essentially confirmed previous views relating to the minimal assessment. There was general agreement as to its structure, small deletions could be tolerated with only a Limited/Moderate effect on peak individual risks, but more extensive deletions resulted in a general feeling that too much of substance had been deleted and that the degree of bias would be unquantifiable without modelling studies, which effectively corresponds to reintroducing the factors/phenomena into the assessment.

3.5 Comparison of the Minimal Assessment with Dry Run 3

It is of interest to compare the characteristics of the minimal assessment with those factors/phenomena which were included in the Dry Run 3 exercise. This is done in Table 8 and is illustrated in Figure 6.

Table 8 demonstrates that, in the judgement of the Expert Group, Dry Run 3 is significantly sub-minimal when evaluated against the requirements for a comprehensive post-closure radiological assessment. This is as expected, since the main objectives of Dry Run 3 related to the performance of a demonstration assessment of time-dependent pra, emphasising those aspects not covered by earlier trials (Section 1.1). It was never the intention that it should, in itself, be a comprehensive assessment, though it was intended that enough work should be undertaken to estimate the resource requirements for such as assessment (Section 1.1).

On specific topics, the main concerns identified by the author on the basis of this analysis are listed below.

(i) The lack of detailed models of gas generation and transport, and a consistent way of incorporating these processes into the assessment structure (c.f. Volume 3 for a detailed discussion of gas generation and transport).

(ii) The limited amount of experimental work on, or theoretical models of, the evolution of fracture characteristics.

(iii) The current lack of understanding of the likely importance of organic compounds, colloids and starved microbes in determining radionuclide mobility through the geosphere.

(iv) The failure to pay sufficient attention to transient greenhouse gas induced warming, which may have effects persisting for 104 years or more (c.f. Berger, 1990).

(v) The lack of an underlying detailed model of the surface hydrological system, though this is currently being rectified within the HMIP programme (Thompson, B.G.J. pers. comm., 1990) and is a major component of Nirex biosphere research (Thorne, 1990).

(vi) The limited concern with the dynamics of ecological development under changing climatic regimes (c.f. Goodess et al., 1991).

(vii) The lack of an explicit and consistent account of how human activities, specifically land management practices, may influence geomorphological change, ecological development, hydrology, biosphere transport and human exposure pathways.

(viii) The limited attention given to date to short-circuit pathways associated with losses of integrity of borehole, shaft and tunnel seals.

(ix) The need to consider further the implications of intruding, in various ways, into the radioactive plume downstream of the repository.

4 Modelling Studies

Following completion of Stages 1 and 2 of the work of the expert group (Sections 3.2 and 3.3), it became clear that the factors/phenomena identified could be considered as mediating or influencing five general pathways of radionuclide release and transport.

(a) Waste dissolution in the aqueous phase of near-field porewaters, with subsequent transport to the biosphere dissolved in groundwaters.

(b) Transport in the gas phase in the near-field with dissolution in groundwaters in the far-field.

(c) Transport in the gas phase in both the near-field and the far-field.

(d) Human intrusions into the near-field or into the plume of activity in the far-field.

(e) Natural disruptive events and processes transferring activity from the near-field to the biosphere.

Pathway (a) is generally considered to be the 'normal' route of radionuclide release and transport. It was considered in detail in Dry Run 3 (c.f. Volume 5 and 6). However, not all factors/phenomena which influenced this pathway were taken into account, while some others, while considered, were modelled less than adequately. This topic is discussed further in Section 4.2. In contrast, essentially no modelling was performed in Dry Run 3 in relation to pathways (b) to (e), so a variety of scoping calculations were required. These are outlined in Section 4.1.

Details of the various calculations performed are not included here, but are provided in Appendix B, as a full record of the work undertaken.

For consistency with the main part of the Dry Run 3 exercise, attention was concentrated on a limited number of radionuclides. These are listed, with their initial and decay-corrected inventories, in Tables 2 and 3. It is emphasised that the inventory adopted is not necessarily representative of future UK waste arisings and the results obtained should be considered as illustrative only. More details of the adopted inventory are given in Volume 1 (Chapter 1) and Volume 3 (Chapter 1).

4.1 Scoping Calculations

The main series of scoping calculations undertaken related to two types of disruptive event (meteorite impact and major incision), gas transport and human intrusion. Details of these calculations are presented in Appendix B (Calculation Notes 1 to 4), so this Chapter is limited to a brief description of the approaches adopted. Results are presented and discussed in Chapter 5.

4.1.1 Meteorite Impact

Based on geological evidence of past impacts, it is possible to estimate the fractional area of land covered per year by craters of greater than a given diameter. This approach is inherently uniformitarian, i.e. it assumes that impact rates are time-independent. Also, many of the geological features which have been attributed to meteorites are of debatable origin, so a further uncertainty in impact rate is introduced. Finally, erosive processes, which differ in different environments, tend to obscure the evidence of previous impacts. Thus, the geological record is intrinsically biased toward more recent events and more resistant terrain.

Nevertheless, it is possible to use the estimates of fractional area of land covered per year to derive mean numbers of craters of different sizes per unit area per year. Using an empirical relationship between crater depth and diameter, in conjunction with a repository plan area of 4 km^2, the frequency of gross disruption of repositories at different depths can be estimated.

For rock fracturing, the conservative assumption is made that meteorites of substantial size impacting within 10 km of the repository would be of importance.

The likely effect of rock fracturing is taken to be enhancement of hydraulic conductivities of the rocks in the vicinity of the repository. The overall pattern of groundwater flows is not expected to alter substantially, though groundwater velocities might. Thus, meteorite impact is most reasonably aggregated with a variety of other potential causes of changes in hydraulic conductivity and its potential effects on individual risk may be treated in groundwater flow and transport sensitivity studies.

In respect of gross disturbance, the scoping calculation adopted was to consider a crater just sufficiently deep to grossly disturb the ILW repository. The total radionuclide inventory of LLW plus ILW at 10^4 y post-closure was taken to be uniformly distributed throughout the disturbed material and radionuclide concentrations calculated. These were compared with Generalised Derived Limit values and naturally occurring radionuclide concentrations. Values of committed effective dose equivalent, conditional risk and absolute risk were also calculated. The major assumption underlying these calculations is that meteorite impact is an efficient process in mixing repository derived materials with the rest of the disturbed material.

4.1.2 Major Incision

As described in Volume 3, Chapter 7, glaciers are expected to reach and, in some cases, cover the hypothetical site. While these glaciers might cause only superficial erosion (as assumed in the calculations reported in Volume 6), it is possible that gross generalised erosion or incision could occur. In the scoping calculations, attention is concentrated on major incisions. Quaternary geological evidence was used to estimate the number of incisions of this type, with depths of up to 400 m, expected in Britain during a major glacial episode and hence the number expected over the next 10^6 years.

Notional dimensions of an incision were used to estimate the volume of material into which repository derived materials would be diluted. The assessment methodology employed was similar to that adopted in analysing to radiological consequences of gross disturbance by meteorites (Section 4.1.1), in that the incisions were assumed to be randomly distributed and that the radionuclides from the repository were assumed to be uniformly distributed throughout the incised materials.

4.1.3 Release of radioactive gases

In terms of radiological impact, the worst case is that in which radioactive gases evolved in the repository are transported rapidly to the surface in gaseous form and are released into confined overground spaces. The major alternative, in which the gases dissolve in far-field groundwaters is radiologically less interesting and can be treated as a variant of the 'normal' groundwater pathway.

As a basis, for discussion, the following scoping calculations were undertaken.

(a) 50% of the LLW inventory of ^{14}C was assumed to be released from the repository as $^{14}CH_4$, to leak upward to the surface and to be released without modification to its chemical form;

(b) 50% of the LLW inventory of ^{14}C was assumed to be released as $^{14}CH_4$ and 50% as $^{14}CO_2$, via the pathway described in (a);

(c) As for (b), but taking the total LLW inventory of ^{129}I, ^{79}Se and ^{126}Sn also to be released to the environment in methylated forms;

(d) As for (a), but for LLW and ILW;

(e) As for (b), but for LLW and ILW;

(f) As for (c), but for LLW and ILW.

Options (a) and (d) are most likely. The other options are less likely because CO_2 will react strongly with any cementitious materials it encounters and because methylated forms of iodine, selenium and tin are of limited stability.

At the surface, the area of release was taken as equal to the repository area (4 km^2), to give radionuclide fluxes, which were assumed to enter houses. Doses were assessed using an approach similar to that usually adopted for radon daughters, together with exposure-to-dose conversion factors derived specifically for this study. In practice, more localised releases, eg. via access shafts or surrounding damaged rock, might occur, reducing the likelihood of exposure, but increasing risks conditional on such exposure occurring.

4.1.4 Intrusion

On the basis of material included in Volume 3, Chapter 8, it was concluded that the most likely type of intrusion is that associated with exploratory drilling for reserves of coal or oil shale. Historical NCB data were used to estimate the frequency of such drilling in prospective areas and hence the frequency with which such drilling would penetrate the repositories for LLW and ILW.

It was noted that planning controls could continue to limit exploratory drilling subsequent to site restriction being lifted and that downhole logging of such boreholes might identify the anomalous nature of the repository and cause actions to be taken to prevent human exposures. However, in each case, positive safety related responses by future generations would be required and the desire to dispense with the need for such responses is seen as part of the rationale for deep geological disposal of radioactive wastes. It is an open question to what extent the hypothetical prudent actions of future generations should be incorporated into safety assessments.

Two general types of intrusive actions are considered. Type A relate primarily to the examination of small amounts of excavated material, whereas type B relate to actions which occur after excavated material has been spread over the surface of the land or removed from the site. For type A actions, the exposed individual was taken to be a worker in a geotechnical laboratory examining cores. The exposure pathways considered were:

- external irradiation from the core material;
- ingestion of contaminated diet;
- inhalation of resuspended material;
- inhalation of radon and radon daughters.

For type B actions, the exposed individual was taken to be a householder self-sufficient in vegetable production living in the contaminated area. Ingestion of contaminated drinking water, meat, meat products and milk were not included in the calculations, though a methodology was set out by which they could be included, if required. The routes of exposure which were included comprised:

- external irradiation;
- inhalation of resuspended material;
- radon daughter inhalation;
- ingestion of soil;
- ingestion of vegetables.

4.2 PRA Related Studies

4.2.1 Geological and hydrogeological context

It will be recalled (Chapter 2 and Table 1), that a fundamental component of this uncertainty and bias audit related to alternative interpretations of the geological and hydrogeological context consistent with the available data. Strictly, this should have been undertaken by an expert group independent of the assessment team. In practice, interpretations of the geology and hydrogeology at closure and of the subsequent evolution of the geological and hydrogeological regime, were made by an expert group which included both members of the assessment team and outside experts (c.f. Volume 3, Chapters 3 and 9). The conclusions of this expert group are summarised below.

In respect of present-day hydrogeology, four alternative conceptualisations of the groundwater flow pattern in the Harwell area were presented.

1. Up-dip flow in the Corallian and Great Oolite aquifers is countered by down-dip flow from the outcrops of these aquifers and results in artesian upwelling through the confining aquicludes.

2. Down-dip flow in the Corallian and Great Oolite is retarded, but not reversed. In this hypothesis, the Corallian is thought to discharge somewhere to the southeast of Harwell, in the vicinity of Goring or beyond.

3. Down-dip flow in the Great Oolite is retarded, but not reversed. In contrast, the Corallian behaves as described for conceptualisation (1).

4. This conceptual model addresses the possible significance of the Upper Greensand aquifer as a distinct route for radionuclide migration. The Upper Greensand is separated from the overlying Chalk by a glauconitic marl, a thin but effective hydraulic and geochemical barrier. This is a valid variant of each of (1), (2) and (3), and would be expected to increase the concentration of radionuclides released to the biosphere via springs along the scarp slope.

The expert group considered that conceptualisation 1 is the least plausible interpretation of the facts and arises from over-interpretation of data gathered at Harwell. They were unable to discriminate between conceptualisations 2 and 3 on the basis of available data and considered that each carried an equal degree of belief. Finally, the expert group, commented that there is evidence that the Upper Greensand aquifer is generally isolated from the Chalk, especially in the east, where they are separated by a thin marl band. Even where there is hydraulic continuity, the different flow regimes were thought likely to produce a stratification of flow. Thus, conceptualisations 2 and 3, but incorporating variant 4, were preferred over the basic versions of conceptualisations 2 and 3. Nevertheless, conceptualisation 3, excluding variant 4, was adopted as a basis for the Dry Run 3 calculations (see also Volume 3, Chapter 3).

The expert group also commented on the potential risk of radionuclide escape to the biosphere for the various conceptualisations. Model 3 was thought likely to produce the central risk estimate compared with the other models and was adopted as the reference case for Dry Run 3. Model 1 was expected to produce a higher risk estimate than model 3, due to the up-dip flow in the Great Oolite, though this view could only be confirmed by modelling, since relevant head gradients would also be modified. Conversely, Model 2 was expected to produce a lower risk estimate than Model 3. For Variant 4, the bias with respect to Models 1 to 3 was not clear, but is was commented that the transport path through the Upper Greensand is shorter and that radionuclide activity at discharge could be more concentrated. Therefore, the exclusion of variant 4 from detailed analyses is difficult to understand from the documentation.

In practice, studies with the calibrated network developed for conceptualisation 3, indicate that the dominant transport pathways are sub-vertically down from the LLW repository into the Corallian and sub-vertically up from the ILW repository into the Corallian. The Great Oolite, Chalk and Upper Greensand are of relevance in defining the overall hydrological characteristics of the system, but are of little direct relevance to radionuclide transport in present-day conditions. Thus, the reference case for Dry Run 3 was conceptually identical to that for Dry Run 2 (Gralewski et al., 1987); except that both upward and downward migration of activity into the Corallian is assumed rather than downward only. Other routes considered in Dry Run 2 (Gralewski et al., 1987) were:

- upward diffusion into the base of the Chalk/Upper Greensand aquifer, if advective flow in the clay were sufficiently slow;
- releases via the Lower Greensand/Portland and Purbeck aquifer system.

Detailed studies (see below) indicate that, under present-day conditions, vertical advective flows are too large to permit the first of these routes to be of major significance. The general lack of data concerning the Lower Greensand/Portland and Purbeck aquifer system makes assessment of this route highly speculative. If present, it would be of relevance only to the LLW repository and, in practice, a repository design would be selected (c.f. Volume 1, Chapter 6) which maintained a suitable distance from such a potentially high conductivity formation.

Thus, overall, it appears that the reference conceptualisation adopted in Dry Run 3 is an adequate representation of the present-day hydrogeology of the site, encompassing the primary radionuclide transport path via the Corallian and including the main controls on the hydrology of that path.

Potential future changes in the hydrogeology of the Dry Run 3 study area are discussed in Volume 3, Chapter 9. These were discussed by the expert group under five headings:

- climatic changes;
- tectonic activity;
- repository evolution;
- time required by the geological/hydrogeological system for re-equilibrium with respect to the altered environmental conditions;
- the evolution of the geological and hydrogeological regime as influenced by human intrusion.

Two alternative climatic evolutions were proposed:

(a) Temperate, greenhouse-induced "super" - interglacial, boreal, tundra, glacial, tundra, boreal, followed by sequences of these climatic states in full or incomplete cycles for the next 106 years (possibly excluding the "super" – interglacial component).

(b) Long-term control by the "greenhouse effect" and associated positive feedbacks, leading to mass melting of the polar icecaps and stabilisation of a "super" -interglacial climate.

Modelling studies for the various climate states were undertaken (see Volumes 3 and 5). Results are summarised below.

"Super" - Interglacial

Advective flow directions are the same as those for the present-day hydrological regime, although piezometric heads are lower. Travel times to the River Ock increase relative to present-day conditions and groundwater discharges to the biosphere into the rivers at the spring line decreases compared with the present day.

Boreal

Advective flow regimes are the same as those for the present-day hydrological regime and piezometric heads, at least in the Chalk, Gault and Kimmeridge Clays and the Great Oolite, are increased. In the Corallian, however, heads are decreased. Under the particular boundary conditions studied, the shortest travel time to the biosphere decreased by about 30% due to increased hydraulic gradients across the Gault clay to the Corallian aquifer.

Groundwater discharge to the biosphere was found to be increased into the Windrush, Ock and scarp springs, but decreased into the Thames and Kennet.

Tundra - no permafrost

Piezometric heads are generally depressed compared with present-day levels, but the advective flow regime and travel times are similar to those of the present day, though with decreased groundwater discharges to the biosphere.

Tundra - permafrost developed

If hydraulic connectivity is maintained between the rivers and the aquifers, advective flow directions are changed. The shortest travel time to the biosphere is along a pathway upward from the LLW repository into the chalk, discharging as baseflow to the River Thames. However, the travel time is much increased.

With no hydraulic connectivity between rivers and aquifers, the shortest travel time to the biosphere is 8.4 10^6 years, ie. much longer than climatic or geological stability can be assumed.

Glacial

Under glacial conditions, the component modelling studies presupposed that the whole area was covered by an ice sheet. Recharge was taken to occur by sub-glacial melting and a tunnel valley was hypothesised to develop in the Chalk, south of the Berkshire Downs. Faults were taken to develop due to the high pore water pressures generated by ice loading. These were hypothesised as forming in the Chalk adjacent to Harwell, cutting the Corallian and Kimmeridge Clay near outcrop.

Pathways to the biosphere involve up-dip flow in the Corallian followed by transport along the fault plane. These pathways were assessed to have a similar travel time relative to that under present-day conditions.

At a later stage in the study (c.f. Volume 6), two alternative glacial pictures were considered, comprising:

(a) A cold-based glacier entirely overlying the site;

(b) A warm-based glacier with its toe at the foot of the scarp.

For both these additional glacial pictures, groundwater flow patterns differed from those occurring under present-day conditions, but flow velocities were generally slower.

As well as the tectonic effects discussed above in the context of glaciation, consideration was given to the implications of faulting in a temperate state and of uplift of the NW of the study area. In general, the effects of such changes are to slightly reduce travel times.

Overall, the general picture for future hydrogeology is of a regional pattern similar to that existing at present, albeit with somewhat reduced or enhanced water velocities, or a very different, but near-stagnant pattern. Thus, periods of advective transport to the Corallian and thence up-dip are likely to alternate with periods of quasi-stagnation. This analysis alone would suggest that modelling on the basis of present-day conditions would be likely to over-estimate radionuclide fluxes to the biosphere, except if faults are induced by some mechanism (but see also Section 5.1.3).

4.2.2 Repository-induced hydrogeological change

The main processes potentially relevant to geological/hydrogeological evolution are discussed in Volume 3, Chapter 9. The following is a summary of the material presented there.

Process	Effects
Chemical evolution of pore fluids	Includes clay transformations, which tend to increase hydraulic conductivities, and calcite and silica sedimentation, which tend to reduce hydraulic conductivities. Net effect is uncertain.
Gas generation	May cause increased hydraulic heads within the repository and, therefore, increased hydraulic gradients away from the repository.
Heat generation	In principle, could result in the production of convection cells within the generally low permeability clays. In practice, modelling studies indicate that such effects will be negligible.
Fractures developed during repository construction	May respond to crustal stresses, either by closing or opening. Net effect uncertain.

The effects of local fractures developed during repository construction are investigated in the pra studies (Volume 6) by defining a damaged zone around the vaults with altered hydrological properties. Chemical evolution of pore fluids is evaluated in detailed chemical modelling studies (Volume 5).

Some implications of over-pressurisation due to gas generation on groundwater flow have been investigated in this study (see Volume 5, Chapter 3). In addition, in evaluating the potential radiological impact of radioactive gas production, it has been assumed that existing or induced pathways will result in gas venting to the surface. Results of these studies (Chapter 5 and Appendix B) indicate that annual risks would only exceed 10^{-6} in an extreme combination of circumstances. For this reason, it may be prudent to consider incorporation of design features which would facilitate gas venting from an intact or degrading repository, since the studies incorporating gas over-pressurisation demonstrated an additional pathway to the biosphere upward from the Gault Clay repository to the Chalk scarp springs and the River Thames as well as a much reduced groundwater travel time in the Corallian.

4.2.3 Post-closure human actions affecting the hydrogeology

As discussed in Appendix A [Document EG(90)P4], human actions can have a major impact on site and regional hydrogeology. Urbanisation is an example of land use change and can result in reduced groundwater recharge. Also of major concern is the future management of water resources. At present, there is concern within the Thames catchments that projected resource demand is approaching the reliable yield of existing sources. On the timescale of 10^1 to 10^2 years, climate change and gradual economic growth are likely to exacerbate existing problems. Progressive exploitation of deeper groundwater sources may be postulated and much more active management of shallow groundwater in conjunctive use schemes, with induced or injected winter recharge and ephemeral streams increasingly maintained by pumped groundwater.

Apart from land use changes associated with changing patterns of agriculture, urbanisation and recreational land use, near-surface mineral extraction would be expected to affect surface water/groundwater interactions, as well as evaporation.

Notwithstanding the above, it is relevant to note (Volume 3, Chapter 9) that groundwater abstraction from the Corallian and Great Oolite aquifers is not thought to be a feasible proposition because of their high salinity. Thus, attention should be concentrated on groundwater abstraction from the chalk.

4.2.4 Conclusions

Overall, Dry Run 3 has included a detailed study of the natural hydrogeology of the Harwell site and uncertainties as to its interpretation. These are reflected in the various results presented (Volume 6). However, somewhat less attention has been directed to repository related effects, or the effects of changes in human behaviour (Sections 4.2.2 and 4.2.3). A summary of the various considerations, and the degree to which they have been addressed, is presented overleaf.

It should also be noted that a variety of factors relating to radionuclide transport in the geosphere and the creation of short-circuit pathways due to borehole, shaft and tunnel seal failure have not been addressed in this trial assessment (c.f. Chapter 3 and Table 8).

Summary of key judgements and biases in Dry Run 3

Area of Judgement	Decision	Comments on Bias
Geological context	Taken to be well-defined.	Relatively simple geology and extensive borehole information, so a single conceptual model is thought appropriate.
Hydrological regime	(i)Three present-day conceptualisations were developed and one selected for detailed study.	The conceptualisation expected to give the highest risk estimates was considered unlikely to be correct and excluded from further consideration. Of the two remaining conceptualisations, that which was though likely to give the higher risk estimate was selected. Bias is more likely to be a pessimism then an optimism, but could only be quantified by carrying the various conceptualisations through the assessment.
	(ii) Upper Greensand aquifer not considered as a distinct route for radionuclide migration.	Basis for this decision not obvious. Bias is thought to be an optimism, but cannot be quantified from the data available.
	(iii) Future hydrology: only one conceptualisation was developed for each climate state, except that two alternative deterministic glacial pictures were considered one of which was thought to be a worst hydrological case.	No exploration of alternative possibilities. Substantial optimistic or pessimistic biases could exist. The Expert Group felt that glaciation reaching the site would be a catastrophic event and that, if it were considered likely to occur, it should be the subject of a separate study (c.f. Section 3.4).
Effects of repository on hydrology	(i) Fracture development during repository construction is represented explicitly in the pra studies.	No significant bias considered to exist.
	(ii) Heat generation neglected.	Modelling studies indicate negligible bias.
	(iii) Chemical evolution of pore fluids.	Net effect on hydraulic conductivities is uncertain. Bias could be optimism or pessimism and has not been quantified.
	(iv) Gas generation neglected in pra studies.	Deterministic studies demonstrated the possibility of an additional pathway to the biosphere and much reduced travel times for existing pathways in the early post-closure period. Bias is considered to be an optimism, but available data are not sufficient for quantification.

5 Interpretation of Results

5.1 Results from Individual Studies

5.1.1 Scoping Calculations

Detailed results of the various scoping calculations are provided in Appendix B. A brief summary only is given below.

Meteorite Impact

Over 10^6 y, the cumulative probability of gross repository disturbance is estimated to be 7.4 10^{-6} (LLW) and 3.1 10^{-6} (ILW). If gross disturbance of the LLW and ILW repositories occurs the conditional risk to exposed individuals is estimated as no more than 6 10^{-4} y^{-1}. Thus, the peak absolute risk over the period is $\leq$2 10^{-9}. For rock fracturing, the cumulative probability over 10^6 y is estimated to be $\sim 10^{-3}$. The likely effect would be to enhance hydraulic conductivities of the rocks in the vicinity of the repository. The overall pattern of groundwater flows would probably not be altered substantially, though groundwater velocities might. Thus, meteorite impact is most reasonably aggregated with other potential causes of changes in hydraulic conductivity, which can be treated in groundwater flow and transport sensitivity studies. However, this was not done in Dry Run 3.

Gross Erosion and Incision

Over 10^6 years, the cumulative probability of gross repository disturbance is estimated as $\sim 10^{-1}$. If such disturbance occurs, the conditional risk to exposed individuals is estimated as $\leq$5 10^{-7} y^{-1}. Thus, the peak absolute risk over the period is estimated as $\leq$5 10^{-8} y^{-1}.

Generation, Transport, Release and Radiological Impact of Radioactive Gases

A certain amount of bulk plus radioactive gas release is likely to occur. Six scoping calculations give the results shown in the table overleaf.

For a minimum release period of 100 y and a minimum ventilation rate of 0.3 h^{-1}, the values given could be increased by up to a factor of 17. It should be noted that (a) is considered the most likely, with (d) a reasonable bounding calculation. This suggests that exposure to radioactive gases is of limited concern, though more detailed analysis of this topic, in a variety of sensitivity calculations and by exploration of other routes of exposure (e.g. via foodchain pathways), would be needed to confirm this view.

Calculation	Gases/Nuclides	Wastes	Dose Rate (Sv/y)	Annual Risk*
a	$^{14}CH_4$	LLW	3.5 10^{-10}	7.0 10^{-12}
b	$^{14}CH_4/^{14}CO_2$	LLW	1.8 10^{-8}	3.6 10^{-10}
c	$^{14}CH_4/^{14}CO_2/^{79}Se/^{129}I/^{126}Sn$	LLW	1.2 10^{-7}	2.4 10^{-9}
d	$^{14}CH_4$	LLW/ILW	6.4 10^{-9}	1.3 10^{-10}
e	$^{14}CH_4/^{14}CO_2$	LLW/ILW	3.3 10^{-7}	6.6 10^{-9}
f	$^{14}CH_4/^{14}CO_2/^{79}Se/^{129}I/^{126}Sn$	LLW/ILW	3.1 10^{-5}	6.2 10^{-7}

* Based on a risk coefficient of 0.02 Sv^{-1}.

Human Intrusion

The most likely type of intrusion is considered to be that associated with exploratory drilling for reserves of coal or oil shale. Based on NCB data, a realistic estimate of the frequency of such exploratory drilling over the repository area is 0.01 y^{-1}, indicating that, on the basis of the modelling assumptions set out in Appendix B, it is virtually certain that exploratory drilling through the repository would occur within a few hundred years of site restrictions being lifted and planning controls having failed.

In mitigation, downhole logging of such boreholes might identify the anomalous nature of the repository and cause actions to be taken to prevent human exposures.

Limitation of exploratory drilling subsequent to site restrictions being lifted, and identification and response to the anomalous nature of the repository during exploratory drilling, require positive safety-related responses by future generations. The desire to dispense with the need for such positive safety related responses is seen as part of the rationale for deep geological disposal of radioactive wastes. The degree to which such prudent responses by future generations should be taken into account in safety assessments is an open question.

Two general types of consequence of intrusive actions are considered. Type A relates primarily to the examination of small amounts of excavated material, whereas type B relates to consequences which occur after excavated material has been spread over the surface of the land or removed from the site. For type A, the exposed individual is taken to be a worker in a geotechnical laboratory examining cores. Estimated committed effective dose equivalents to such a worker, from the adopted inventory, are listed below.

Route	**Effective Dose Equivalent (Sv/y)**
External irradiation	$2.58\ 10^{-5}$
Inhalation	$1.02\ 10^{-2}$
Ingestion	$1.14\ 10^{-2}$
Radon inhalation	$1.25\ 10^{-6}$

Uncertainties in respect of these values can be summarised as follows.

Uncertainty	Scale Factor			
	External	Ingestion	Inhalation	Radon
Period of exposure	0.5 to 2.0	0.5 to 2.0	0.5 to 2.0	0.5 to 2.0
Volume of active material	0.2 to 5.0	N/A	N/A	0.2 to 5.0
Distance from cores	0.25 to 4.0	N/A	N/A	N/A
Laboratory volume	N/A	N/A	N/A	0.33 to 3.0
Ventilation rate	N/A	N/A	N/A	0.33 to 3.0
Fractional exhalation	N/A	N/A	N/A	<1
Mass ingested	N/A	0.1 to 10.0	N/A	N/A
Dust load in air	N/A	N/A	0.5 to 5.0	N/A

Thus, the total committed effective dose equivalent is estimated to be in the range $6\ 10^{-3}$ to $1.6\ 10^{-1}$ Sv, with a best estimate of $2.2\ 10^{-2}$ Sv. This dose should be taken to be incurred in the year of intrusion. Taking a risk factor of $2\ 10^{-2}\ Sv^{-1}$ and an intrusion frequency of $0.01\ y^{-1}$, the annual risk is $\sim 4.4\ 10^{-6}$ (range $1.2\ 10^{-6}$ to $3.2\ 10^{-5}$).

For type B, the exposed individual is taken to be a householder self-sufficient in vegetable production living on the contaminated area. Ingestion of contaminated drinking water, meat, meat products and milk is not included in the calculations.

Estimated committed effective dose equivalents incurred by such a householder in the year following intrusion, from the adopted inventory, are listed below.

Route	**Effective Dose Equivalent Rate (Sv/y)**
External irradiation	$1.10\ 10^{-6}$
Inhalation	$8.59\ 10^{-7}$
Radon daughter inhalation	$2.54\ 10^{-7}$
Ingestion of soil	$1.82\ 10^{-6}$
Ingestion of vegetables	$8.86\ 10^{-6}$

Major unquantified uncertainties exist in the assumptions relating to the area and type of contamination (see Section 2.2.1). However, given that these are appropriately specified, uncertainties in the various dosimetric calculations lead to a best estimate total initial dose rate of $1.3\ 10^{-5}$ Sv/y (range 10^{-6} to $2\ 10^{-5}$ Sv/y). Given that intrusion is postulated to be almost certain to happen on a timescale of centuries, comparable with radionuclide residence times in soil, the individual risk for type B actions is assessed as $\leq 4\ 10^{-7}\ y^{-1}$, ie. an order of magnitude lower than the best estimate of the risk to the geotechnical worker and a factor of three lower than the lower bound estimate for that worker.

Conclusions

Of the additional routes of exposure, intrusion is found to be of greatest concern, with individual risks computed to in excess of the target figure. On the basis of the calculations presented, the following conclusions may be drawn.

(i) The risks from gross disturbance of a repository due to meteorite impact are small and do not need to be considered further.

(ii) In respect of changes in rock properties, the effects of meteorite impact are most reasonably aggregated with other potential causes of changes in hydraulic conductivity, which can be treated in groundwater flow and transport sensitivity studies.

(iii) Gross erosion of the repository is likely to occur over a period of 10^6 years (see also Chapter 3 and Appendix A). However, even if such erosion occurs, the degree of dilution of waste materials by physical transport processes may well be sufficient to reduce individual risks below the target figures, though this question is deserving of further study as a variety of styles of incision may occur.

(iv) To limit effects on the groundwater pathway, release of bulk gases is preferred. Initial studies suggest that the radiological impact of such gas releases is likely to be acceptable, but additional sensitivity analyses and investigations of alternative exposure pathways are needed to confirm that this is the case.

(v) Both exposures of intruders and of individuals inhabiting the site subsequent to intrusion are of concern. A major uncertainty for this route in this model is the annual frequency of intrusion. To explore this factor, much more attention must be given to patterns of human actions than has been the case to date. Other major uncertainties relating to exposure of site inhabitants are the area and type of contamination (c.f. Appendix B, Section 2.2.1).

However, it must be recognised that a single conceptual model has been used to generate the results and, that, furthermore, these results derive from simple scoping calculations. Alternative conceptual models could be developed (eg. event tree approaches, which would represent explicitly changes in human knowledge of the repository, for example, and sensitivity studies could be used to extend the scoping calculations.

5.1.2 Deterministic groundwater calculations

A variety of deterministic calculations were undertaken in Dry Run 3 as essential preparation prior to the full pra study. The initial deterministic studies related to time-independent modelling of temperate conditions (c.f. Volume 6, Chapter 2). Their objectives were to:

- ensure the validity of the input;
- identify the main mechanisms of release and their consequence;
- eliminate from further consideration any radionuclide which can never give rise to any appreciable risk.

It is in the last area, where judgements are made on the basis of the results obtained, that the potential for bias in subsequent calculations enters. However, in this particular context, and for a 10^6 y assessment period, groundwater transit times are such that only poorly sorbed radionuclides are likely to enter the biosphere. Thus, the carrying through of ^{129}I, ^{36}Cl and ^{99}Tc only is readily justified by the arguments presented in Volume 6, Chapter 2.

Furthermore, in Volume 6, Chapter 5, it is demonstrated, by alternative deterministic time-dependent calculations, that full time-dependent pra calculations are justified only for ^{129}I.

It must be recognised that the above deterministic studies were based on a limited inventory of radionuclides (Volume 6, Chapter 2) and that the combination of factors/phenomena considered is judged to be subminimal (c.f. Section 3.4). For these reasons, it cannot be concluded that ^{129}I would be the only radionuclide of concern on a 10^6 y timescale for LLW and ILW disposal at the Dry Run 3 site. Nevertheless, in the context of the exercise, an appropriate methodology is seen to have been applied in limiting the number of radionuclides carried through to full pra studies. This methodology, incorporating a variety of deterministic calculations, is of general applicability, though the conclusions reached would not necessarily be as simple as those obtained here.

5.1.3 Probabilistic studies

A variety of time-independent pra studies were undertaken as part of the process of defining appropriate time-dependent pra calculations. These are not discussed further herein. On the basis of deterministic time-dependent calculations, it was decided that stochastic time-dependent TIME4-VANDAL simulations should be carried out only for ^{129}I. These studies demonstrated that the mean annual risk rose to a value of 10^{-9} at around 4 10^4 years post-closure and then remained essentially constant to at least 5 10^5 years post-closure, the main distinction being that the curve is smoother at later times, reflecting the achievement of an essentially time-independent probability of being in each climate state after about three glacial/interglacial cycles. However, it should be emphasised that relatively few runs contributed significantly to the risk and that the time-dependent case was not considered to be well converged.

An alternative TIME4-VANDAL simulation was based on the historic climate sequence. This generated a much more peaky response, since the times of transition between the climate states were fixed. While the risk estimate based on the historic sequence reaches peaks similar to, or even slightly above, the maximum risk estimated in the fully stochastic simulations, the time-averaged risk is approximately an order of magnitude lower. Therefore, the fully stochastic simulation must include sequences of environmental change that lead to higher doses and risks than the historic sequence.

While the fully stochastic case is not considered to be well converged, the stability of the annual risk with time indicates that results from a well-converged case would not differ significantly. The ability to make this judgement arises because the convergence criterion is in relation to results at a particular time, whereas examination of the full risk curve gives the possibility of considering, at least semi-quantitatively, results at all times after the risk has risen to near its maximum value.

Reanalysis of a high risk run from the fully stochastic case indicated that key characteristics of such runs may well be a protracted period of high recharge causing relatively rapid transport of activity along the Corallian aquifer, followed by a period of very low near-surface dilution. In view of the time-independent nature of the mean risk result, the low dilution factor is judged to be more significant than the rapid transit time.

5.2 Aggregation Procedures

In Section 2.5, details of the principles of risk aggregation were set out. These principles are applicable in circumstances where extensive data sets have been generated. This is not the case with Dry Run 3. Thus, the most that can be undertaken is a brief presentation and illustrative discussion of the few results actually available.

(a) Expert opinion is that glacial episodes at the site would result in gross erosion and potential disruption of the system. In contrast, the time-dependent pra studies are based on two ad hoc glacial pictures, neither of which is associated with gross erosion of the scarp structure. Thus, there are two conceptually different, and not readily reconcilable, views of site evolution. However, on looking at the results, recalling that they are provisional and derive from a limited exercise, the position is as follows.

   (i) If gross erosion and incision occurs, peak individual annual risks may well be $\leq 5\ 10^{-8}$.

   (ii) If gross erosion and incision do not occur, peak individual annual risks are likely to be $\sim 10^{-9}$.

   In this case, the mutually exclusive possibilities both give acceptable peak individual annual risks and no aggregation is required.

(b) Expert opinion is that gas production and transport should be included in a minimal assessment. No provision is made for this in the time-dependent pra. The scoping studies assume that radioactive gases are readily released to the environment. Again, two possibilities are identified.

   (i) Gases escape readily and the groundwater pathway is not modified substantially. Peak annual individual risks are almost certainly $<10^{-8}$ from exposure to radioactive gases and $\sim 10^{-9}$ from groundwater pathway.

   (ii) Gases cannot escape readily and the groundwater pathway is likely to be modified substantially. The radiological impact of particular combination has not been investigated and so remains an unresolved issue.

On the basis of the above, potential developments of the assessment would be either to demonstrate that the gases would definitely escape (since the peak individual annual risk appear to be acceptable) or to show that the peak individual annual risks would be acceptable if the gases were contained.

(c) On the basis of the approach presented here, human intrusion is seen as giving rise potentially to peak individual annual risks of somewhat in excess of 10^{-6}, ie. dominating other routes. Furthermore, intrusion is judged almost certain to occur on a timescale of centuries, so modifying the groundwater and gas release pathways. There is considerable scope for undertaking more comprehensive assessments of this route.

In particular, potential developments of the assessment would be:

(i) Development of an event-tree based approach;

(ii) Detailed re-evaluation of intrusion frequencies;

(iii) Scoping studies of the potential radiological impact of build-ups of gas released during intrusion;

(iv) Groundwater modelling studies incorporating the hydrological changes associated with one or more intrusion events.

The above discussion demonstrates that, in practice, inspection of the results obtained from an assessment is often sufficient to:

- establish whether impacts would be acceptable even if there is not a consensus on site evolution (see (a));
- identify issues that would have to be resolved to make an acceptable safety case and outline alternative approaches to their resolution (see (b) and (c));
- identify exposure routes that give rise to unacceptable impacts and outline ways in which those impacts might be reduced (see (c)).

Thus, aggregation, while an important tool in demonstrating compliance with regulatory requirements, is not always necessary in initial assessments undertaken to establish a provisional view as to the performance of a proposed disposal concept and to identify issues which have to be resolved prior to the construction/licensing of such a facility.

Where confounding factors exist and the relevant combinations have not been explored in quantitative modelling studies, there is a need to indicate how the results of an assessment would be modified by taking these factors into account. Generally, it will only be possible to do this in a qualitative or, at most, semi-quantitative way. This is illustrated schematically in Figure 7 for the interactions between gas production and transport and groundwater flow and transport. The data shown are simplified idealisations of the results presented in this Volume and in Volume 6. In this figure, the potential biases due to neglect of interactions between the pathways are indicated by arrows. Thus:

(a) The presence of groundwater may inhibit gas release and, therefore, reduce the radiological impact of the gas pathway;

(b) If this happens, over-pressurisation is likely to occur, so reducing groundwater transit times substantially and enhancing the maximum individual risk to a limited degree.

In order to quantify this bias, it would be necessary as a minimum, to carry out deterministic radionuclide transport calculations to provide appropriate scaling factors. Such calculations could reasonably be based on the hydrological studies described in Volume 5, Chapter 3 and outlined in Section 4.2.2 of this Volume.

6 Discussion and Conclusions

6.1 Parts of the Procedure Exercised

In Table 1 and Figure 2, the components of an assessment incorporating an uncertainty and bias audit are illustrated. It is appropriate to examine the degree to which this procedure was exercised during Dry Run 3.

(a) Collection and documentation of geological and hydrogeological data was performed (boxes 1, 5, 9 and 11). The particular context of the site was such that scope for variant interpretations was limited (box 10), though the topic was addressed. In this context, there was little scope for assigning probabilities to alternative geological and hydrogeological interpretations (box 13).

(b) Repository design data were collected and documented. The designs considered were adapted to the geological context (boxes 2, 6, 12 and 14).

(c) The analysis of contingency plans was defined to be outside the scope of the project (boxes 3 and 7).

(d) Wastes were characterised and divided into major categories. This work was reviewed within the assessment team (boxes 4, 8, 15, 16 and 17).

(e) Consolidated factual documentation was produced (Volume 1) and issued to the Expert Group as a basis for their work (box 18).

(f) The full procedure for generating, reviewing and documenting factors and phenomena to be included in an assessment was exercised (boxes 19, 20, 21, 22, 23, 24, 25 and 26).

(g) The major loop of selecting variants as a basis for system and scoping calculations (boxes 27 to 59) was not exercised, though specific activities within the loop were performed. Thus, different sets of phenomena were selected and degrees of belief in their adequacy as a characterisation of the system were established (box 28; c.f. Section 3.4).

(h) Direct representation of factors/phenomena in the system model was performed (box 29), but there was little work on using the system model to represent phenomena not explicitly represented (e.g. gas build-up and thermal effects) (boxes 30, 31, 32 and 33), though the representation of hydrology under glacial conditions could be considered an example of this procedure. Thus, there was little scope for investigating alternative interpretations of the factors/phenomena in the model (boxes 34 and 49).

(i) System model studies included data collection and documentation (boxes 34, 35, 36, 37 and 38), data elicitation procedures using expert judgements were also exercised (Volume 4; boxes 40 and 41). As the data were mainly for use directly in the system model, there was little scope for selecting alternative models for data interpretation (boxes 42, 43, 44, 45 and 48). However, the chemistry studies used, in part, to select Kd values (Volume 5) indicate the flow from input data to detailed models to output data used in combination with other information to generate input data for the system model (box 46).

(j) For scoping studies, in each case a preferred approach was defined, documented and utilised (boxes 50, 52, 54 and 55). However, alternative approaches were not explored (boxes 51, 53 and 56), because of limitations of time.

(k) The system model was used for calculating measures of consequence (box 47) and the results documented (box 57).

(l) The number of results obtained was limited, so computation and documentation of combined consequence measures could not be attempted (boxes 60 and 61; but see also Section 5.2).

Overall, considerable efforts were made to conform to the predefined structure and no major difficulties were encountered in the areas that were exercised.

6.2 Resource Requirements

Within the context of the work conducted as part of the uncertainty and bias audit, the major new area explored was in the use of an Expert Group to define overall assessment structures and to define their adequacy.

This work requires a central secretariat as well as the participation of various individual experts. Resource requirements are set out below.

Item	Man-Days
Compilation of data for use by the Expert Group, identification of appropriate group members, and preparation of an initial guidance note.	10
Preparation of 6 further guidance notes of substance and analysis of replies received.	20
Organisation and documentation of 3 meetings of the Group (i.e. one more than occurred in this exercise).	15
Preparation of an overall analysis of the exercise.	5
Participation of individual experts (assuming a group of 11, with 8 substantial contributors to the work).	50

Thus, an exercise similar to that documented in Appendix A requires approximately 100 man-days of professional effort, to which should be added approximately 15 man-days of secretarial support. However, it should be noted that this is probably close to a minimum estimate, since it assumes that the secretariat staff are familiar with all the areas to be addressed by the group, i.e. it includes no component for background study by the secretariat.

Also, it should be noted that such an exercise typically involves senior staff from a variety of organisations. Such staff typically have many demands on their time, so that only very limited inputs to the group can be expected if excessively tight deadlines are imposed, or if meetings are arranged at short notice. In view of these considerations, **it is considered that it would be unreasonable to attempt an exercise such as that documented in Appendix A on a timescale of less than 9 months, and that 12 months would be more realistic.**

6.3 Areas for Further Development

6.3.1 Application of expert judgement

In this study, expert judgement was applied primarily in defining factors and phenomena that should be considered, in defining assessment structures of different levels of complexity, and in estimating the adequacy of these various assessment structures, given that the underlying mathematical and computational models are adequate to represent the factors and phenomena involved. Selection of mathematical and computation models and judgements as to their adequacy was not part of the procedure which was exercised (c.f. Section 6.1), largely because the Dry Run 3 exercise was set up to exercise and test particular aspects of the performance of a prescribed set of models, and was performed in parallel to the uncertainty and bias studies. In practice, the potential to select between alternative models may be limited for any assessment but the general procedure of examining whether legitimate alternatives are available should always be exercised.

Ideally, the work reported in Chapter 3 should be undertaken prior to modelling and would provide a basis for judging the adequacy and comprehensiveness of the models available. In practice, time constraints are such that a repeat of the Chapter 3 exercise might have to be undertaken in parallel with assessments of model adequacy based largely on the work undertaken to date.

In the context of the expert judgement studies undertaken, the methodology generally operated well, though there is room for the use of more meetings relative to communications by correspondence. As a general rule, dates for such meetings must be set at least two months in advance, which is a major constraint on the flexibility of the process and is an important determinant of its timescale.

In respect of communication by correspondence, the method of briefing notes, questionnaires and reproduction of all material received for consideration by the group worked well. It is emphasised that the secretariat cannot merely reproduce contributed items in the briefing notes. There must be a substantial input of interpretation and comparison in order to help the group progress their work. Considerable care has to be exercised, when providing supplementary material, not to direct or constrain responses from group members.

In the context of meetings, it is relevant to note the conclusions of an observer at the Expert Group meeting of 25th September 1990 (c.f. Appendix A). His view was that the meeting was well controlled and that, from a practical point of view, the potential for introduction of bias was limited. Areas which require consideration in the conduct of such meetings are listed below.

(a) Physical facilities are important and provision should be made for rapid updating of the complex reference material which forms the basis of discussion at such meetings. Visual presentation of this material to facilitate the work is also important.

(b) The potential motivational bias of the generalist (Chairman), who is typically a member of the secretariat, should be noted and a suitably qualified observer should be present, if practical, to detect such bias.

(c) Positive confirmation of the secretariat's judgement should always be sought (this applies also to correspondence).

(d) Policy and underlying assumptions should be defined clearly prior to discussions, as should definitions of the terms used.

(e) Training of Expert Group members and peer review of their deliberations is important. The latter requires that a comprehensive audit trail is maintained of all discussions (c.f. Appendix A).

Finally, in this area, **it is noted that the group was able to come to semi-quantitative judgements on the adequacy of different assessment structures, but that exploration of this topic was necessarily limited (c.f. Section 3.4). Further work in this area would be desirable, to further test and extend the methodology adopted herein.**

6.3.2 Scoping calculations

A limited number of scoping calculations were undertaken during this study. These are reported in detail in Chapters 4 and 5, and Appendix B. Detailed conclusions are not reproduced here, but it is emphasised that a great deal of information and guidance was obtained from approximately 10 man-days of effort. Thus, given the variety of interactions set out in Table 6, **there would be considerable merit in exploring the degree to which the minimal assessment could be simplified by a variety of scoping calculations.**

6.3.3 Groundwater pathway calculations

For the existing systems model, a relatively comprehensive methodology exists, and has been exercised, for moving from available data through conceptual models of the repository and its environs, to detailed and assessment models, and to deterministic and pra simulations. **The main concern is the long timescale for this process (in excess of 12 months) and the difficulty in obtaining an adequate number of converged pra results. It is clear that in the current state-of-the-art, this is the major unresolved issue in determining whether the full methodology can be adequately applied at sites of more uncertain and less predictable hydrogeology than that considered in Dry Run 3.**

7 References

Bull, R.K. (1990). Uncertainties of Dosimetric and Metabolic Models, with Some Consideration of Non-Fatal Cancers and Effects on the Fetus. Nirex Safety Series Report, In preparation for publication.

Gralewski, Z.A., Kane, P. and Nicholls, D.B. (1987). Development of a Methodology for Post-Closure Radiological Risk Analysis of Underground Waste Repositories. Illustrative Assessment of the Harwell Site. DoE Report No. DOE/RW/87.034.

Goodess, C.M., Palutikof, J.P. and Davies, T.D. (1991). Studies of Climatic Effects and Impacts Relevant to Site-Specific Assessments of the Radiological Impact of Disposal. Nirex Safety Series Report, In preparation for publication.

Hodgkinson, D.P. (ed.). (1988). Systematic Approaches to Scenario Development: A Preliminary Report of the NEA Working Group on the Identification and Selection of Scenarios of Nuclear Waste Disposal. PAAG/DOC(88)/2.

Hofer, E. and Hoffman, F.O. (1987). Selected examples of practical approaches for the assessment of model reliability - parameter uncertainty analysis. In: Uncertainty Analysis for Performance Assessment of Radioactive Waste Disposal Systems, NEA/OECD, Paris, pp132-148.

International Atomic Energy Agency (1989). Evaluating the Reliability of Predictions Made Using Environmental Transfer Models. IAEA Safety Series, No. 100, IAEA, Vienna.

International Commission on Radiological Protection (1989). Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 1. Annals of the ICRP, Vol. 20(2), ICRP Publication 56.

Nuclear Energy Agency (1987). Uncertainty Analysis for Performance Assessments of Radioactive Waste Disposal Systems. NEA/OECD, Paris.

Ringrose, P.S., Chadwick, A.F., Kleissen, F.A.T., Larkin, J.P.A., Pollock, D.T., Wilmot, R.D. (1989). Probabilistic simulation of the long-term evolution of radioactive waste disposal sites. In Proc. IAEA/CEC/NEA(OECD) Symposium, Paris.

Thompson, B.G.J. (1987). The development of procedures for the risk assessment of underground disposal of radioactive wastes: Research funded by the Department of the Environment 1982-1987. Rad. Waste Management and the Nucl. Fuel Cycle, 9(1-3), 215-256.

Thompson, B.G.J. (1987a). Uncertainty analysis in assessing the risk associated with the disposal of low and intermediate level radioactive wastes. In: Uncertainty Analysis for Performance Assessments of Radioactive Waste Disposal Systems, NEA/OECD, Paris, pp206-220.

Thompson, B.G.J. (1989). The time dimension in risk analysis: Examples of recent work in the United Kingdom. In Saltelli, A. et al. (eds.) Risk Analysis in Nuclear Waste Management, pp231-262.

Thorne, M.C. (1988). Assessment of the Radiological Risks of Underground Disposal of Solid Radioactive Wastes. DoE Report No. DOE/RW/89/030. December 1988.

Thorne, M.C. (1990). The Biosphere: Current Status, December 1989. Nirex Safety Series Report NSS/G114. Available from UK Nirex Ltd.

Thorne, M.C. and Laurens, J-M. (1989). The development of an overall assessment procedure incorporating an uncertainty and bias audit. In Proc. IAEA/CEC/NEA(OECD) Symposium, Paris.

UK Departments of the Environment and Ministry of Agriculture, Fisheries and Food (1984). Disposal Facilities on Land for Low and Intermediate-Level Radioactive Wastes: Principles for the Protection of the Human Environment. HMSO.

Watson, S.R. and Buede, D.M. (1987). Decision Synthesis, Cambridge University Press.

Box	Activity (Responsible Persons)
1 (a)	Collect all relevant geological and hydrogeological data and review them for factual accuracy. (Assessment Team).
2 (a)	Collect all repository design data. (Assessment Team).
3 (d)	Collect all data on contingency plans. Proposals for repository operation and sealing should be reviewed by the assessment team. These proposals may include contingency plans to be initiated in the event of abnormal occurrences during the operational and sealing phases. If such contingency plans are included, the assessment team should determine their implications for repository state at closure or abandonment. If such states are substantially different from that which would apply following normal operations and sealing, the various alternative states should be considered as part of the post-closure radiological safety assessment procedure. It is assumed that the probability of such states occurring will be investigated as part of the operational safety assessment. (Assessment Team). (It is not considered to be a proper part of the activities of the post-closure radiological safety assessment team to speculate on the likelihood of abnormal occurrences during the operational or sealing phases, or to invent contingency plans for dealing with such occurrences).
4 (a)	Collect all relevant data on the physical, chemical and radiochemical characteristics of the wastes. (Assessment Team).
5 (a)	Summarise the geological and hydrogeological data in a reference document, which should not include any interpretation of the data. (Assessment Team).
6 (a)	Summarise repository design data, including information on potential variant designs (see box 12). (Assessment Team).
7 (d)	Document contingency plans, their implications and the probability that they will have to be invoked. (Assessment Team).
8 (a)	Wastes should be divided into major classes with broadly similar characteristics. For each such class, estimates should be made of: i) ranges in radionuclide concentrations and total amounts; ii) variability in physical and chemical characteristics. (Assessment Team).

Table 1: Detailed assessment procedure: definition of activities

Box	Activity (Responsible Persons)
9 (a)	An expert group should derive a preferred interpretation of the geology and hydrogeology. This is an expert judgement and should be obtained under controlled conditions. (Expert Group).
10 (b)	An expert group should be asked to speculate on alternative interpretations of the geological and hydrogeological context which would be consistent with the data document under box 5. At this stage, no attempt should be made to constrain interpretations on the basis of probability. In defining such alternative interpretations, attention should be directed to the possibility of undetected site features. These may include any of the following: i) strata presumed to be present which may actually be absent; ii) additional strata which might occur and would have a significant effect on site hydrogeology; eg. interbedded thin sandy layers in a clay formation; iii) faults and fracture networks; iv) gas pockets; v) brine pockets. Particular attention should be paid to the superficial 100 to 200 m, where substantial modifications may have occurred during the Quaternary and features such as hidden valleys may be present. Alternative interpretations should differ in kind and not merely in the parameter values considered appropriate to each stratum. (Expert Group).
11 (a)	Summarise alternative interpretations of the geology and hydrogeology in a reference document. (Expert Group).
12 (d)	The proposed design may not be suitable for all variant geologies proposed. Variant designs, identified under box 6, may have to be assigned. Alternatively, the proposed designs may have to be modified to conform to the variant geologies. (Assessment Team/Repository Designers).
13 (c)	The expert group should assign probabilities to each of the geological and hydrogeological interpretations. These are expert judgements and should be obtained under controlled conditions. (Expert Group).

Table 1 (Contd.)

Box	Activity (Responsible Persons)
14 (a)	The repository designs appropriate to each geological and hydrogeological interpretation should be summarised. This summary should include a justification for the designs adopted. (Assessment Team/Repository Designers).
15 (a)	Waste characteristics, methods of aggregating into classes, and the physical, chemical and radiochemical characteristics of the classes, including variability, should be documented. (Assessment Team).
16 (a)	The data summarised under box 15 should be inspected by a group of experts (not necessarily members of the assessment team) for the purpose of identifying any undeclared characteristics of the wastes which might have implications for the post-closure safety assessment (eg. likely presence of complexing agents). (Expert Group).
17 (a)	Queries raised under box 16, together with responses from the originators of the waste characteristics should be documented. An update of the document produced under box 15 should be created. (Assessment Team).
18 (a)	A consolidated database document for the rest of the assessment should be produced. This should include: i) variant geological and hydrogeological contexts; ii) associated repository designs; iii) probability of each variant; iv) probabilities of contingency plans having to be invoked for each variant; v) status of the repository and environs if contingency plans are invoked; vi) waste characteristics, including uncertainties. This defines all possible states of the repository at closure and their probabilities. Each such state is henceforth referred to as a variant. (Assessment Team).
19 (a)	A small group from the assessment team should prepare a comprehensive list of phenomena that need to be considered in assessing the post-closure evolution of the repository and its environs.

Table 1 (Contd.)

Box	Activity (Responsible Persons)
19 cont.	This list should be structured so as to highlight any phenomena that have been omitted. It is recommended that this structure be closely related to the systems modelling approach to be adopted. (Assessment Team).
20 (a)	The structured list should be documented using an unambiguous numbering scheme. (Assessment Team).
21 (a)	The documented list should be distributed to experts in a variety of disciplines for suggestion of extra items. (Expert Group).
22 (a)	Replies from experts should be collated and documented. An updated list of phenomena should be produced to form the basis of the assessment. (Assessment Team).
23 (a)	A small group from the assessment team should eliminate trivial phenomena from the list. Elimination can be on the grounds of inapplicability to the repository/site combination, negligible implications for the safety assessment or low cumulative probability over the assessment period. Low annual probability is not sufficient justification, since the phenomenon may have a long-term cumulative impact. (Assessment Team).
24 (a)	The phenomena eliminated and the reasons for elimination should be documented. (Assessment Team).
25 (a)	Adversarial sessions should be conducted involving the whole of the assessment team and an expert group at which the elimination of phenomena can be challenged. These sessions may result in the reinstatement of some phenomena, if the justifications for elimination are found to be inadequate. (Assessment Team/Expert Group).
26 (a)	The adversarial discussions and the final list of phenomena to be included in the assessment should be documented. (Assessment Team).
27 (c)	Select a variant of the system (as defined at box 18) for detailed study. It will be usual to commence with the most probable variants. (Assessment Team).
28 (a)	From the list of phenomena to be considered select an internally consistent sub-set to be modelled. (Assessment Team).

Table 1 (Contd.)

Box	Activity (Responsible Persons)
28 cont.	Estimate a degree of belief that this sub-set of phenomena adequately represent the factors determining the future evolution of the repository. The degree of belief is an expert judgement. It is permissible to carry forward a range of values if no consensus view is reached. (Expert Group).
29 (a)	Evaluate whether this variant and complex of phenomena can be represented in the system model without adopting gross approximations and simplifications. (Assessment Team).
30 (c)	Evaluate whether this variant and complex of phenomena can be represented in the system model by adopting gross approximations and simplifications. (Assessment Team).
31 (c)	Given that simplifications and approximations are required, there may be several alternative approaches which can be adopted. As a basis for further discussion, a preferred approach is adopted at this stage, on the basis of discussions in the assessment team. (Assessment Team).
33 (c)	Document the alternative interpretations and the degrees of belief in each. Note that these degrees of belief are assigned prior to any consequence calculations. (Assessment Team).
34 (b)	Select an interpretation for modelling. The order in which interpretations are selected will be conditioned by degree of belief and ease of modelling. (Assessment Team).
35 (a)	Collect data relevant to modelling the variant and phenomena under this interpretation. System data are primarily derived from box 18. The data needed to represent the phenomena will be interpretation specific, eg. complexes may be treated either as totally stable across the near-field/far-field boundary or as totally degraded at that boundary, either approach is a potential simplification of reality to fit into the systems model framework and each requires different far-field data. (Assessment Team).
36 (a)	Examine the data to determine whether they are sufficient for systems modelling studies of the particular interpretation. (Assessment Team).
37 (a)	If the data are insufficient, the relevant literature should be reviewed for supplementary or collateral data. (Assessment Team/Expert Group).
38 (a)	The additional data and their origins should be documented. (Assessment Team/Expert Group).

Table 1 (Contd.)

Box	Activity (Responsible Persons)
39 (a)	Re-examine the data to determine whether they are sufficient for systems modelling. (Assessment Team).
40 (a)	If additional data are required and are not available in the literature, they will have to be elicited by expert judgements. Procedures for data elicitation using expert judgement have been exercised previously and a similar approach is recommended here. Actual data collected at boxes 35 and 37 may be used as a basis for the expert judgements. (Expert Group).
41 (a)	Document data derived from expert judgements and the basis of those judgements. (Expert Group).
42 (c)	In general, the available data, including those elicited by expert judgement will not be in a form which is directly usable in the systems model. Thus there will be a need to transform these data using supplementary, or detailed, models, e.g. chemical speciation and transport models, or 2-D and 3-D groundwater flow and radionuclide transport models. At this stage, the assessment team should select the detailed models preferred for data interpretation. (Assessment Team).
43 (c)	Alternative models for interpreting the data may be available. These should be identified. This should be done in adversarial sessions where modelling approaches are propounded and challenged. Note that, in this context, models include alternative conceptual approaches to handling data and are not restricted to those models which are implemented in computer programs. Thus, given a variety of sorption data, alternative interpretative models are: i) give equal weight to batch and diffusion studies ii) ignore batch studies as worthless and use data from diffusion studies directly; iii) use selected batch and diffusion studies to define relationships between the two approaches and apply these relationships to transform all the data to a consistent basis. The degree of belief in each of these models should be assigned at this stage. The approach is as described at box 32. (Assessment Team/Expert Group).
44 (c)	Document the alternative approaches to the data, their justification and the degree of belief in them. (Assessment Team/Expert Group).

Table 1 (Contd.)

Box	Activity (Responsible Persons)
45 (c)	Select an approach to data interpretation. The order of selection will be determined by degree of belief and ease of computation. (Assessment Team).
46 (b)	Compute the input data for the systems model using the adopted approach to data interpretation. (Assessment Team).
47 (a)	Calculate the measures of consequence (individual risk, detriment to health, etc) using the systems model. These measures will, in general, take into account parameter uncertainty, since the data elicitation and interpretation procedure (boxes 35-46) relates both to point values and to distributions. (Assessment Team).
48 (c)	Loop on alternative approaches to data interpretation as many times as required. (-).
49 (c)	Loop on alternative interpretations of the modelled phenomena in the context of the systems model. (-).
50 (a)	Some combinations of phenomena cannot be represented in the systems model. However, their implications need to be assessed. Thus, an ad hoc modelling approach is adopted. The first stage is to agree a preferred ad hoc modelling approach by discussions within the assessment team. (Assessment Team).
51 (c)	Alternatives to the preferred approach should be devised in adversarial sessions and degrees of belief should be assigned to each approach. These degrees of belief should have the same meaning and be assigned by the same techniques as described at box 32. (Assessment Team/Expert Group).
52 (c)	Document the alternative approaches and their associated degrees of belief prior to undertaking any consequence calculations. (Assessment Team/Expert Group).
53 (c)	Select an ad hoc modelling approach, beginning with those associated with the higher degrees of belief. (Assessment Team).
54 (a)	Collect the required data. Generally these will be limited. Thus, documentation of data collection and consequence calculations is deferred to box 57.
55 (a)	Calculate consequence measures (c.f. box 47) using the selected approach. Box 57. (Assessment Team).

Table 1 (Contd.)

Box	Activity (Responsible Persons)
56 (c)	Loop on alternative approaches to ad hoc modelling. (-).
57 (a)	Document consequence measures for this variant and set of phenomena, including results for alternative interpretations of the phenomena in terms of the systems model, alternative databases for systems modelling and alternative ad hoc modelling approaches, as appropriate. Also document the degrees of belief assigned to the various interpretations, databases and ad hoc modelling approaches. (Assessment Team).
58 (c)	Loop on sets of phenomena to be considered for a particular variant. (-).
59 (c)	Loop on variants. (-).
60 (c)	Compute combined consequence measures utilising probabilities of variants, degrees of belief and measures of consequence calculated under specific assumptions and systems of belief. Formal approaches to this topic are provided in Section 2.5. (Assessment Team).
61 (c)	Document the combined consequence measures and the basis upon which they are derived. (Assessment Team).

Notes: This list is reproduced, unaltered from an unpublished report distributed to selected members of the assessment team prior to commencement of the Dry Run 3 exercise, except is so far as the degree to which each component was exercised in Dry Run 3 is indicated with the box number according to the following key (see also Section 6.1):

a - undertaken
b - undertaken to a limited degree
c - not undertaken
d - not applicable in the context of Dry Run 3

Table 1 (Contd.)

	Activity (Bq)					
Radionuclide	10^1 y	10^2 y	10^3 y	10^4 y	10^5 y	10^6 y
C-14	2.797 10^{13}	2.766 10^{13}	2.481 10^{13}	8.349 10^{12}	1.556 10^{8}	-
Cl-36	1.820 10^{10}	1.820 10^{10}	1.816 10^{10}	1.779 10^{10}	1.446 10^{10}	1.825 10^{9}
Se-79	5.409 10^{9}	5.404 10^{9}	5.352 10^{9}	4.861 10^{9}	1.856 10^{9}	1.220 10^{5}
Tc-99	5.660 10^{9}	5.658 10^{9}	5.642 10^{9}	5.479 10^{9}	4.089 10^{9}	2.194 10^{8}
Sn-126	5.420 10^{9}	5.416 10^{9}	5.383 10^{9}	5.057 10^{9}	2.710 10^{9}	5.301 10^{6}
I-129	5.400 10^{9}	5.400 10^{9}	5.400 10^{9}	5.398 10^{9}	5.376 10^{9}	5.167 10^{9}
Cs-135	5.410 10^{9}	5.410 10^{9}	5.408 10^{9}	5.394 10^{9}	5.250 10^{9}	4.004 10^{9}
Pb-210	4.181 10^{11}	9.693 10^{10}	2.242 10^{11}	4.981 10^{11}	2.350 10^{11}	8.443 10^{10}
Ra-226	6.317 10^{10}	8.138 10^{10}	2.285 10^{11}	4.980 10^{11}	2.349 10^{11}	8.443 10^{10}
Th-229	5.400 10^{11}	5.400 10^{11}	5.399 10^{11}	5.319 10^{11}	3.676 10^{11}	1.166 10^{10}
Th-230	5.400 10^{11}	5.395 10^{11}	5.352 10^{11}	4.941 10^{11}	2.306 10^{11}	8.447 10^{10}
Pa-231	5.399 10^{11}	5.389 10^{11}	5.288 10^{11}	4.382 10^{11}	7.109 10^{10}	7.119 10^{9}
U-233	5.400 10^{11}	5.398 10^{11}	5.377 10^{11}	5.172 10^{11}	3.509 10^{11}	1.131 10^{10}
U-234	5.696 10^{9}	5.860 10^{9}	6.216 10^{9}	8.369 10^{9}	2.713 10^{10}	8.673 10^{10}
U-235	7.120 10^{9}	7.120 10^{9}	7.120 10^{9}	7.121 10^{9}	7.125 10^{9}	7.119 10^{9}
U-238	9.180 10^{10}	9.180 10^{10}	9.180 10^{10}	9.180 10^{10}	9.180 10^{10}	9.179 10^{10}
Np-237	5.456 10^{9}	5.507 10^{9}	5.758 10^{9}	5.820 10^{9}	5.652 10^{9}	4.223 10^{9}
Pu-239	1.720 10^{11}	1.715 10^{11}	1.671 10^{11}	1.290 10^{11}	9.667 10^{9}	5.350 10^{-2}
Pu-242	5.590 10^{9}	5.589 10^{9}	5.580 10^{9}	5.488 10^{9}	4.651 10^{9}	8.878 10^{8}
Am-243	4.746 10^{8}	4.706 10^{8}	4.324 10^{8}	1.857 10^{8}	3.969 10^{4}	-

Table 2: LLW radionuclide inventory used in calculations in this volume

	Activity (Bq)					
Radionuclide	10^1 y	10^2 y	10^3 y	10^4 y	10^5 y	10^6 y
C-14	$4.844\ 10^{14}$	$4.792\ 10^{14}$	$4.297\ 10^{14}$	$1.446\ 10^{14}$	$2.696\ 10^{9}$	-
Cl-36	$5.830\ 10^{11}$	$5.829\ 10^{11}$	$5.817\ 10^{11}$	$5.697\ 10^{11}$	$4.632\ 10^{11}$	$5.845\ 10^{10}$
Se-79	$2.210\ 10^{12}$	$2.208\ 10^{12}$	$2.186\ 10^{12}$	$1.986\ 10^{12}$	$7.581\ 10^{11}$	$4.983\ 10^{7}$
Tc-99	$1.860\ 10^{14}$	$1.859\ 10^{14}$	$1.854\ 10^{14}$	$1.801\ 10^{14}$	$1.344\ 10^{14}$	$7.211\ 10^{12}$
Sn-126	$3.640\ 10^{12}$	$3.637\ 10^{12}$	$3.615\ 10^{12}$	$3.396\ 10^{12}$	$1.820\ 10^{12}$	$3.560\ 10^{9}$
I-129	$4.220\ 10^{11}$	$4.220\ 10^{11}$	$4.220\ 10^{11}$	$4.218\ 10^{11}$	$4.201\ 10^{11}$	$4.038\ 10^{11}$
Cs-135	$5.580\ 10^{12}$	$5.580\ 10^{12}$	$5.578\ 10^{12}$	$5.563\ 10^{12}$	$5.415\ 10^{12}$	$4.130\ 10^{12}$
Pb-210	$5.242\ 10^{11}$	$1.033\ 10^{12}$	$7.655\ 10^{11}$	$1.802\ 10^{12}$	$1.510\ 10^{13}$	$1.987\ 10^{13}$
Ra-226	$1.095\ 10^{12}$	$1.054\ 10^{12}$	$7.580\ 10^{11}$	$1.809\ 10^{12}$	$1.510\ 10^{13}$	$1.987\ 10^{13}$
Th-229	$3.529\ 10^{9}$	$4.297\ 10^{9}$	$1.822\ 10^{10}$	$6.996\ 10^{11}$	$1.397\ 10^{13}$	$3.374\ 10^{13}$
Th-230	$5.045\ 10^{9}$	$2.388\ 10^{10}$	$2.380\ 10^{11}$	$2.306\ 10^{12}$	$1.531\ 10^{13}$	$1.986\ 10^{13}$
Pa-231	$3.476\ 10^{10}$	$3.803\ 10^{10}$	$7.045\ 10^{10}$	$3.675\ 10^{11}$	$1.689\ 10^{12}$	$1.955\ 10^{12}$
U-233	$8.782\ 10^{10}$	$1.009\ 10^{11}$	$2.522\ 10^{11}$	$1.924\ 10^{12}$	$1.529\ 10^{13}$	$3.365\ 10^{13}$
U-234	$2.182\ 10^{13}$	$2.442\ 10^{13}$	$2.691\ 10^{13}$	$2.672\ 10^{13}$	$2.503\ 10^{13}$	$1.966\ 10^{13}$
U-235	$1.750\ 10^{12}$	$1.751\ 10^{12}$	$1.756\ 10^{12}$	$1.802\ 10^{12}$	$1.945\ 10^{12}$	$1.955\ 10^{12}$
U-238	$1.920\ 10^{13}$	$1.920\ 10^{13}$	$1.920\ 10^{13}$	$1.920\ 10^{13}$	$1.920\ 10^{13}$	$1.920\ 10^{13}$
Np-237	$3.256\ 10^{13}$	$3.404\ 10^{13}$	$4.151\ 10^{13}$	$4.370\ 10^{13}$	$4.245\ 10^{13}$	$3.171\ 10^{13}$
Pu-239	$6.038\ 10^{15}$	$6.023\ 10^{15}$	$5.869\ 10^{15}$	$4.534\ 10^{15}$	$3.398\ 10^{14}$	$1.881\ 10^{13}$
Pu-242	$3.410\ 10^{13}$	$3.409\ 10^{13}$	$3.404\ 10^{13}$	$3.348\ 10^{13}$	$2.837\ 10^{13}$	$5.416\ 10^{12}$
Am-243	$3.177\ 10^{13}$	$3.150\ 10^{13}$	$2.895\ 10^{13}$	$1.243\ 10^{13}$	$2.657\ 10^{9}$	-

Table 3: ILW radionuclide inventory used in calculations in this volume

Item	Description	Inc.	Comments
1.	Near-field	√	General area important
1.1	Chemical/physical degradation	√	General area important
1.1.1	Structural and container metal corrosion	√	Short-term barrier degradation; relevant to gas production
1.1.1.1	Metal corrosion: localised	x	Minutes[1]
1.1.1.2	Metal corrosion: bulk	√	See 1.1.1
1.1.1.3	Metal corrosion: crevice	x	Minutes[1]
1.1.1.4	Stress corrosion	x	Minutes[1]
1.1.2	Physical degradation of concrete	√	Short-term barrier degradation; relevant to chemical conditioning
1.1.2.1	Cracking	√	Water penetration and characteristics
1.1.2.2	Sealing of Cracks	√	As 1.1.2.1
1.1.2.3	Pore blockage	√	As 1.1.2.1
1.1.2.4	Alkali-aggregate reaction	√	Possibility of occurrence needs investigation
1.1.2.5	Cement-sulphate reaction	√	As 1.1.2.4
1.1.3	Chemical degradation of concrete	√	Major control on near-field chemistry
1.1.3.1	Changes in pore water composition, pH, Eh	√	See 1.1.3
1.1.3.2	Exchange capacity exceeded	√	Possibly not an independent item
1.1.3.3	Alkali-aggregate reaction	√	See 1.1.2.4
1.1.3.4	Cement-sulphate reaction	√	See 1.1.2.5
1.1.4	Degradation of wastes	√	Major control on source term
1.1.4.1	Metal corrosion	√	Major component
1.1.4.2	Leaching	√	Important process
1.1.4.3	Complex formation	√	Potential major control on solubility and sorption
1.1.4.4	Colloid formation	√	As 1.1.4.3
1.1.4.5	Microbial degradation of organic waste	√	Important process
1.1.4.6	Microbial corrosion	√	Potentially important modifying factor
1.1.4.7	Radiolysis	√	Probably secondary consideration
1.2	Gas production, transport and flammability	√	Major potential pathway
1.2.1	Hydrogen by metal corrosion	√	Major component
1.2.1.1	Structural steel	√	Major item
1.2.1.2	Container steel	√	Major item
1.2.1.3	Waste steel	√	Major item
1.2.1.4	Waste Magnox	√	EG(90)P4, Minutes[1], EG(90)P6, Minutes[2]

Table 4: Comprehensive list of all factors and phenomena considered

Item	Description	Inc.	Comments
1.2.1.5	Waste aluminium	x	EG(90)P4, Minutes[1], EG(90)P6, Minutes[2]
1.2.1.6	Waste Zircaloy	x	EG(90)P4
1.2.1.7	Waste other metals	x	EG(90)P4
1.2.1.8	Effects of microbial growth on concrete	√	Potentially important modifier of local chemical regime and directly relevant to gas production
1.2.2	Methane and carbon dioxide by microbial degradation	√	Major components
1.2.2.1	Cellulosics	√	Major item
1.2.2.2	Other susceptible organic materials	x	Minor source of gas, but relevant to organic complexation (item 1.1.4.3)
1.2.2.3	Aerobic degradation	√	Not important in own right, but partly defines initial conditions for anaerobic degradation, see Minutes[1], Minutes[2]
1.2.2.4	Anaerobic degradation	√	Long-term regime
1.2.2.5	Effects of temperature	√	Secondary effect modifying metabolic activity and the chemical degradation of cellulose
1.2.2.6	Effects of lithostatic pressure	x	Supplementary modifying factor (see Minutes[1]), partly determined by hydrology, finally eliminated (Minutes[2])
1.2.2.7	Effects of microbial growth on properties of concrete	x	EG(90)P4, Minutes[1]
1.2.2.8	Effects of biofilms	x	EG(90)P4
1.2.2.9	Effects of hydrogen from metal corrosion	√	Microbial utilisation
1.2.2.10	Inhibition due to the presence of toxic materials	√	Secondary factor
1.2.2.11	Carbonate/bicarbonate exchange with concrete	x	Included in transport (item 1.2.6)
1.2.2.12	Energy and nutrient control of metabolism	√	Primary control
1.2.2.13	Effects of radiation on microbial populations	x	EG(90)P4
1.2.3	Gas generation from concrete	x	EG(90)P4
1.2.4	Active gases	√	Major item
1.2.4.1	Tritiated hydrogen	√	Major component
1.2.4.2	Active methane and carbon dioxide	√	Major component
1.2.4.3	Other active gases	x	EG(90)P4, Minutes[1]
1.2.5	Toxic Gases	x	EG(90)P4, Minutes[1]
1.2.6	Transport	√	Major item

Table 4 (contd.)

Item	Description	Inc.	Comments
1.2.6.1	In the waste container	x	EG(90)P4, Minutes[1]
1.2.6.2	In the vault between containers	√	Secondary factor
1.2.6.3	Between vaults	√	Significant in pressure build-up
1.2.6.4	In the near-field, including vicinity of shafts and adits	√	Depressurisation, routes to surface
1.2.7	Flammability	x	EG(90)P4, Minutes[1]
1.3	Radiation phenomena	√	Fundamental processes
1.3.1	Radioactive decay and ingrowth	√	Fundamental processes
1.3.2	Nuclear criticality	x	EG(90)P4, Minutes[1]
1.4	Mechanical effects	√	Generally, topics in this area can be studied by detailed modelling outside the assessment proper c.f. EG(90)P2
1.4.1	Canister or container movement	√	
1.4.2	Changes in 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	√	Major control on source term
1.5.1	Changes in moisture content	√	Secondary effect at early times (but see 1.5.2.2)
1.5.1.1	Due to dewatering	√	As 1.5.1
1.5.1.2	Due to stress relief	√	As 1.5.1 (but see 1.5.2.2)
1.5.2	Groundwater flow (unsaturated)	√	As 1.5.1
1.5.2.1	Initial	√	As 1.5.1
1.5.2.2	Due to gas production	√	Could feasibly significantly extend unsaturated period
1.5.3	Groundwater flow (saturated)	√	Major control on source term
1.5.4	Transport of chemically active substances into the near-field	√	Modifiers of solubility and sorption
1.5.4.1	Inorganic ions	√	As 1.5.4
1.5.4.2	Humic and fulvic acids	√	As 1.5.4
1.5.4.3	Microbes	√	As 1.5.4 (c.f. Minutes[1], page 11)
1.5.4.4	Organic complexes	√	As 1.5.4
1.5.4.5	Colloids	√	As 1.5.4
1.6	Thermal effects	√	It was generally agreed that this main topic and all its subtopics require consideration (c.f. Minutes[1])
1.6.1	Differential elastic response	√	c.f. 1.4
1.6.2	Non-elastic response	√	c.f. 1.4
1.6.3	Fracture changes	√	c.f. 1.4

Table 4 (contd.)

Item	Description	Inc.	Comments
1.6.3.1	Aperture	√	c.f. 1.4
1.6.3.2	Length	√	c.f. 1.4
1.6.4	Hydrological changes	√	Secondary effect
1.6.4.1	Fluid pressure	√	
1.6.4.2	Density	√	Mainly a far-field concern
1.6.4.3	Viscosity	√	
1.6.5	Chemical changes	√	Thought to be the major item of 1.6 (c.f. Minutes[1])
1.6.5.1	Metal corrosion	√	Secondary effect
1.6.5.2	Concrete degradation	√	Secondary effect
1.6.5.3	Waste degradation	√	Secondary effect
1.6.5.4	Gas production	√	Secondary effect
1.6.5.5	Complex formation	√	Secondary effect
1.6.5.6	Colloid production	√	Secondary effect
1.6.5.7	Solubility	√	Primary effect (Minutes[1])
1.6.5.8	Sorption	√	Primary effect (Minutes[1])
1.6.5.9	Species equilibrium	√	Studied outside assessment to define sorption (Minutes[1])
1.6.6	Microbial effects	√	Secondary (Minutes[1])
1.6.6.1	Cellulose degradation	√	Secondary effect
1.6.6.2	Microbial activity	√	Secondary effect
1.6.6.3	Microbial product reactions	√	Secondary effect
1.7	Transport out of the repository	√	Major new entry (Minutes[1])
1.7.1	Solubility	√	Minutes[1]
1.7.2	Sorption	√	Minutes[1]
2.	Far-field	√	General area important
2.1	Extra-terrestrial	√	Secondary (Minutes[1])
2.1.1	Meteorite impact	√	Secondary (Minutes[1])
2.2	Geological	√	General area important
2.2.1	Regional tectonic	√	Marginal (compare EG(90)P4 and Minutes[1]). Not justified listing sub-items separately
2.2.2	Magmatic	x	EG(90)P4, Minutes[1]
2.2.3	Metamorphism	x	EG(90)P4, Minutes[1]
2.2.4	Diagenesis	x	EG(90)P4, Minutes[1]
2.2.5	Diapirism	x	EG(90)P4, Minutes[1]
2.2.6	Seismicity	√	Secondary
2.2.6.1	Repository induced	√	As 2.2.6
2.2.6.2	Externally induced	√	As 2.2.6
2.2.6.3	Natural	√	As 2.2.6
2.2.7	Faulting/fracturing	√	Related to 2.2.6
2.2.7.1	Activation	√	Secondary
2.2.7.2	Generation	x	Debatable with current UK levels of seismicity

Table 4 (contd.)

Item	Description	Inc.	Comments
2.2.7.3	Change of properties	√	Secondary
2.2.8	Major incision	√	Secondary (Minutes[1])
2.2.9	Weathering	√	Secondary in far-field
2.2.10	Effects of natural gases	x	Minutes[1]
2.2.11	Geothermal effects	x	Minutes[1]
2.3	Hydrological	√	General area important (Minutes[2])
2.3.1	Variation in groundwater recharge	√	Major control
2.3.2	Groundwater losses	√	Major control; includes boundary fluxes and abstractions
2.3.3	Rock property changes	√	Secondary (c.f. 2.2.6, 2.2.7 and 2.2.9)
2.3.3.1	Porosity	√	As 2.3.3
2.3.3.2	Permeability	√	As 2.3.3
2.3.3.3	Microbial pore blocking	√	Theoretical possibility
2.3.3.4	Channel formation, closure	√	Related to 2.2.6, 2.2.7, 2.2.9
2.3.4	Groundwater flow	√	Major process
2.3.4.1	Darcy flow	√	Usual basis
2.3.4.2	Non-Darcy flow	√	Minutes[1], p.10
2.3.4.3	Intergranular (matrix)	√	Secondary
2.3.4.4	Fracture	√	Especially in Chalk (Minutes[1])
2.3.4.5	Effects of solution channels	√	Secondary
2.3.4.6	Unsaturated	√	Possibly not required for geosphere (Minutes[1], p.10)
2.3.5	Salinity	x	EG(90)P4
2.3.6	Variations in groundwater temperature	x	Excluding repository induced effects (see 2.4.13)
2.4	Transport and geochemical	√	General area important
2.4.1	Advection	√	Major process
2.4.2	Diffusion	√	Major process for near-stagnant groundwater
2.4.2.1	Bulk	√	As 2.4.2
2.4.2.2	Matrix	√	Effects on retardation, secondary
2.4.2.3	Surface	x	EG(90)P4, Minutes[1]
2.4.3	Hydrodynamic dispersion	√	Major process
2.4.4	Solubility constraints	x	EG(90)P4, Minutes[1] - This was a major, debated decision, see also Minutes[2]
2.4.5	Sorption	√	Major process, all the sub-heads require consideration, though not all need necessarily be included in an assessment (Minutes[1])
2.4.5.1	Linear	√	

Table 4 (contd.)

Item	Description	Inc.	Comments
2.4.5.2	Non-linear	√	Might be omitted (Minutes[1])
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	√	Probably of much less importance than complexation (Minutes[1])
2.4.5.11	Effects of colloids formed in the near-field	√	As 2.4.5.10
2.4.5.12	Effects of major ions migrating from the near-field	√	Explore in external models and fold into assessment (Minutes[1])
2.4.5.13	Effects of microbial activity	√	Research topic (Minutes[1])
2.4.6	Fracture surface changes	√	Primarily fracture demineralisation in clay when carbonate dissolves (Minutes[2])
2.4.7	Organic colloid transport	√	See 2.4.5.10, Marginal process
2.4.7.1	Porous media	√	See 2.4.7
2.4.7.2	Fractured media	√	See 2.4.7
2.4.7.3	Effects of pH and Eh	√	See 2.4.7
2.4.7.4	Effects of ionic Strength	√	See 2.4.7
2.4.8	Inorganic colloid transport	√	Comments as for 2.4.7
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	√	Possible for starved microbes (Minutes[1], Minutes[2])
2.4.10	Isotopic exchange	√	Contribution to sorption (Minutes[1])
2.4.11	Gas transport	√	Potentially important transport pathway
2.4.11.1	Solution	√	Minutes[2]
2.4.11.2	Gas phase	√	Major process
2.4.12	Gas-induced groundwater transport	√	Potentially significant
2.4.13	Thermally induced groundwater transport	√	Potentially significant

Table 4 (contd.)

Item	Description	Inc.	Comments
2.4.13.1	Repository induced	√	Minutes[1]
2.4.13.2	Naturally induced	x	EG(90)P4, Minutes[1]
2.4.14	Biogeochemical changes	x	EG(90)P4, Minutes[1] (c.f. 2.4.5.7)
3.	Biosphere	√	General area important
3.1	Climatology	√	General area important
3.1.1	Transient greenhouse gas induced warming	√	Minutes[1]
3.1.1.1	Precipitation	√	Minutes[1]
3.1.1.2	Temperature	√	Minutes[1]
3.1.1.3	Sea level rise	x	Minutes[1]
3.1.1.4	Storm surges	x	Minutes[1]
3.1.1.5	Ecological effects	√	Minutes[1], EG(90)P6
3.1.1.6	Potential evaporation	√	Minutes[1]; derived quantity
3.1.2	Glacial/interglacial cycling	√	Minutes[1]
3.1.2.1	Precipitation	√	Minutes[1]
3.1.2.2	Temperature	√	Minutes[1]
3.1.2.3	Sea level fall	√	Rise excluded (Minutes[1]); fall not important locally (EG(90)P6)
3.1.2.4	Storm surges	x	EG(90)P4, Minutes[1]
3.1.2.5	Ecological effects	√	Minutes[1], EG(90)P6
3.1.2.6	Seasonally frozen ground	√	Minutes[1]
3.1.2.7	Permanently frozen ground	√	Minutes[1]
3.1.2.8	Glaciation	√	Minutes[1]
3.1.2.9	Deglaciation	√	Minutes[1]
3.1.2.10	Potential evaporation	√	Minutes[1]; derived quantity
3.1.3	Exit from glacial/interglacial cycling	√	Unlikely, but not excluded (EG(90)P6, Minutes[2])
3.1.3.1	Greenhouse-gas induced	√	Most likely cause
3.1.3.2	Other causes	√	Possible on 10^6 - 10^7 y timescale
3.2	Geomorphology	√	General area important
3.2.1	Generalised denudation	√	Minutes[1]
3.2.1.1	Fluvial	√	Minutes[1]
3.2.1.2	Aeolian	√	Marginal (Minutes[1])
3.2.1.3	Glacial	√	Minutes[1]
3.2.2	Localised denudation	√	Minutes[1]
3.2.2.1	Fluvial (valley incision)	√	Minutes[1], EG(90)P6
3.2.2.2	Fluvial (weathering/mass movement)	√	Minutes[1]
3.2.2.3	Glacial	√	Minutes[1]
3.2.2.4	Coastal	x	EG(90)P4, Minutes[1], EG(90)P6 Minutes[1]
3.2.3	Sediment redistribution	√	Minutes[1]
3.2.3.1	Fluvial	√	Minutes[1]
3.2.3.2	Aeolian	√	Minutes[1]

Table 4 (contd.)

Item	Description	Inc.	Comments
3.2.3.3	Glacial	√	Minutes[1]
3.2.4	Effects of sea level change	√	Marginal; effects only considerable distances downstream from site (EG(90)P6, Minutes[2])
3.2.4.1	River incision/sedimentation	√	As 3.2.4
3.2.4.2	Coastal erosion	x	As 3.2.2.4
3.3	Hydrology	√	General area important, virtually all sub-areas have to be incorporated for a coherent approach
3.3.1	Soil moisture and evaporation	√	
3.3.2	Surface hydrology	√	Includes near-surface components (renamed) (Minutes[1])
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	√	New item; various overlaps in the interpretation of all the above items
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	√	Belongs more under geomorphology
3.3.4.4	Natural lake formation/sedimentation	√	Marginal (EG(90)P6, Minutes[2])
3.3.4.5	Effects of sea level change	√	Debated significance (EG(90)P4, Minutes[1], EG(90)P6, Minutes[2])
3.3.5	Surface flow characteristics (estuarine)	√	Marginal; only if there are substantial reconcentrating processes in the estuarine environment (Minutes[1])
3.3.5.1	Tidal cycling	√	As 3.3.5
3.3.5.2	Sediment transport	√	As 3.3.5
3.3.5.3	Successional development	√	As 3.3.5 (NB. This is in relation to hydrological factors, see also item 3.4.2)
3.3.5.4	Effects of sea level change	√	As 3.3.5
3.3.6	Coastal waters	√	Marginal (Minutes[1])
3.3.6.1	Tidal mixing	√	As 3.3.6

Table 4 (contd.)

Item	Description	Inc.	Comments
3.3.6.2	Residual current mixing	√	As 3.3.6
3.3.6.3	Effects of sea level change	√	As 3.3.6
3.3.7	Ocean waters	x	EG(90)P4, Minutes[1]
3.4	Ecological development	√	General area important, included sub-items consistent with hydrology (Minutes[1])
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	√	Marginal, see 3.3.5
3.4.3	Coastal waters	√	Marginal, see 3.3.6
3.4.4	Oceans	x	
3.5	Radionuclide transport	√	General area important, sub-topics, follow assignment in previous headings
3.5.1	Erosive	√	
3.5.1.1	Fluvial	√	
3.5.1.2	Aeolian	√	
3.5.1.3	Glacial	√	
3.5.1.4	Coastal	√	Marginal (EG(90)P4, Minutes[1])
3.5.2	Groundwater discharge to soils	√	Potential major route of contamination,all components relevant
3.5.2.1	Advective	√	
3.5.2.2	Diffusive	√	
3.5.2.3	Biotic	√	
3.5.2.4	Volatilisation	√	Specific radionuclides
3.5.3	Groundwater discharge to wells or springs	√	Potential major route of contamination
3.5.4	Groundwater discharge to freshwaters	√	As 3.5.3
3.5.5	Groundwater discharge to estuaries	√	Marginal (compare EG(90)P4 and Minutes[1])
3.5.6	Groundwater discharge to coastal waters	√	Marginal (compare EG(90)P4 and Minutes[1])
3.5.7	Surface water bodies	√	Defines initial redistribution, all sub-items potentially important
3.5.7.1	Water flow	√	
3.5.7.2	Suspended sediments	√	
3.5.7.3	Bottom sediments	√	
3.5.7.4	Biogeochemical cycling	√	Generalised description

Table 4 (contd.)

Item	Description	Inc.	Comments
3.5.7.5	Effects of fluvial system development	√	
3.5.8	Estuaries	√	Marginal (compare EG(90)P4 and Minutes[1])
3.5.8.1	Water flow	√	As 3.5.8
3.5.8.2	Suspended sediments	√	As 3.5.8
3.5.8.3	Bottom sediments	√	As 3.5.8
3.5.8.4	Effects of salinity and pH variation	√	As 3.5.8; extended description
3.5.8.5	Biogeochemical cycling	√	As 3.5.8; generalised description
3.5.8.6	Effects of estuarine development	√	As 3.5.8
3.5.8.7	Effects of sea level change	√	As 3.5.8
3.5.9	Coastal waters	√	Marginal (compare EG(90)P4 and Minutes[1])
3.5.9.1	Water transport	√	As 3.5.9
3.5.9.2	Suspended sediment transport	√	As 3.5.9
3.5.9.3	Bottom sediment transport	√	As 3.5.9
3.5.9.4	Effects of sea-level change	√	As 3.5.9
3.5.9.5	Effects of estuarine development	√	As 3.5.9
3.5.9.6	Effects of coastal erosion	√	As 3.5.9
3.5.9.7	Effects of sea level change	√	As 3.5.9
3.5.10	Plants	√	Important that all items are represented either explicitly or in aggregated parameters (Minutes[1])
3.5.10.1	Root uptake	√	
3.5.10.2	Deposition on surfaces	√	
3.5.10.3	Vapour uptake	√	Specific radionuclides
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 process	√	
3.5.11	Animals	√	As 3.5.10
3.5.11.1	Uptake by ingestion	√	
3.5.11.2	Uptake by inhalation	√	Generally less important than ingestion
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	√	New area (Minutes[1])
3.6.1	Urbanisation	√	Minutes[1]
3.6.2	Management of water resources	√	Minutes[1]

Table 4 (contd.)

Item	Description	Inc.	Comments
3.6.2.1	Lake formation	√	Minutes[2]
3.6.3	Agricultural policy	√	Minutes[1]
3.6.4	Recreation policy	√	Minutes[1]
3.7	Human Exposure	√	Fundamental component, previously item 3.6, virtually all sub-items important and included in biosphere models (Minutes[1])
3.7.1	External	√	Minutes[1]
3.7.1.1	Land	√	Minutes[1]
3.7.1.2	Sediments	√	Minutes[1]
3.7.1.3	Water bodies	√	Minutes[1]
3.7.2	Ingestion	√	Minutes[1]
3.7.2.1	Drinking water	√	Minutes[1]
3.7.2.2	Agricultural crops	√	Minutes[1]
3.7.2.3	Domestic animal products	√	Minutes[1]
3.7.2.4	Wild plants	√	Marginal (Minutes[1])
3.7.2.5	Wild animals .	√	Marginal (Minutes[1], Minutes[2])
3.7.2.6	*Soils and sediments*	√	Minutes[1]
3.7.3	Inhalation	√	Minutes[1]
3.7.3.1	Soils and sediments	√	Minutes[1]
3.7.3.2	Gases and vapours (indoors)	√	Minutes[1]
3.7.3.3	Gases and vapours (outdoors)	x	Minutes[1]
3.7.3.4	Biotic material	√	Marginal (Minutes[1])
3.7.3.5	Salt particles	x	EG(90)P4, Minutes[1]
4.	Short-circuit pathways related to human activities	√	General area important
4.1	Related to repository construction	√	Minutes[1] (by inference)
4.1.1	Loss of integrity of borehole seal	√	Minutes[1] (by inference), Minutes[2]
4.1.1.1	Failure	√	Minutes[1] (by inference)
4.1.1.2	Degradation	√	Minutes[1] (by inference)
4.1.2	Loss of integrity of shaft or access tunnel seal	√	Minutes[1] (by inference), Minutes[2]
4.1.2.1	Failure	√	Minutes[1] (by inference)
4.1.2.2	Degradation	√	Minutes[1] (by inference)
4.1.3	Damage to the host medium around shafts or access tunnels	√	Minutes[2]
4.2	Post-closure	√	Minutes[1]
4.2.1	Deliberate recovery of wastes or associated materials	x	EG(90)P4, Minutes[1]
4.2.2	Malicious intrusion	x	EG(90)P4, Minutes[1]
4.2.3	Exploratory drilling	√	Minutes[1]
4.2.4	Exploitation drilling	√	Minutes[1]
4.2.5	Geothermal energy production	x	EG(90)P4, Minutes[1]

Table 4 (contd.)

Item	Description	Inc.	Comments
4.2.6	Resource mining	√	Minutes[1]
4.2.7	Tunnelling	√	Minutes[1]
4.2.8	Construction of underground storage/disposal facilities	√	Minutes[1]
4.2.9	Construction of underground dwellings/shelters	√	Minutes[1]
4.2.10	Archaeological investigations	√	Minutes[1]
4.2.11	Injection of liquid wastes	√	Minutes[1]
4.2.12	Groundwater abstraction	√	Minutes[1]
4.2.13	Underground weapons' testing	x	EG(90)P4, Minutes[1]

Notes:

Inc. = Requires consideration (i.e. would be included in a comprehensive, but not necessarily in a minimal, assessment); √ = yes, x = no

Minutes[1] = Minutes of the meeting of 26th June 1990 (Appendix A)

Minutes[2] = Minutes of the meeting of 25th September 1990 (Appendix A)

Based on EG(90)P7; Table 1, with modifications from EG(90)P8.

Table 4 (contd.)

a) Neglect metal corrosion, but include physical and chemical degradation of concrete and degradation of wastes.

Item	Description	Status
1.1.1	Structural and container metal corrosion	x
1.1.2	Physical degradation of concrete	L/M
1.1.3	Chemical degradation of concrete	H
1.1.4	Degradation of wastes	H

b) Gas generation in the repository must be included, but only selected aspects of transport in the near-field need be included explicitly.

Item	Description	Status
1.2.1	Generation of hydrogen by metal corrosion	H
1.2.2	Generation of methane and carbon dioxide by microbial degradation	H
1.2.3	Gas generation from concrete	x
1.2.4	Generation of active gases	H
1.2.5	Generation of toxic gases	x
1.2.6	Transport in the near-field, especially in the vicinity of shafts and adits	M/H
1.2.7	Flammability	x

c) Radiation phenomena must be included, but not criticality.

Item	Description	Status
1.3.1	Radioactive decay and ingrowth	H
1.3.2	Nuclear criticality	x

d) Effects of fracturing in the near-field should be included. Mechanical effects of gas production on the stress field should be studied outside the assessment. All other mechanical effects can be neglected.

Item	Description	Status
1.4.1	Canister or container movement	x
1.4.2	Changes in in situ stress field	s
1.4.3	Embrittlement	x
1.4.4	Subsidence/collapse	x
1.4.5	Rock creep	x
1.4.6	Fracturing	L/M

Table 5: Characterisation of a minimal assessment

e) Only groundwater flows in saturated conditions in the near-field should be included.

Item	Description	Status
1.5.1	Changes in moisture content	x
1.5.2	Groundwater flow (unsaturated)	x
1.5.3	Groundwater flow (saturated)	H

f) Neglect transport of chemically active substances into the near-field.

Item	Description	Status
1.5.4	Transport of chemically active substances into the near-field	x

g) Repository induced thermal effects should be included. Thermo-mechanical effects should be the subject of a supplementary geotechnical study outside the assessment. Thermal modifications of microbial effects can be neglected.

Item	Description	Status
1.6.1	Differential elastic response	s
1.6.2	Non-elastic response	s
1.6.3	Fracture changes	s
1.6.4	Hydrological changes	L
1.6.5	Chemical changes	L
1.6.6	Microbial effects	x

h) Transport out of the repository should be included, taking account of solubility constraints and sorption in the near-field.

Item	Description	Status
1.7.1	Solubility controls on transport	H
1.7.2	Sorption controls on transport	H

i) Extra-terrestrial processes can be neglected.

Item	Description	Status
2.1.1	Meteorite impact	x

Table 5 (contd.)

j) Regional tectonic effects, seismicity and the effects of faulting and fracturing should be included in supplementary studies outside the assessment. Weathering should be included, but as a component of geomorphology rather than under geology.

Item	Description	Status
2.2.1	Regional tectonics	s
2.2.2	Magmatic effects	x
2.2.3	Metamorphism	x
2.2.4	Diagenesis	x
2.2.5	Diapirism	x
2.2.6	Seismicity	s
2.2.7	Faulting/fracturing	s
2.2.8	Major incision	x
2.2.9	Weathering	moved
2.2.10	Effects of natural gases	x
2.2.11	Geothermal effects	x

k) Far-field hydrological characteristics generally need to be included.

Item	Description	Status
2.3.1	Variation in groundwater recharge	H
2.3.2	Groundwater losses	H
2.3.3	Rock property changes	M
2.3.4	Groundwater flow	H
2.3.5	Salinity effects on flow	x
2.3.6	Effects of variations in groundwater temperatures on flow	x

l) Transport should be assumed to be in aqueous form, taking speciation and complexation into account.

Item	Description	Status
2.4.1	Advective transport	H
2.4.2	Diffusive transport	H
2.4.3	Hydrodynamic dispersion	H
2.4.4	Solubility constraints	x
2.4.5	Sorption	H
2.4.6	Fracture surface changes, notably demineralisation	M
2.4.7	Organic colloid transport	M
2.4.8	Inorganic colloid transport	H

Table 5 (contd.)

Item	Description	Status
2.4.9	Transport of radionuclides bound to microbes	M
2.4.10	Isotopic exchange	x
2.4.11	Gas transport	H
2.4.12	Gas-induced groundwater transport	M/H
2.4.13	Thermally induced groundwater transport	x
2.4.14	Biogeochemical changes	x

m) Glacial/interglacial cycling should be assumed. Greenhouse gas warming giving rise to an end of such cycling is considered to be a low-probability event with huge non-radiological consequences.

Item	Description	Status
3.1.1	Transient greenhouse gas induced warming	M
3.1.2	Glacial/interglacial cycling	H
3.1.3	Exit from glacial/interglacial cycling	x

n) Geomorphological change should generally be included.

Item	Description	Status
3.2.1	Generalised denudation	H
3.2.2	Localised denudation	L
3.2.3	Sediment redistribution	M/H
3.2.4	Effects of sea-level change	x
2.2.9	Weathering	H

o) Surface hydrology should be included in a comprehensive and coherent way. Development and application of a detailed model outside the assessment would be appropriate. Estuarine and coastal water hydrology could be investigated in supplementary studies and not included directly in the assessment.

Item	Description	Status
3.3.1	Soil moisture and evaporation	H, d
3.3.2	Terrestrial near-surface hydrology	H, d
3.3.3	Groundwater recharge	H, d
3.3.4	Surface flow characteristics (freshwater)	H, d
3.3.5	Surface flow characteristics (estuarine)	s
3.3.6	Flow characteristics (coastal waters)	s
3.3.7	Flow characteristics (ocean waters)	x

Table 5 (contd.)

p) Effects of ecological development on the terrestrial surface hydrological system should be included. Effects of estuarine and coastal water ecology can be investigated in a supplementary study and not included directly in the assessment. Effects of oceanic ecology need not be considered.

Item	Description	Status
3.4.1	Effects of terrestrial ecological development on hydrology	M,d
3.4.2	Effects of estuarine ecological development on hydrology	s
3.4.3	Effects of coastal water ecological development on hydrology	s
3.4.4	Effects of oceanic ecological development on hydrology	x

q) Radionuclide transport processes in the environment should generally be included. However, groundwater discharges to estuaries and coastal waters can be ignored, while transport in estuaries and coastal waters can be treated in a supplementary study outside the assessment.

Item	Description	Status
3.5.1	Erosive transport (N.B. glacial and coastal erosion to be treated outside the assessment)	H
3.5.2	Groundwater discharge to soils	H
3.5.3/ 3.5.4 3.5.7	Groundwater discharge to wells, springs, streams, rivers and surface water bodies	H
3.5.5	Groundwater discharge to estuaries	x
3.5.6	Groundwater discharge to coastal waters	x
3.5.7	(see above)	
3.5.8	Radionuclide transport in estuaries	s
3.5.9	Radionuclide transport in coastal waters	s
3.5.10	Radionuclide uptake, retention and cycling in plants	H
3.5.11	Radionuclide uptake, retention and cycling in animals	H

r) Planning considerations, including land and water management policies, should be taken into account in determining the range of potential human influences on the disposal system.

Item	Description	Status
3.6.1	Urbanisation	M
3.6.2	Management of water resources	H
3.6.3	Agricultural policy	M
3.6.4	Recreation policy	L

Table 5 (contd.)

s) The assessment should include a comprehensive treatment of human exposure pathways.

Item	Description	Status
3.7.1	External exposure	H
3.7.2	Ingestion	H
3.7.3	Inhalation	H

t) Short-circuit pathways related to repository construction, including those associated with damage to the host media in the vicinity of boreholes, should be included.

Item	Description	Status
4.1.1	Loss of integrity of borehole seals	M
4.1.2	Loss of integrity of shaft or access tunnel seals	M
4.1.3	Damage to the host medium around shaft or access tunnels	H

u) A limited number of post-closure short-circuit pathways should be included, others could, if necessary, be covered by scoping or scaling calculations.

Item	Description	Status
4.2.1	Deliberate recovery of wastes or associated materials	x
4.2.2	Malicious intrusion	x
4.2.3	Exploratory drilling	H
4.2.4	Exploitation drilling	x, sc
4.2.5	Geothermal energy production	x
4.2.6	Resource mining	x, sc
4.2.7	Tunnelling	x, sc
4.2.8	Construction of underground storage/disposal facilities	x, sc
4.2.9	Construction of underground dwellings/shelters	x, sc
4.2.10	Archaeological investigations	x
4.2.11	Injection of liquid wastes	x
4.2.12	Groundwater abstraction	H
4.2.13	Underground weapons' testing	x

Table 5 (contd.)

Notes: x - excluded
L - low priority
M - medium priority
H - high priority
s - subject of a supplementary study outside the assessment
d - component of a detailed model of the surface hydrological system to be applied outside the assessment
sc - appropriate topic for scoping or scaling calculations

From EG(90)P7 modified to take into account the comments in EG(90)P8.

Table 5 (contd.)

Origins	Targets	Comment
1.1.3	1.7.1/1.7.2	Degradation of wastes produces substances which influence solubility and sorption, and hence transport out of the near field
1.1.4	1.2.1/1.2.2/1.2.4	Degradation of wastes is the source of gas production
1.1.4	1.7	Degradation of wastes is the source of radionuclides for transport out of the near-field, as well as leading to the formation of organic complexing agents and sorption sites
1.2.1/1.2.2/1.2.6	1.1.2	Over-pressurisation may lead to cracking of concrete. CO_2 production and sorption may also be significant
1.2.1/1.2.2/1.2.6	1.5.3	Gas production can induce or impede groundwater flow in the near-field
1.2.1/1.2.2/1.2.6	1.4.6	Gas production can lead to over-pressurisation and fracturing
1.2.1/1.2.2/1.2.4/1.2.6	1.7	Gas can migrate out of the near-field
1.3.1	1.1/2.4/3.5	Radioactive decay and ingrowth occurs primarily during residence in the near-field, transport through the far-field and transport in the biosphere
1.4.6	1.5.3	Fracturing influences groundwater flow characteristics of the near-field
1.4.6	1.2.6	Fracturing influences gas transport properties of the near-field
1.5.3	1.7	Groundwater flow in the near-field is a primary determinant of radionuclide transport out of the near-field
1.6.4	1.5.3	Thermal effects modify near-field hydrological transport

Table 6: Structural relationships incorporated in the minimal assessment

Origins	Targets	Comment
1.6.5	1.1.2/1.1.3/1.1.4	Thermal effects modify near-field chemcial degradation
1.7	2.4	Transport out of the near-field is the source term for far-field transport
1.7	4.1	Transport out of the near-field is the source term for transport via preferential pathways associated with repository construction
2.3	1.5.3	Far-field hydrology controls groundwater flow through the repository
2.3	2.4	Far-field hydrology controls far-field transport
2.3	4.1	Far-field hydrology controls transport via preferential pathways associated with repository construction
2.3	3.3.2/3.3.4	Groundwater discharge as a determinant of surface hydrology (e.g. springs, baseflow)
2.4	3.5	Far-field transport as a source of radionuclides to the biosphere
2.4	4.2.12	Far-field transport as a source of radionuclides via groundwater abstraction
2.4.11	3.7.1/3.7.3	Direct exposure to active gases
3.1	3.2.1/3.2.2/3.2.3/2.2.9	Climate as a primary determinant of denudation and weathering
3.1	3.3	Climate as a primary determinant of surface hydrology
3.1	3.4.1	Climate as a control on terrestrial ecological development

Table 6 (contd.)

Origins	Targets	Comment
3.1	3.6.2/3.6.3	Climate as a determinant of the management of water resources and of agricultural policy
3.2	2.3	Land form change modifies the boundary conditions of the far-field hydrological system, weathering alters the hydraulic properties of far-field materials
2.2.9	2.4.5/2.4.6	Weathering alters the transport properties of far-field materials
3.2	3.3	Land form change modifies the characteristics of the surface hydrological system
3.2	3.4	Land form change influences ecological development
3.2.1/3.2.2/3.2.3	3.5.1	Denudation and sediment redistribution control the erosive transport of radionuclides
3.3	2.3	Surface hydrology defines the boundary conditions for far-field hydrology
3.3.1/3.3.2/3.3.4	3.4.1	Surface hydrology constrains the types of ecosystems that can develop
3.3.2/3.3.4	3.2	Surface hydrology is a major determinant of denudation, sediment redistribution and weathering
3.3	3.5.2/3.5.3/3.5.4/3.5.7	Surface hydrology is a major determinant of radionuclide transport in the environment, both in solution and bound to sediments
3.4.1	3.2.1/3.2.2/3.2.3	Vegetation cover as a control on denudation and sediment transport
3.4.1	3.3.1/3.3.2/3.3.3	Vegetation cover as a control on surface hydrology

Table 6 (contd.)

Origins	Targets	Comment
3.4.1	3.5.10/3.5.11	Ecological development partly defines the foodchain pathways
3.5	3.7	Biosphere transport is the primary determinant of human exposure pathways, except possibly for some active gases
3.6.2	2.3.4	Management of water resources modifies groundwater flow
3.6.1/3.6.3/3.6.4	3.2.1/3.2.2/3.2.3	Land management controls denudation and sediment redistribution
3.6	3.3	All aspects of land management can influence the surface hydrological system
3.6	3.4.1	Land management and management of water resources are primary determinants of ecological development
3.6	3.5	Land management determines the type of biosphere pathways likely to occur, while management of water resources can influence the utilisation and distribution of contaminated water
3.6	3.7	Management practices partly determine behavioural characteristics and hence exposure pathways
4.1	3.5	Short-circuit pathways related to repository construction primarily provide source terms for biosphere transport
4.2	3.5	Post-closure short-circuit pathways provide source terms for biosphere transport
4.2.3	3.7	Exploratory drilling results directly in exposures of those involved in the operation or examination of the extracted material.

Table 6 (contd.)

Notes: Where secondary headings only are listed, all the tertiary headings included in Figure 1 are implied.

From EG(90)P7, modified to take account of the comments in EG(90)P8.

Table 6 (contd.)

1. Are there any factors or phenomena excluded from the minimal assessment (Figure 1) which could render estimates of peak individual risk substantially in error?

2. What are these factors and/or phenomena?

3. What are your estimates of their probability of occurrence on the following timescales.

   0 - 10^2 years post-closure
   10^2 - 10^3 years post-closure
   10^3 - 10^4 years post-closure
   10^4 - 10^5 years post-closure
   10^5 - 10^6 years post-closure

   Note that these timescales increase as a geometric progression.

4. What are your estimates of their likely separate effects on the values of peak individual risk calculated from the minimal assessment?

   Limited (less than a factor of two)
   Moderate (less than a factor of ten)
   Severe (greater than a factor of ten)
   Unquantifiable without modelling studies
   Unquantifiable even with modelling studies

5. If several factors and/or phenomena are listed under item (2), are there any interactions between their various probabilities of occurrence and/or their likely effects on the results of the assessment?

6. As described in Section 2.2, the following components were excluded from the minimal assessment to produce the reduced assessment shown in Figure 2:

Item	Description
1.6.4	Thermally induced hydrological changes in the near-field
1.6.5	Thermally induced chemical changes in the near-field
3.2.2	Localised denudation
3.6.4	Recreation policy developments

All of these are likely to occur. What is your estimate of the effects on calculated values of peak individual risk of their combined exclusion from the assessment?

Table 7: Questionnaire on assessment adequacy

Limited (less than a factor of two)
Moderate (less than a factor of ten)
Severe (greater than a factor of ten)
Unquantifiable without modelling studies

7. What were the main considerations you took into account in responding to item 6?

8. As described in Section 2.2, the following components were excluded from the minimal assessment to produce the reduced assessment shown in Figure 3:

Item	Description
1.1.2	Physical degradation of concrete
1.4.6	Fracturing in the near field
1.6.4	Thermally induced hydrological changes in the near-field
1.6.5	Thermally induced chemical changes in the near-field
2.3.3	Modification to far-field hydrology due to rock property changes
2.4.6	Fracture surface changes in the far-field, notably demineralisation
2.4.7	Organic colloid transport
2.4.9	Transport of radionuclides bound to microbes
3.1.1	Transient greenhouse gas induced warming
3.2.2	Localised denudation
3.6.4	Recreation policy developments
4.1.1	Short-circuit pathways relating to loss of integrity of borehole seals
4.1.2	Short-circuit pathways relating to loss of integrity of shaft or access tunnel seals

8a. What are your estimates of their probabilities of occurrence on the following timescales.

$0 - 10^2$ years post-closure
$10^2 - 10^3$ years post-closure
$10^3 - 10^4$ years post-closure
$10^4 - 10^5$ years post-closure
$10^5 - 10^6$ years post-closure

Note that these timescales increase as a geometric progression.

8b. What are your estimates of the effects on calculated values of peak individual risk of their combined exclusion from the assessment?

Limited (less than a factor of two)
Moderate (less than a factor of ten)
Severe (greater than a factor of ten)
Unquantifiable without modelling studies

9. What were the main considerations you took into account in responding to item 8.

Table 7 (contd.)

Component of the Minimal Assessment	Status in Dry Run 3		
	VANDAL/ TIME4	Detailed Model	Scoping Calculation
a) Near-field and waste degradation			
1.1.2 Physical degradation of concrete	x (a)	x	x
1.1.3 Chemical degradation of concrete	x (t)	x	x
1.1.4 Degradation of wastes	√	√ (b)	x
b) Gas generation and transport in the near field			
1.2.1 Generation of hydrogen by metal corrosion	x	x	√ (c) (w)
1.2.2 Generation of methane and carbon dioxide by microbial degradation	x	x	√ (c) (w)
1.2.4 Generation of active gases	x	x	√ (c)
1.2.6 Transport in the near field, especially in the vicinity of shafts and adits	x	x	√ (c)
c) Radioactive decay and ingrowth			
1.3.1 Radioactive decay and ingrowth	√ (d)	√ (d)	√ (d)
d) Near-field fracturing			
1.4.6 Fracturing	x (a)	x	x
e) Groundwater flow in the near field			
1.5.3 Groundwater flow (saturated)	√	√	x
f) Thermal effects in the near field			
1.6.4 Hydrological changes	x (u)	x	√ (w)
1.6.5 Chemical changes	x (u)	x	√ (w)
g) Transport out of the near field			
1.7.1 Solubility controls on transport	√	√ (b)	x
1.7.2 Sorption controls on transport	√	√ (b)	x

Table 8: Comparison of the minimal assessment with Dry Run 3

Component of the Minimal Assessment	Status in Dry Run 3		
	VANDAL/ TIME4	Detailed Model	Scoping Calculation
h) Far-field hydrology			
2.3.1 Variation in groundwater recharge	√	√ (e)	x
2.3.2 Groundwater losses	√	√ (e)	x
2.3.3 Rock property changes	x (f)	x	x
2.3.4 Groundwater flow	√	√ (e)	x
i) Far-field transport			
2.4.1 Advective transport	√	x (g)	x
2.4.2 Diffusive transport	√	x (g)	x
2.4.3 Hydrodynamic dispersion	√	x (g)	x
2.4.5 Sorption	√	√ (x)	x
2.4.6 Fracture surface changes, notably demineralisation	x	x	x
2.4.7 Organic colloid transport	x	x	x
2.4.8 Inorganic colloid transport	x	x	x
2.4.9 Transport of radionuclides bound to microbes	x	x	x
2.4.11 Gas transport	x	x	√ (c)
2.4.12 Gas-induced groundwater transport	x	x	√ (e)
j) Climate change			
3.1.1 Transient greenhouse gas induced warming	x	x	x (v)
3.1.2 Glacial/interglacial cycling	√ (h)	x	x
k) Geomorphological change			
3.2.1 Generalised denudation	√ (i) (m)	x	x
3.2.2 Localised denudation	x	x	√ (j)
3.2.3 Sediment redistribution	x	x	x
2.2.9 Weathering	x (k)	x (k)	x (k)
l) Surface hydrology			
3.3.1 Soil moisture and evaporation	√ (l)	x (n)	x
3.3.2 Terrestrial near-surface hydrology	√ (l)	x (n)	x

Table 8 (contd.)

Component of the Minimal Assessment	Status in Dry Run 3		
	VANDAL/ TIME4	Detailed Model	Scoping Calculation
3.3.3 Groundwater recharge	√ (l)	x (n)	x
3.3.4 Surface flow characteristics (freshwater)	√ (i) (m)	x (n)	x
m) Ecological development			
3.4.1 Effects of terrestrial ecological development on hydrology	x	x	x
n) Biosphere transport			
3.5.1 Erosive transport	√	x	√ (j)
3.5.2 Groundwater discharge to soils	√	x	x
3.5.3/ 3.5.4/ 3.5.7 Groundwater discharge to wells, springs, streams, rivers and surface water bodies	√	x	x
3.5.10 Radionuclide uptake, retention and cycling in plants	√ (o)	x	√ (p)
3.5.11 Radionuclide uptake, retention and cycling in animals	√ (o)	x	√ (p)
o) Land management practices			
3.6.1 Urbanisation	x (u)	x	x
3.6.2 Management of water resources	x (t)	x	x
3.6.3 Agricultural policy	x (q) (t)	x	x
3.6.4 Recreation policy	x (q) (t)	x	x
p) Human exposure pathways			
3.7.1 External exposure	√	x	√ (p)
3.7.2 Ingestion	√	x	√ (p)
3.7.3 Inhalation	√	x	√ (p)
q) Short circuits: repository construction			
4.1.1 Loss of integrity of borehole seals	x (t)	x	x
4.1.2 Loss of integrity of shaft or access tunnel seals	x (t)	x	x
4.1.3 Damage to host medium around shaft or access tunnels	√ (t)	√ (r)	x

Table 8 (contd.)

Component of the Minimal Assessment	Status in Dry Run 3		
	VANDAL/ TIME4	Detailed Model	Scoping Calculation
r) Post-closure short circuits			
4.2.3 Exploratory drilling	x	x	√ (s)
4.2.12 Groundwater abstraction	√ (t)	x	x

Notes: x - not included
√ - included
a - not modelled, but taken into account in choice of material properties
b - see Volume 5, Chapter 5
c - this Volume, Appendix B, Calculation Note 3
d - included throughout, wherever appropriate
e - see Volume 5, Chapter 3
f - not modelled explicitly in this study, but can be represented in the VANDAL geosphere module
g - detailed models are available and have been used in previous Dry Run exercises. However, for Dry Run 3, network representations, compatible with VANDAL/TIME4, were used throughout
h - represented in the input data to TIME4
i - represented in TIME4
j - this Volume, Appendix B, Calculation Note 2
k - deep weathering is implied in this entry
l - represented implicitly in model boundary conditions
m - represented in DECOS
n - model currently under development
o - represented in terms of observed equilibrium factors
p - this Volume, Appendix B, for non-groundwater-mediated pathways
q - only in so far as choices on these matters are reflected in the data used
r - see Volume 5, Chapter 2
s - this Volume, Appendix B, Calculation Note 4
t - generalised abstraction from the chalk was represented, but not discrete wells
u - effects could, in principle, be represented in TIME4/VANDAL
v - limited hydrological studies of "super-interglacial" conditions (Volume 5, Chapter 5)
w - see Volume 3, Chapter 6
x - see Volume 5, Chapter 5

Table 8 (contd.)

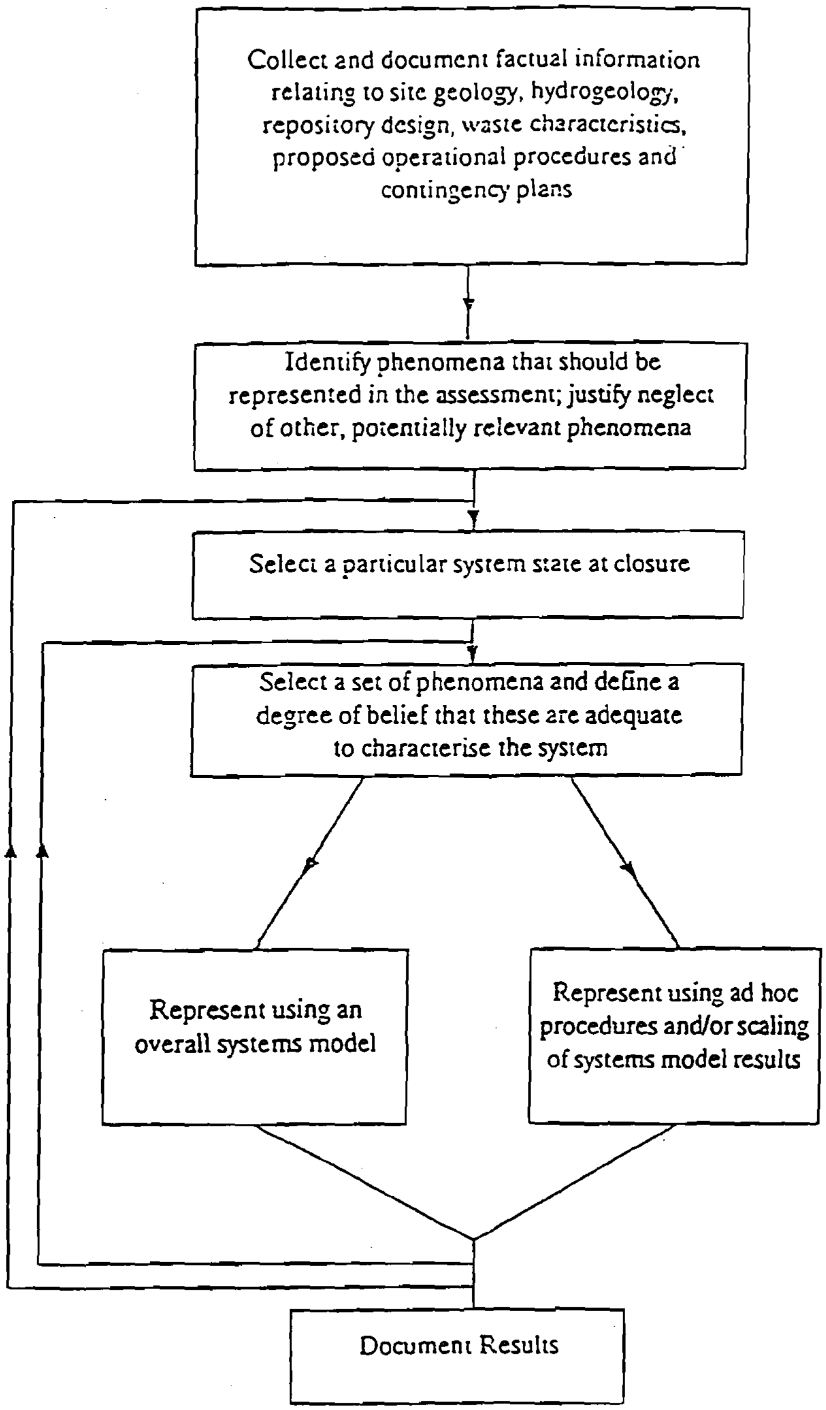


Figure 1: Outline of the assessment procedure

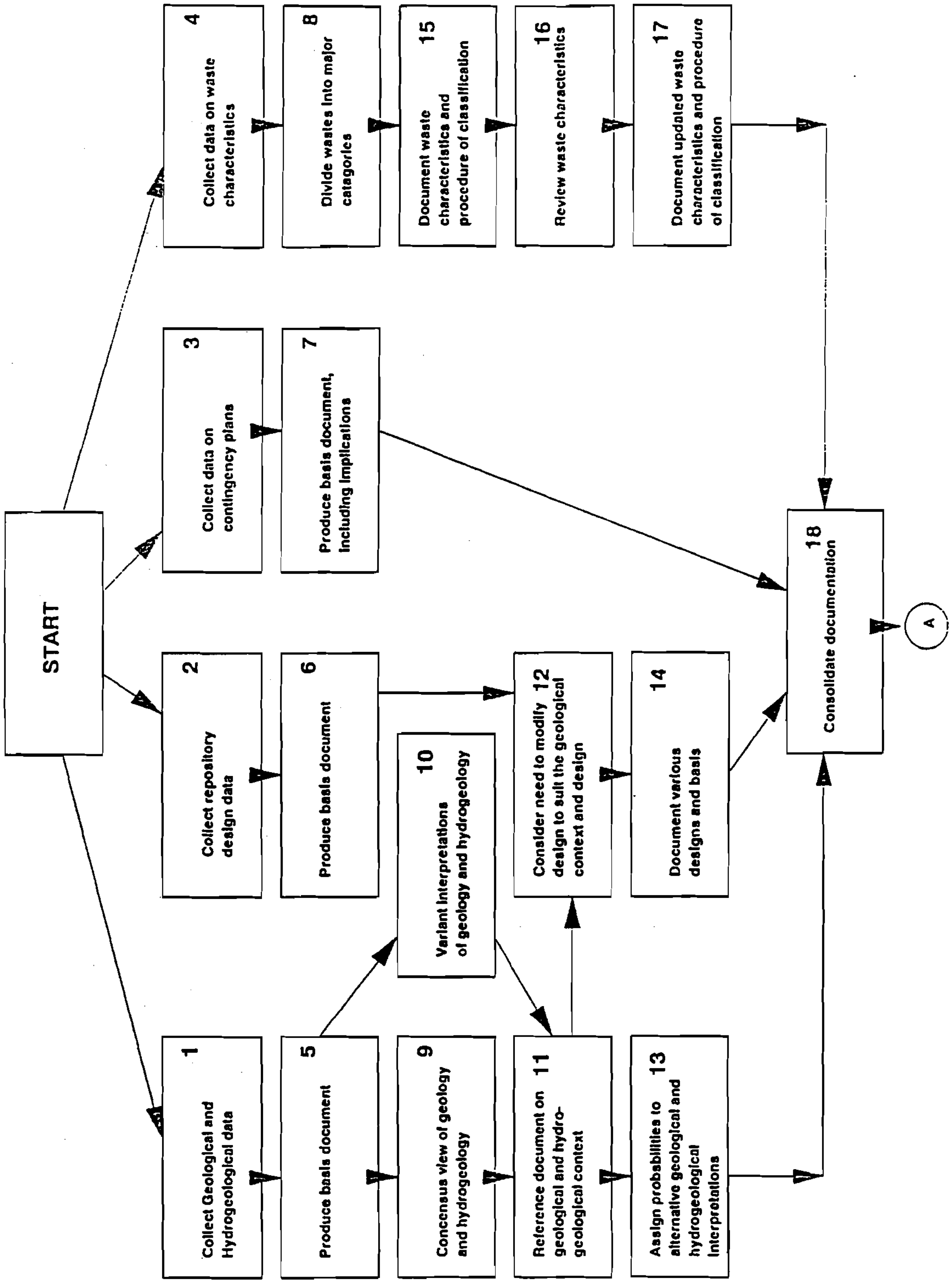


Figure 2.1: Details of the assessment procedure : 1 to 18

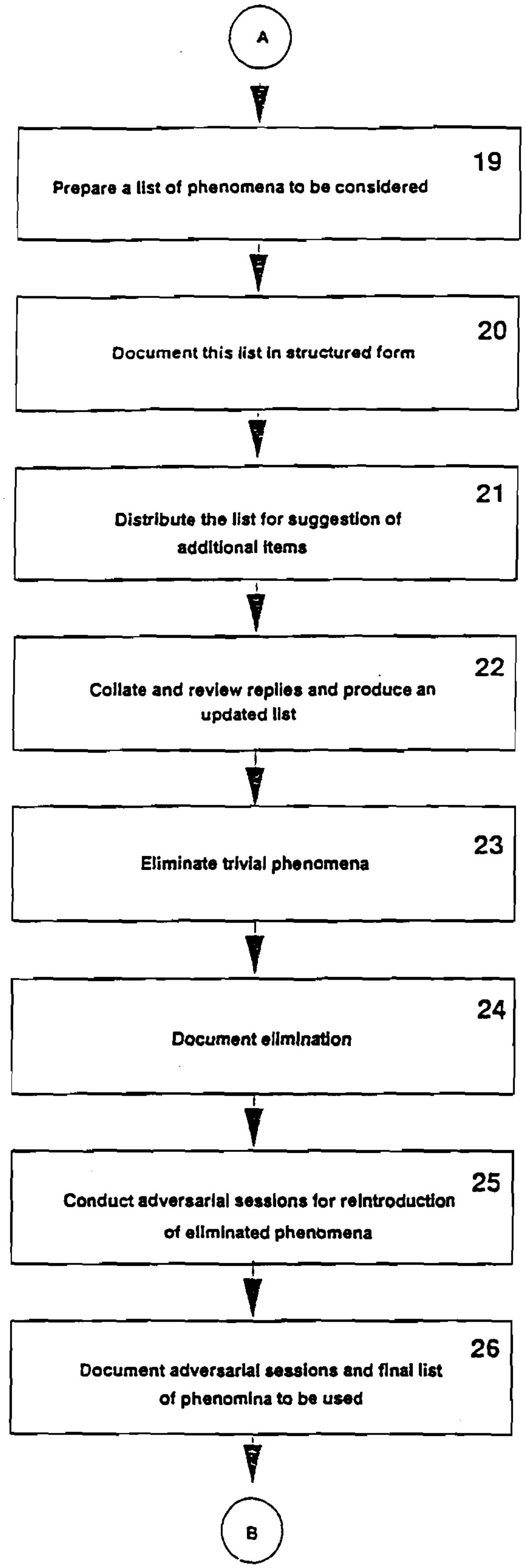


Figure 2.2: Details of the assessment procedure : 19 to 26

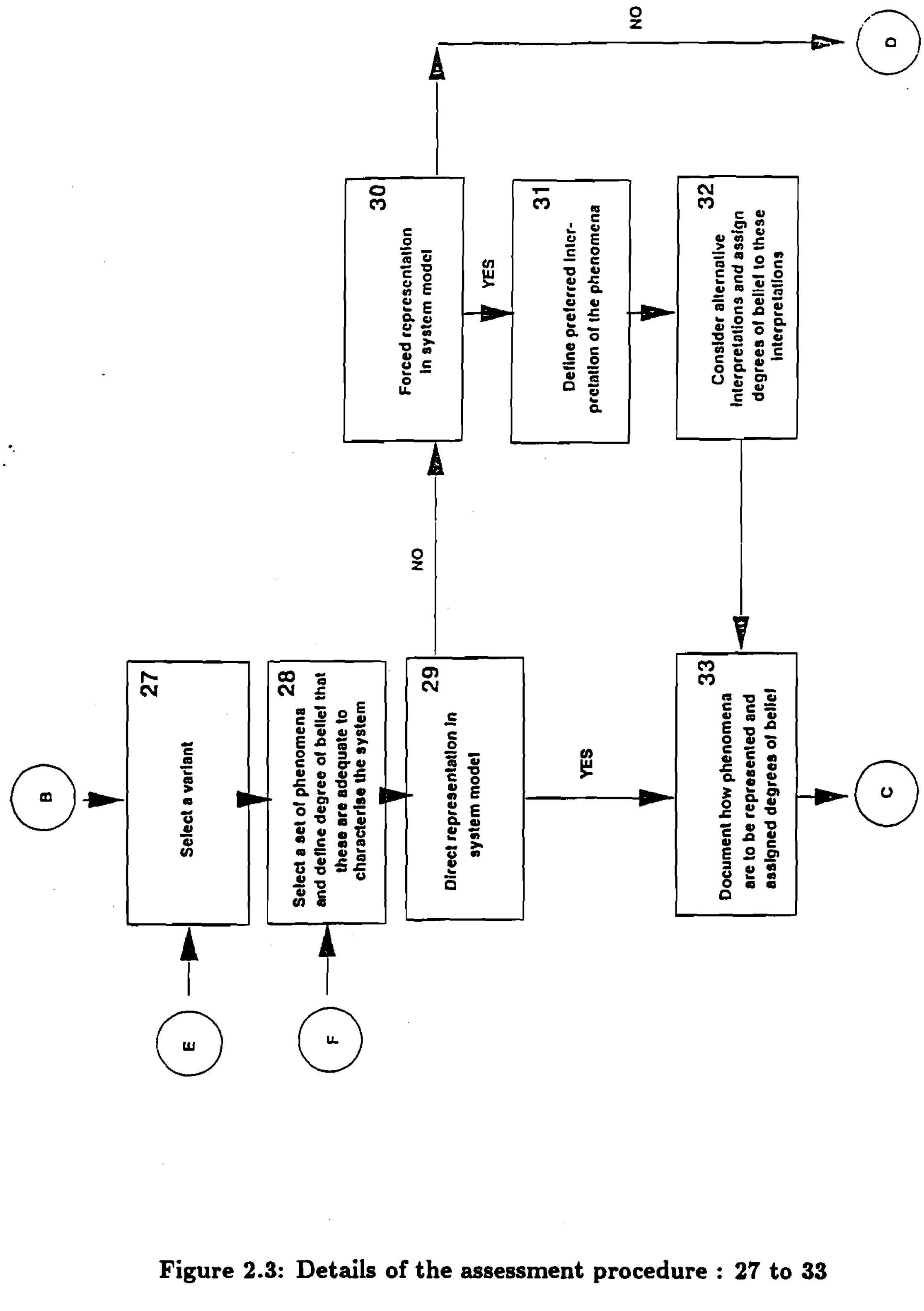


Figure 2.3: Details of the assessment procedure : 27 to 33

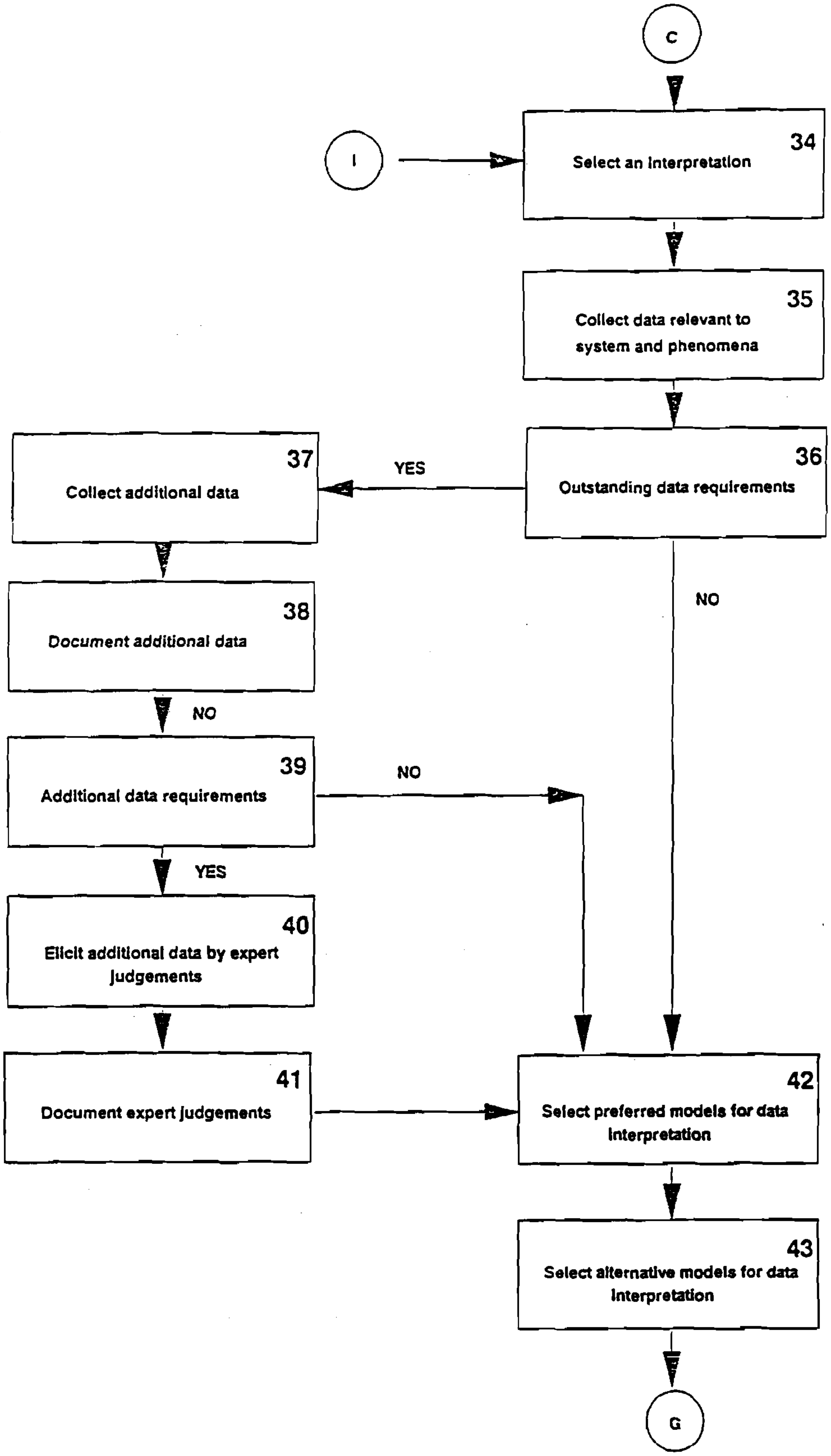


Figure 2.4: Details of the assessment procedure : 34 to 43

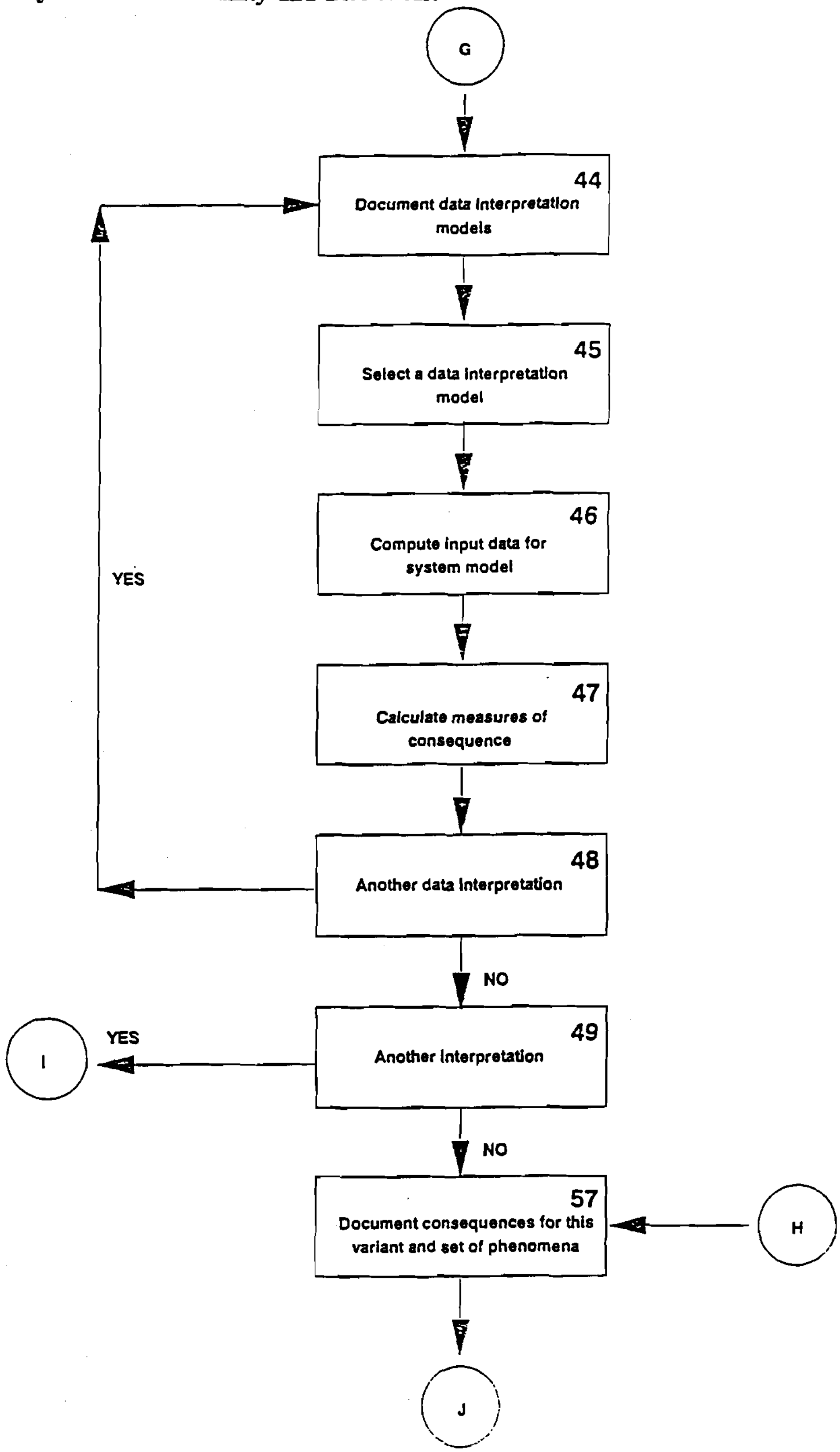


Figure 2.5: Details of the assessment procedure : 44 to 49 and 57

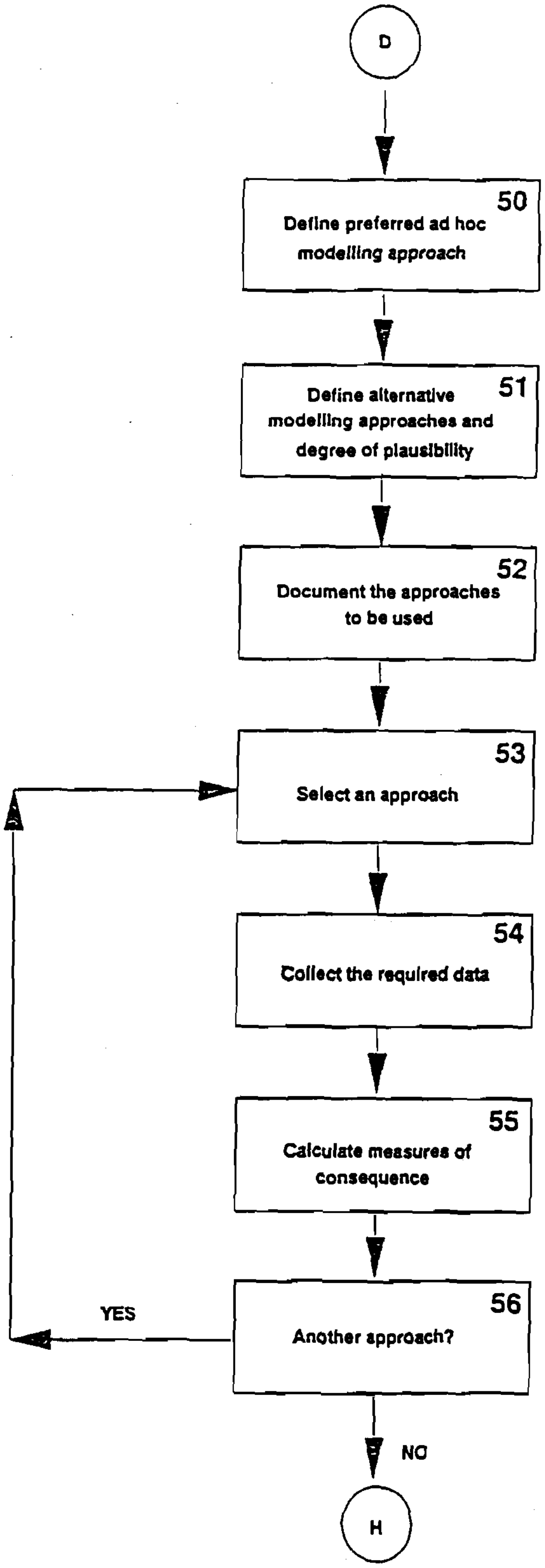


Figure 2.6: Details of the assessment procedure : 50 to 56

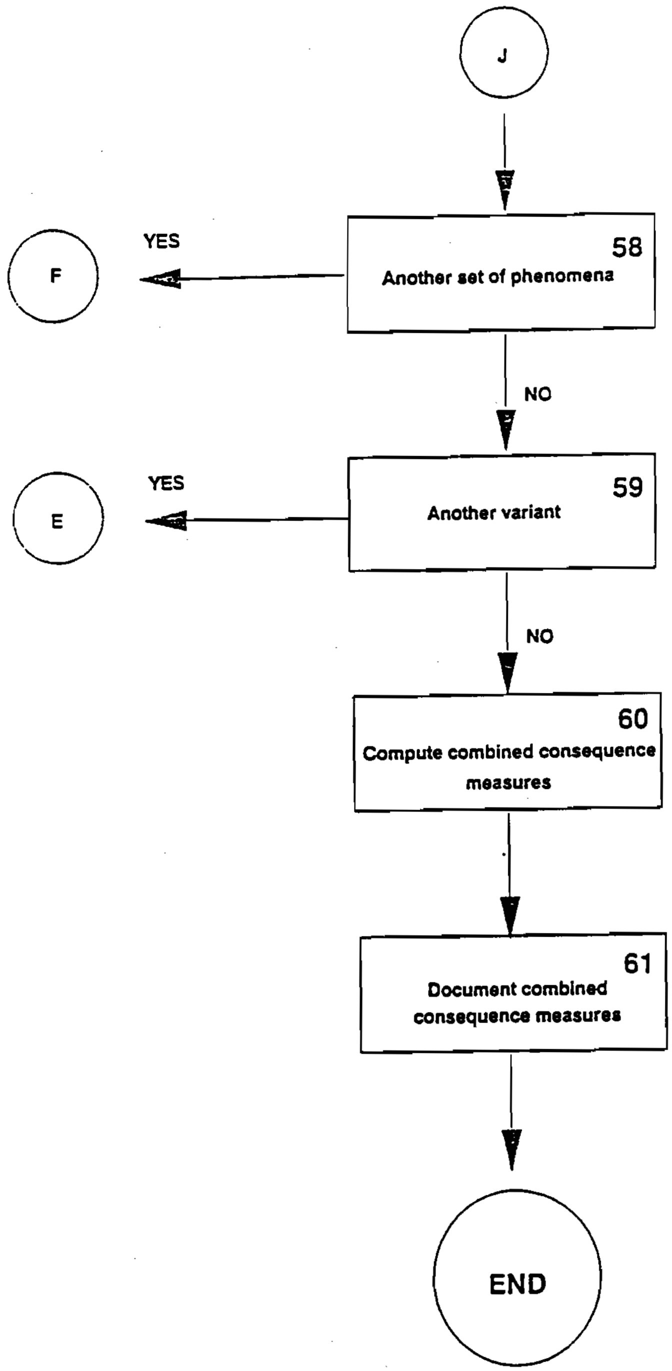


Figure 2.7: Details of the assessment procedure : 58 to 61

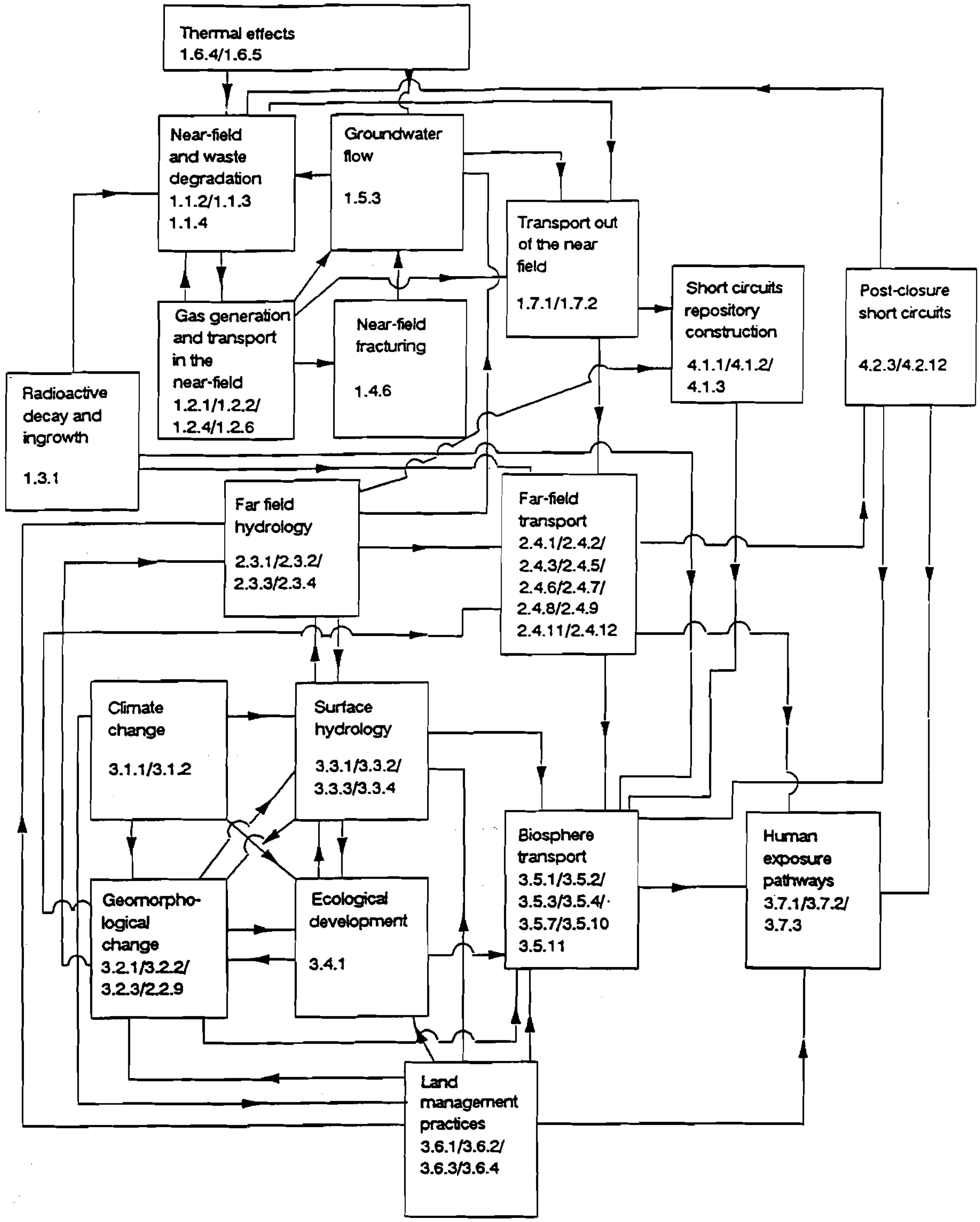


Figure 3: The minimal assessment

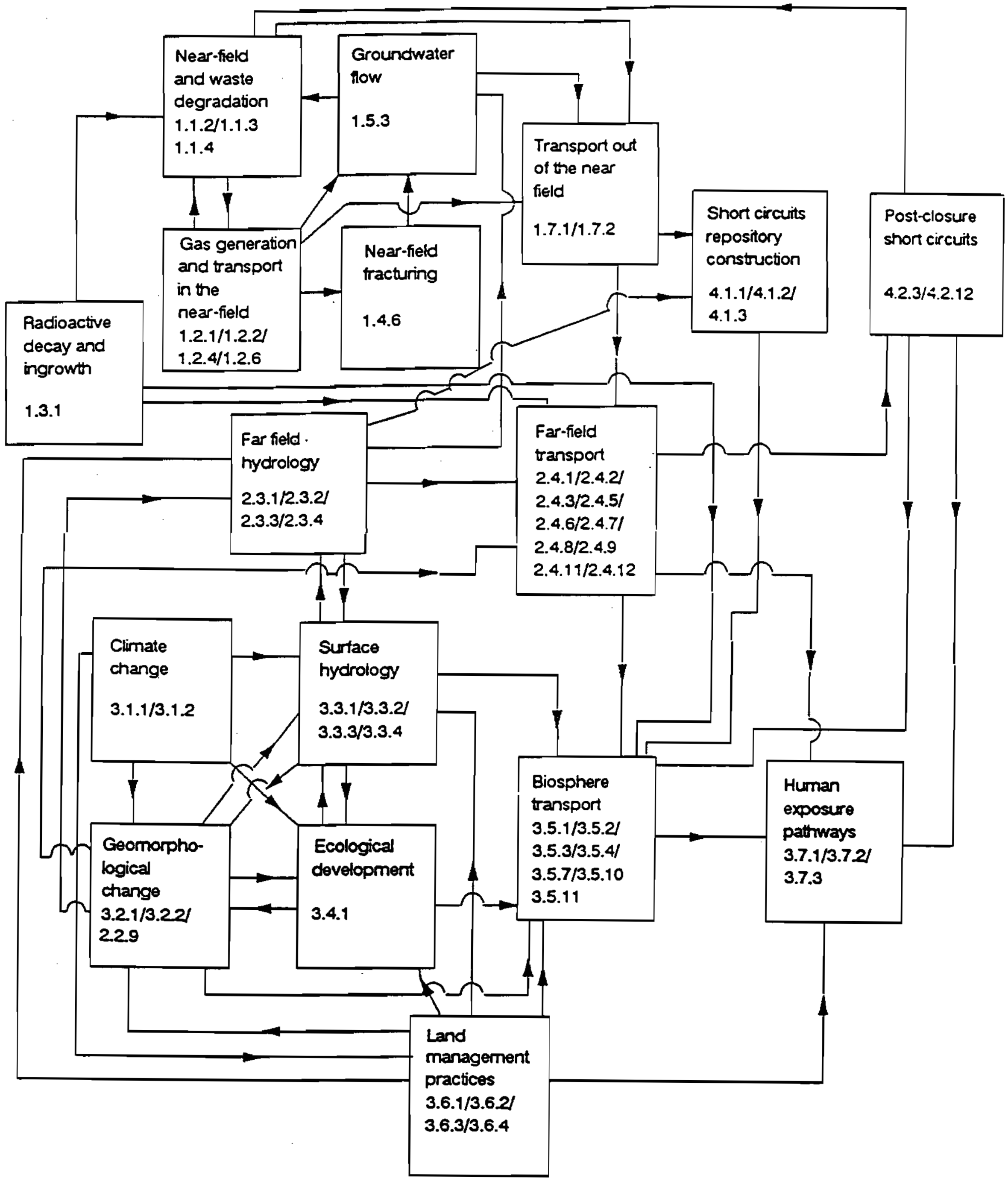


Figure 4: The minimal assessment: First level of reduction

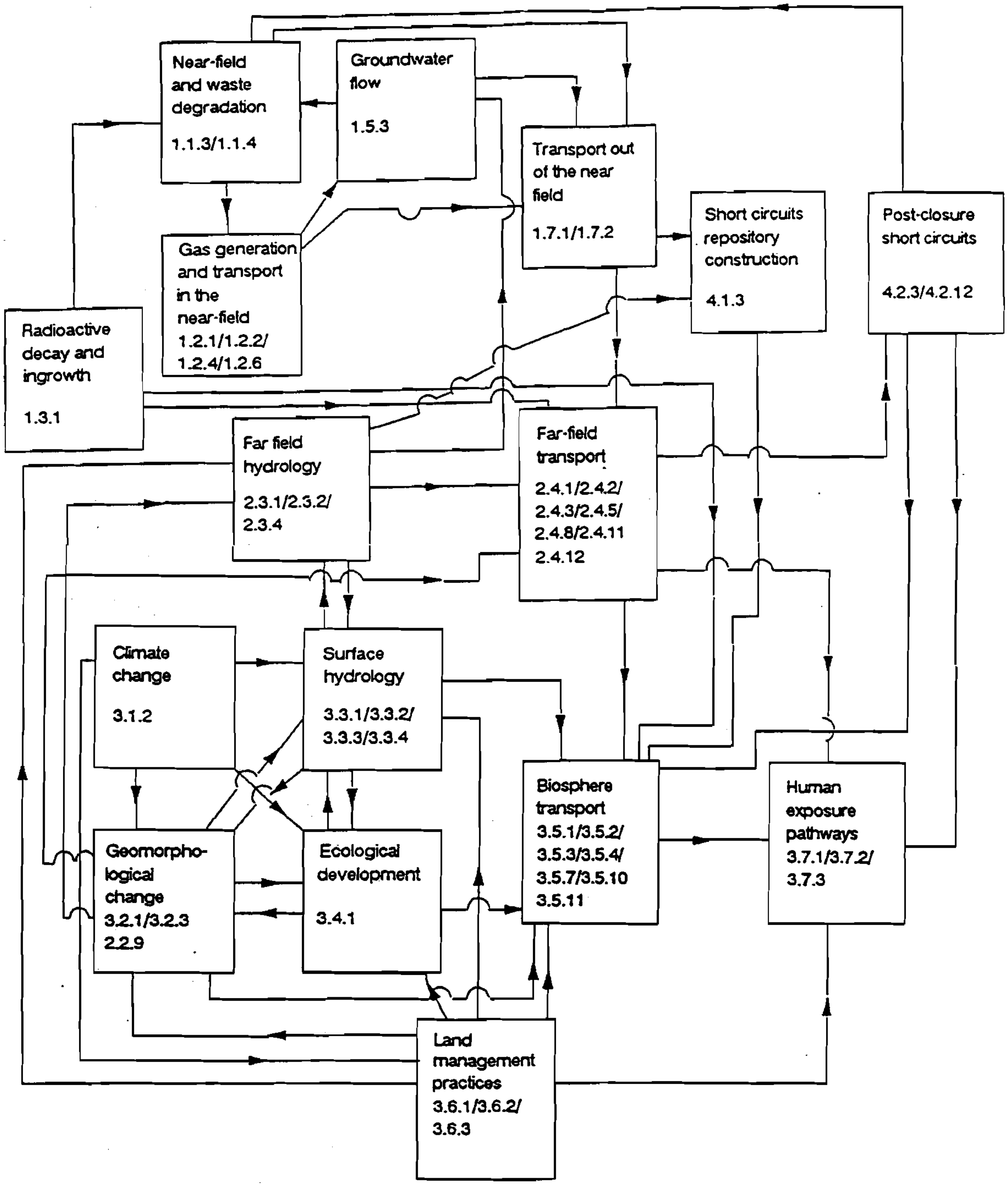


Figure 5: The minimal assessment: Second level of reduction

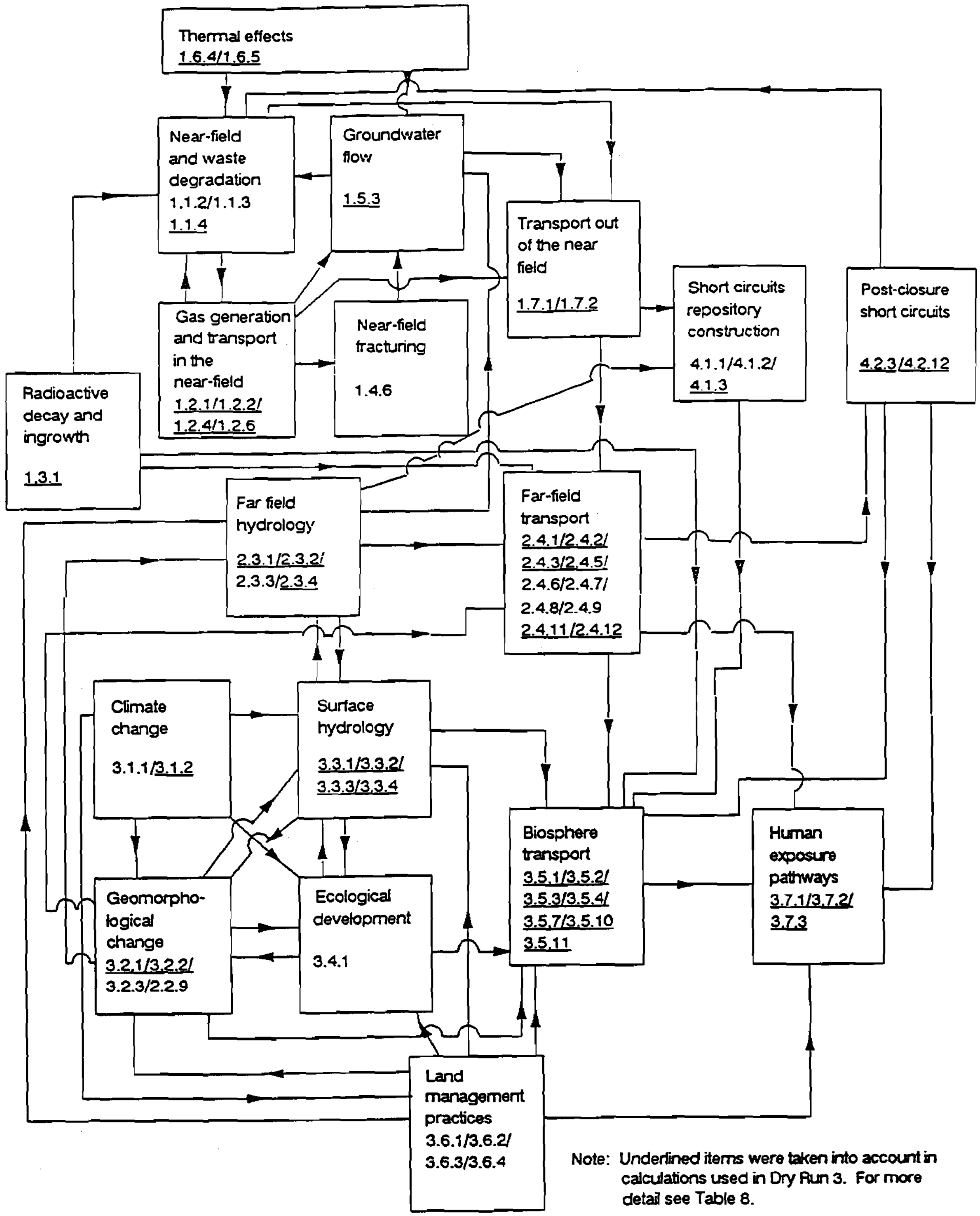


Figure 6: Comparison of the minimal assessment with Dry Run 3

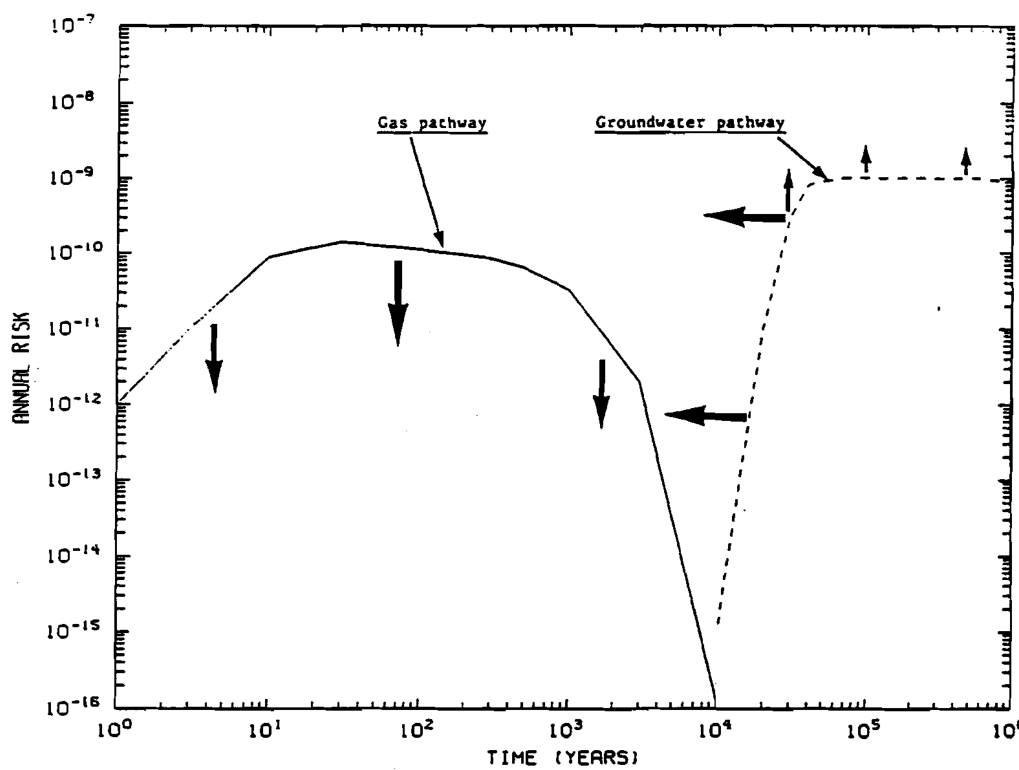


Figure 7: Schematic results for the gas and groundwater pathways treated separately

Note: An indication of the likely effects of considering interactions between pathways is given by the arrows which indicate magnitude and direction of likely changes.

Dry Run 3: Uncertainty and Bias Audit

Dry Run 3: Report History

Volume 8: Uncertainty and Bias Audit

Version, Authors, Reviewers	Date	Ref.
Volume 8, TR-DR3-8, Draft 1		
Author: M C Thorne (EWE)	Jan 91	8.33
Reviewer: T J Sumerling (Intera)	Mar 91	8.34
Comment: Substantial and detailed comments.		
Volume 8, TR-DR3-8, Draft 2		
Author: M C Thorne (EWE)	May 91	8.37
Comment: Draft volume accepted.		
Volume 8, TR-DR3-8, Draft 3		
Author: M C Thorne (EWE)	Feb 92	2.63
Comment: Version takes account of review/comments above and includes editorial changes taking limited account of SNL review/comments (see TR-DR3-11) and is submitted as draft final report.		
Approved by HMIP as DoE/HMIP/RR/92.040.	May 92	2.74
Volume 8, TR-DR3-8, Edition 1, Final		
Comment: This document.	Aug 92	-

Notes

Ref.	= Dry Run 3 file reference
DoE	= Department of the Environment
EWE	= Electrowatt Engineering Services Ltd
HMIP	= Her Majesty's Inspectorate of Pollution
Intera	= Intera Information Technologies
SNL	= Sandia National Laboratories

This report has been prepared by Intera Information Technologies for Her Majesty's Inspectorate of Pollution of the Department of the Environment (DoE) under the terms of DoE Contract Reference PECD 7/9/497.

The above is an accurate record of the preparation and quality assurance of this report.

Trevor Sumerling .... Date 24 August 1992

T J Sumerling
Intera Information Technologies

Department of the Environment:

HMIP-Commissioned Research

Report Title:

Dry Run 3
A Trial Assessment of Underground Disposal of Radioactive Wastes Based on Probabilistic Risk Analysis
Volume 8:
Uncertainty and Bias Audit (Appendices)

DOE Report No: DoE/HMIP/RR/92.040

Contract Title: Analysis of Uncertainties in Risk Estimation

DOE Reference: PECD 7/9/445 **Sector No:** 3.4

Contractor's Reference: Electrowatt Project 2636

Author/Affiliations etc: M C Thorne
Electrowatt Engineering Services (UK) Ltd

Date of submission to DOE: February 1992

Period covered by the report 1989-1991

Abstract (100-200 words as desired):

Development of an overall procedure for incorporating an uncertainty and bias audit into post-closure radiological assessments is an on-going component of the UK DoE programme. Dry Run 3 has provided a convenient opportunity to test certain aspects of the methodology. In particular:

- an Expert Group has been utilised to advise on factors/phenomena that should be included in a comprehensive assessment and to determine priorities for modelling;
- scoping calculations have been carried out to provide illustrative results, which have been used to demonstrate the potential biases inherent in the trial assessment;
- expert judgements have been used to assess the status of Dry Run 3 relative to a minimal assessment.

Department of the Environment:

HMIP-Commissioned Research

Report Title:

Dry Run 3
A Trial Assessment of Underground Disposal of Radioactive Wastes Based on Probabilistic Risk Analysis
Volume 8:
Uncertainty and Bias Audit (Appendices)

DOE Report No: DoE/HMIP/RR/92.040

Contract Title: Analysis of Uncertainties in Risk Estimation

DOE Reference: PECD 7/9/445 **Sector No:** 3.4

Contractor's Reference: Electrowatt Project 2636

Author/Affiliations etc: M C Thorne
Electrowatt Engineering Services (UK) Ltd

Date of submission to DOE: February 1992

Period covered by the report 1989-1991

Abstract (100-200 words as desired):

Development of an overall procedure for incorporating an uncertainty and bias audit into post-closure radiological assessments is an on-going component of the UK DoE programme. Dry Run 3 has provided a convenient opportunity to test certain aspects of the methodology. In particular:

- an Expert Group has been utilised to advise on factors/phenomena that should be included in a comprehensive assessment and to determine priorities for modelling;
- scoping calculations have been carried out to provide illustrative results, which have been used to demonstrate the potential biases inherent in the trial assessment;
- expert judgements have been used to assess the status of Dry Run 3 relative to a minimal assessment.

APPENDIX A
Documentation Relating to the Expert Group

Dry Run 3: Uncertainty and Bias Audit

APPENDIX A

DOCUMENTATION RELATING TO THE EXPERT GROUP

A1 INTRODUCTION

This appendix includes a complete record of all material issued to the expert group, except in the case of document EG(90)P1. In this case, the background information on the hypothetical site is not reproduced.

EG(90)P1

HMIP Expert Group on Post-Closure Radiological Assessment

Information Pack

1) Membership List
2) Background Information on the Hypothetical Site
3) Briefing Note 1

M C Thorne

January 1990

HMIP Expert Group on Post-Closure Radiological Protection

Membership:

Professor K M Clayton
School of Environmental Sciences
University of East Anglia
Norwich NR4 7TJ

Dr T D Davies
Climatic Research Unit
School of Environmental Sciences
University of East Anglia
Norwich NR4 7TJ

Professor F P Glasser
Department of Chemistry
University of Aberdeen
Meaton Walk
Old Aberdeen AB9 2UE

Ms J Higgo
British Geological Survey
Nicker Hill
Keyworth
Nottingham RG12 5GG

Dr A D Horrill
Institute of Terrestrial Ecology
Merlewood Research Station
Grange-over-Sands
Cumbria LA11 6JU

Professor J Knill
Natural Environment Research Council
Polaris House
North Star Avenue
Swindon
Wiltshire SN2 1DU

Dr G P Marsh
Harwell Laboratory
Building 393
UKAEA
Oxfordshire OX11 ORA

Professor M L Parry
Atmospheric Impacts Research Group
Department of Geography
University of Birmingham
PO Box 363
Birmingham B15 2TT

Dr J H Rees
Harwell Laboratory
Chemistry Division
Building 220
UKAEA
Oxfordshire OX11 ORA

Mr E Tufton
Ove Arup & Partners
13 Fitzroy Street
London W1P 6BA

Dr J West
British Geological Survey
Nicker Hill
Keyworth
Nottingham RG12 5GG

Dr H S Wheater
Imperial College
Department of Civil Engineering
Prince Consort Road
London SW7 2BU

Secretariat:

Dr M C Thorne
Electrowatt Engineering Services (UK) Ltd
Grandford House
16 Carfax
Horsham
West Sussex RH12 1UP

Correspondence should be copied for information to:

Dr B G J Thompson
Her Majesty's Inspectorate of Pollution
Room A5.33
Romney House
43 Marsham Street
London SW1P 3PY

Mr T J Sumerling
INTERA-ECL
Chiltern House
45 Station Road
Henley-on-Thames
Oxfordshire RG9 1AT

HMIP Expert Group on Post-Closure Radiological Assessment

Briefing Note 1

1. INTRODUCTION

The work of the Expert Group is to be seen in the context of the current trial assessment of the post-closure radiological safety of a deep geological repository for low and intermediate level radioactive wastes being undertaken by Her Majesty's Inspectorate of Pollution (HMIP) and its contractors. This trial assessment is the third in a series and is known as Dry Run 3 (DR3).

The objectives of DR3 can be summarised as follows.

a) To perform a demonstration assessment of time-dependent probabilistic risk assessment (pra), emphasising those aspects not covered by Dry Runs 1 and 2.

b) To provide a reliable estimate of resources and information required for full implementation of the time-dependent pra methodology.

c) To demonstrate an audit of bias throughout a risk assessment.

d) To rehearse a presentation of the time-dependent pra procedure.

e) To publish a technical and scientifically based report for wide review.

The primary objective is to practice and demonstrate a fully time-dependent probabilistic risk assessment.

Published reports on Dry Runs 1 and 2 are available [1, 2].

In undertaking an assessment, it is important to ensure, as far as possible, that all relevant factors and phenomena are taken into account, and that these factors and phenomena are appropriately represented in the assessment models used.

Expert judgments will be used to:

- draw up lists of factors/phenomena to be taken into account;
- select sub-sets of factors/phenomena to be modelled;
- decide on approaches to modelling;
- assign degrees of belief in the adequacy of the various modelling approaches adopted;
- estimate parameter values and ranges for use in the models.

The Expert Group will be involved in all these activities, but, in the first instance, will concentrate on drawing up a list of factors/phenomena to be taken into account.

In this note, Section 2 provides initial suggestions for factors/phenomena which require consideration and Section 3 gives guidance on the approach by which members of the Expert Group should provide information regarding factors/phenomena to be taken into account.

This briefing note is supplemented by a compilation of factual information on the hypothetical site and by a membership list. Communication between group members, with the secretariat and with other interested parties is encouraged.

2. INITIAL LIST OF FACTORS/PHENOMENA

Members of HMIP's Assessment Team have drawn up an initial list of factors/phenomena to be considered. For convenience, this list, which is shown in Table 1, has been structured as follows.

1. Factors/phenomena relating primarily to the engineered structure of the repository and surrounding disturbed zone.

2. Factors/phenomena relating primarily to the solid geological context of the repository. This distinguishes:

    2.1 Extra-terrestrial effects that could change the geological context or result in transfer of waste materials to the accessible environment;

    2.2 Geological processes that could change the context;

    2.3 Hydrological processes which determine the characteristics of the groundwater flow system;

    2.4 Factors/phenomena determining or modifying radionuclide transport in the geosphere.

3. Factors/phenomena relating primarily to the biosphere, which is effectively all parts of the environment other than the local geological context of the repository, e.g. it includes regions such as deep ocean sediments. Here, a subdivision has been made between factors/phenomena affecting the context in which radionuclide transport takes place (3.1 - climate; 3.2 - geomorphology; 3.3 - surface and near-surface hydrology; 3.4 - ecological development), those which affect radionuclide transport directly (Section 3.5) and those which determine the magnitude of human exposures given a particular contaminated environment (Section 3.6).

4. Factors/phenomena related to human activities which result in by-passing or degradation of one or more of the barriers to radionuclide transport to the accessible environment. These are distinguished into those related to repository construction (Section 4.1), though they may cause relevant changes at a later time, and those which are initiated subsequent to closure of the repository (Section 4.2).

It is emphasised that there is currently no cut-off to the period post-closure for which radiological assessments have to be undertaken. Studies covering 10^6 - 10^7 years post-closure are typical, while studies extending to 10^8 years, or even longer, have been undertaken. This is why long-term geological, climatological and geomorphological processes are included in the initial table.

It is also emphasised that any tabulation imposes an artificial structure on the real world and that relevant factors/phenomena may exist which do not fit comfortably into the structure used herein. Members of the Expert Group should not feel constrained in their suggestions by the structure of the table, nor should they worry overmuch as to how additional factors/processes should be included in the table, since it may be necessary for the Assessment Team to revise the structure in the light of replies received. However, it should be noted that there is an attempt at structure in the table, with the following levels.

- general area (barrier or barrier by-pass);
- broad scientific area (e.g. climatology, hydrology);
- topic within a scientific area, i.e. the type of subject one might hold a conference to discuss;
- specific factor/phenomenon.

It would be convenient, for restructuring purposes, if members of the Expert Group could indicate the level of their additions to the table.

At this stage, factors/phenomena should not be excluded on the grounds of negligible impact or low probability. Screening to reduce the revised list and eliminate trivia will take place at a later stage.

3. GUIDANCE

It is suggested that each expert should undertake the following:

a) Review the general headings in Table 1 to see if any item has been omitted, then repeat the procedure at each lower level of indexing.

b) Where specific factors/phenomena are not listed at the lowest order, he should give consideration to the specific factors/phenomena that should be listed.

c) Identify factors/phenomena that should be considered, but which do not fall naturally within the framework provided.

d) Prepare a brief note listing the additional factors/phenomena to be included, their position in the table (if appropriate) and a brief note as to why each factor or phenomenon requires consideration. This note should be sent to:

Dr M C Thorne
Electrowatt Engineering Services (UK) Ltd
Grandford House
16 Carfax
Horsham
RH12 1UP

Collated responses will be distributed to group members and other interested parties by the secretariat. A response by 9th February 1990 would be appreciated.

1. <u>Near-field</u>

1.1 Chemical/Physical Degradation
1.1.1 Structural and container metal corrosion
1.1.1.1 Pitting
1.1.1.2 Bulk
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
1.1.3 Chemical degradation of concrete
1.1.3.1 Changes in pore water composition, pH, Eh
1.1.3.2 Exchange capacity exceeded
1.1.4 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
1.1.4.6 Radiolysis

1.2 Gas Production and Transport
1.2.1 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
1.2.1.6 Waste other metals
1.2.2 Microbial degradation
1.2.2.1 Cellulosics
1.2.2.2 Plastics
1.2.2.3 Other organic materials
1.2.2.4 Aerobic degradation
1.2.2.5 Anaerobic degradation
1.2.2.6 Effects of temperature
1.2.2.7 Effects of lithostatic pressure
1.2.2.8 Effects of microbial growth on concrete
1.2.2.9 Effects of hydrogen from metal corrosion
1.2.2.10 Carbonate/bicarbonate exchange with concrete
1.2.2.11 Inhibition
1.2.2.12 Nutritional control of metabolism
1.2.3 Transport
1.2.3.1 In compacted wastes
1.2.3.2 In the waste container
1.2.3.3 In individual vaults
1.2.3.4 Between vaults
1.2.3.5 Up and around access shafts and adits

TABLE 1
Initial List of Phenomena to be Taken into Consideration

1.3 Radiation Phenomena
- 1.3.1 Radioactive decay and ingrowth
- 1.3.2 Nuclear criticality

1.4 Mechanical Effects
- 1.4.1 Canister or container movement
- 1.4.2 Changes in in situ stress field
- 1.4.3 Embrittlement
- 1.4.4 Subsidence/collapse
- 1.4.5 Rock creep
- 1.4.6 Fracturing

1.5 Hydrological Effects
- 1.5.1 Undersaturation
- 1.5.2 Groundwater flow
- 1.5.3 Transport of chemically active substances into the near-field
  - 1.5.3.1 Inorganic ions
  - 1.5.3.2 Humic and fulvic acids
  - 1.5.3.3 Microbes
  - 1.5.3.4 Organic complexes
  - 1.5.3.5 Colloids

1.6 Thermal Effects
- 1.6.1 Differential elastic response
- 1.6.2 Non-elastic response
- 1.6.3 Fracture aperture changes
- 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

TABLE 1 (Cont.)

2. Far-field

- 2.1 Extra-terrestrial
  - 2.1.1 Meteorite impact

- 2.2 Geological
  - 2.2.1 Tectonic
    - 2.2.1.1 Uplift
    - 2.2.1.2 Subsidence
    - 2.2.1.3 Flexure
  - 2.2.2 Magmatic
    - 2.2.2.1 Intrusive
    - 2.2.2.2 Extrusive
  - 2.2.3 Metamorphosis
  - 2.2.4 Diagenesis
  - 2.2.5 Diapirism
  - 2.2.6 Seismicity
    - 2.2.6.1 Repository-induced
    - 2.2.6.2 Natural
  - 2.2.7 Faulting/fracturing
    - 2.2.7.1 Activation
    - 2.2.7.2 Generation
    - 2.2.7.3 Change of properties

- 2.3 Hydrological
  - 2.3.1 Variation in infiltration and evaporation
  - 2.3.2 Water table variations
  - 2.3.3 Rock property changes
    - 2.3.3.1 Porosity
    - 2.3.3.2 Permeability
  - 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 Channelled
    - 2.3.4.6 Undersaturated
  - 2.3.5 Salinity
    - 2.3.5.1 Saline intrusion
    - 2.3.5.2 Freshwater intrusion
    - 2.3.5.3 Effects at the saline-freshwater interface
- 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
  - 2.4.3 Hydrodynamic dispersion

TABLE 1 (Cont.)

- 2.4.4 Solubility constraints
    - 2.4.4.1 Naturally-occurring complexing agents
    - 2.4.4.2 Complexing agents formed in the near-field
    - 2.4.4.3 Naturally-occurring colloids
    - 2.4.4.4 Colloids formed in the near-field
    - 2.4.4.5 Major ions migrating from the near-field
- 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 naturally-occurring complexing agents
    - 2.4.5.6 Effects of complexing agents formed in the near-field
    - 2.4.5.7 Effects of naturally-occurring colloids
    - 2.4.5.8 Effects of colloids formed in the near-field
    - 2.4.5.9 Effects of major ions migrating from the near-field
- 2.4.6 Fracture mineralisation
- 2.4.7 Colloid transport
    - 2.4.7.1 Porous media
    - 2.4.7.2 Fractured media
- 2.4.8 Isotopic dilution
- 2.4.9 Gas Transport
    - 2.4.9.1 Solution
    - 2.4.9.2 Gas phase
- 2.4.10 Gas-induced groundwater transport
- 2.4.11 Thermally induced groundwater transport

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
        - 3.1.1.4 Storm surges
        - 3.1.1.5 Ecological effects
    - 3.1.2 Glacial/interglacial cycling
        - 3.1.2.1 Precipitation
        - 3.1.2.2 Temperature
        - 3.1.2.3 Sea level changes (rise/fall)
        - 3.1.2.4 Storm surges
        - 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
    - 3.1.3 Exit from glacial/interglacial cycling
        - 3.1.3.1 Greenhouse gas induced
        - 3.1.3.2 Other causes

TABLE 1 (Cont.)

- 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
    - 3.2.2.2 Glacial
    - 3.2.2.3 Coastal
  - 3.2.3 Sediment redistribution
    - 3.2.3.1 Fluvial
    - 3.2.3.2 Aeolian
    - 3.2.3.3 Glacial

- 3.3 Hydrology
  - 3.3.1 Infiltration/groundwater recharge
  - 3.3.2 Runoff
  - 3.3.3 Interflow
  - 3.3.4 Perched water tables
  - 3.3.5 Surface flow characteristics (freshwater)
    - 3.3.5.1 Stream/river flow
    - 3.3.5.2 Meander migration
    - 3.3.5.3 Sediment transport
    - 3.3.5.4 Lake formation/sedimentation
  - 3.3.6 Surface flow characteristics (estuarine)
    - 3.3.6.1 Tidal cycling
    - 3.3.6.2 Sediment transport
    - 3.3.6.3 Successional development
  - 3.3.7 Coastal waters
    - 3.3.7.1 Tidal mixing
    - 3.3.7.2 Residual current mixing
    - 3.3.7.3 Effects of sea level change
  - 3.3.8 Ocean waters
    - 3.3.8.1 Water exchange
    - 3.3.8.2 Effects of sea level change

- 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

- 3.5 Radionuclide transport
  - 3.5.1 Erosive
    - 3.5.1.1 Fluvial
    - 3.5.1.2 Aeolian

TABLE 1 (Cont.)

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
3.5.4 Surface water bodies
3.5.4.1 Runoff
3.5.4.2 Streams
3.5.4.3 Rivers
3.5.4.4 Lakes
3.5.5 Estuaries
3.5.5.1 Water flow
3.5.5.2 Suspended sediments
3.5.5.3 Bottom sediments
3.5.5.4 Effects of salinity variation
3.5.5.5 Effects of estuarine development
3.5.6 Coastal waters
3.5.6.1 Water transport
3.5.6.2 Suspended sediment transport
3.5.6.3 Bottom sediment transport
3.5.6.4 Effects of sea level change
3.5.6.5 Effects of estuarine development
3.5.6.6 Effects of coastal erosion
3.5.7 Plants
3.5.7.1 Root uptake
3.5.7.2 Deposition on surfaces
3.5.7.3 Vapour uptake
3.5.7.4 Internal translocation and retention
3.5.7.5 Washoff
3.5.7.6 Leaf-fall and senescence
3.5.7.7 Organic cycling
3.5.8 Animals
3.5.8.1 Uptake by ingestion
3.5.8.2 Uptake by inhalation
3.5.8.3 Internal translocation and retention
3.5.8.4 Organic cycling

3.6 Human Exposure
3.6.1 External
3.6.1.1 Land
3.6.1.2 Sediments
3.6.1.3 Water bodies
3.6.2 Ingestion
3.6.2.1 Drinking water
3.6.2.2 Agricultural crops
3.6.2.3 Domestic animal products

TABLE 1 (Cont.)

3.6.2.4 Wild plants
3.6.2.5 Wild animals
3.6.2.6 Soils and sediments

3.6.3 Inhalation

3.6.3.1 Soils and sediments
3.6.3.2 Gases and vapours
3.6.3.3 Biotic material
3.6.3.4 Salt particles

4. <u>Short-Circuit Pathways Related to Human Activities</u>

4.1 Related to repository construction

4.1.1 Investigation borehole seal

4.1.1.1 Failure
4.1.1.2 Degradation

4.1.2 Shaft or access tunnel seal

4.1.2.1 Failure
4.1.2.2 Degradation

4.1.3 Subsidence

4.1.3.1 Fault/fracture induction

4.2 Post-closure

4.2.1 Deliberate recovery of wastes or associated materials
4.2.2 Malicious intrusion
4.2.3 Exploratory drilling
4.2.4 Exploitation drilling
4.2.5 Geothermal energy production
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 Undergound weapons testing

TABLE 1 (Cont.)

HMIP Expert Group on Post-Closure Radiological Assessment: Briefing Note 2

M C Thorne

Electrowatt Engineering Services (UK) Ltd
Grandford House
16 Carfax
Horsham
West Sussex
RH12 1UP

April 1990

1. INTRODUCTION

This briefing note covers changes to the composition of the Expert Group and provides a basis for the second stage of the Group's deliberations. The hiatus since Stage 1 reflects unavoidable delays in responses from some members of the group, due to sickness and overseas engagements, and some more culpable delays by the secretariat in interpreting and synthesising the replies received.

2. COMPOSITION OF THE GROUP

Dr G P Marsh informed the secretariat, on 13th February 1990, that he had agreed to take up a new post at Harwell which takes him out of the corrosion field. He nominated Dr C C Naish as a potential successor on the Expert Group, and this was agreed on 14th February 1990. His full address is:

Dr C C Naish
Corrosion Technology Group
Materials Development Division
B393 Harwell Laboratory
UKAEA
Oxfordshire
OX11 ORA

Also, Dr J H Rees has notified the secretariat that, from 2nd April 1990, he will be based at the Culham Office of AEA Safety and Reliability. His full address is:

Dr J H Rees
AEA Safety and Reliability
Building E6/116
Culham Laboratory
Abingdon
Oxfordshire
OX14 3DB

His telephone extension is 3286 and his FAX number 3682.

3. TECHNICAL WORK FOR STAGE 2

During Stage 1, an attempt was made to synthesise a comprehensive list of factors/phenomena that might be taken into account in post-closure radiological assessments of deep geological repositories for radioactive wastes. An initial list of factors/phenomena was submitted to the Expert Group for consideration. This list was updated by the secretariat in the light of the replies received and the revised list, which forms the basis for the rest of the study is included herein as Table 1.

In Stage 1, there was no attempt to exclude factors/phenomena on the grounds of negligible impact or low probability. In Stage 2, such exclusion will be attempted. Indeed, the requirements in Stage 2 are as follows.

a) To identify those factors/phenomena that should be excluded from consideration on the grounds of negligible impact.

b) To identify those factors which will undoubtedly be of significance in post-closure radiological assessments, or which will have to be included in order to evaluate their significance.

c) To identify groups of factors/phenomena that could be considered together in the assessment process, because of similarities in their implications.

In order for members of the Expert Group to make an appropriate response on the above topic, it is considered that some additional guidance may be helpful. However, this should be considered as an aid to thinking rather than a constraint.

i) The timescale for the assessment should be taken as 10^6 years. Within this, it would be helpful if members of the Expert Group could indicate:

- the timescales over which individual factors/phenomena may occur;
- the duration of the associated events/processes.

Thus, for example, item 2.1.1 could occur at any time over the next 10^6 years, but the associated event (meteorite impact) has a duration of much less than one year.

ii) The duration of events or processes should not be confused with the duration of their effects. Evaluation of the magnitude and duration of effects is a part of the assessment procedure.

iii) The assessment is concerned only with the radiological consequences of deep geological disposal subsequent to the closure of the facility. Thus, for example, the radiological implications of releases of radioactive effluents during operation are excluded from consideration, as are the potential impacts of releases of non-radioactive toxic substances subsequent to closure.

iv) Members of the Expert Group may find it convenient to think in terms of the following general pathways of radionuclide release and transport.

  - Mediated by dissolution in the aqueous phase of near-field porewaters, with subsequent transport to the biosphere dissolved in groundwaters;

- Mediated by transport in the gas phase in the near-field, with dissolution in groundwaters in the far-field;

- Mediated by transport in the gas phase in both the near-field and the far-field;

- Human intrusions into the near-field or into the plume of activity in the far-field;

- Natural disruptive events and processes transferring activity from the near-field to the biosphere.

v) Members of the Expert Group may also find it convenient to distinguish between transport processes and factors/phenomena which control those transport processes. Submission of hierarchies or influence diagrams is encouraged. For example, variations in groundwater recharge (item 2.3.1) might be considered as influencing groundwater flow (item 2.3.4), which could, in turn, influence advection (item 2.4.1), hydrodynamic dispersion (item 2.4.3) and fracture mineralisation (item 2.4.6).

vi) An attempt should be made to distinguish major controls on transport processes from minor influences.

vii) Where a factor/phenomenon is identified as being suitable for exclusion from consideration, or conversely is identified as having to be included in assessment studies, a brief justification should be provided.

viii) Members of the Expert Group may wish to operate at different levels of generality. For example, they may wish to discuss the significance of climate in a broad sense (item 3.1) or may wish to discuss separately the significance of storm surges in the particular contexts where they occur (items 3.1.1.4 and 3.1.2.4).

ix) All these deliberations should be conducted in the context of the Harwell site and in the light of the information provided with document EG(90)P1.

x) Members of the Expert Group should not feel constrained to comment on factors/phenomena outside their own immediate field of expertise. However, nor should they feel precluded from so commenting.

As a stimulus to thought, the secretariat has provided some views on the items in Table 1. These are included as Appendix A. Members of the Expert Group may wish to defer consideration of this material until they have formed their own initial views on the various factors/phenomena listed in Table 1.

A response to this note by 30th April 1990 would be appreciated.

1. Near-field

1.1 Chemical/Physical Degradation
- 1.1.1 Structural and container metal corrosion
  - 1.1.1.1 Localised
  - 1.1.1.2 Bulk
  - 1.1.1.3 Crevice
  - 1.1.1.4 Stress corrosion cracking
- 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
  - 1.2.1.6 Waste Zircaloy
  - 1.2.1.7 Waste other metals
  - 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
  - 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
  - 1.2.2.7 Effects of microbial growth on properties of concrete
  - 1.2.2.8 Effects of biofilms

TABLE 1

Final List of Factors and Phenomena to be Considered

- 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 with concrete
- 1.2.2.12 Energy and nutrient control of metabolism
- 1.2.2.13 Effects of radiation on microbial populations

1.2.3 Gas generation from concrete
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

1.2.5 Toxic gases
1.2.6 Transport
- 1.2.6.1 In the waste container
- 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
- 1.2.7.1 Fires
- 1.2.7.2 Explosions

1.3 Radiation Phenomena
- 1.3.1 Radioactive decay and ingrowth
- 1.3.2 Nuclear criticality

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

TABLE 1 (Cont.)

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

2. <u>Far-field</u>

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
  - 2.2.2.1 Intrusive
  - 2.2.2.2 Extrusive
  - 2.2.2.3 Hydrothermal
- 2.2.3 Metamorphism
  - 2.2.3.1 Contact
  - 2.2.3.2 Regional
  - 2.2.3.3 Dislocation
- 2.2.4 Diagenesis
- 2.2.5 Diapirism
- 2.2.6 Seismicity

TABLE 1 (Cont.)

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
2.2.7.3 Change of properties
2.2.8 Major incision
2.2.9 Weathering
2.2.10 Effects of natural gases
2.2.11 Geothermal effects
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 Permeability
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
2.3.5.1 Effects of differences in salinity
2.3.5.2 Effects at the saline-freshwater interface
2.3.5.3 Implications of evaporite deposits/minerals
2.3.6 Variations in groundwater temperature

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
2.4.3 Hydrodynamic dispersion
2.4.4 Solubility constraints
2.4.4.1 Effects of pH and Eh
2.4.4.2 Effects of ionic strength
2.4.4.3 Naturally-occurring complexing agents
2.4.4.4 Complexing agents formed in the near-field
2.4.4.5 Naturally-occurring colloids
2.4.4.6 Colloids formed in the near-field
2.4.4.7 Major ions migrating from the near-field
2.4.4.8 Effects of microbial activity

TABLE 1 (Cont.)

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 mineralisation
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 dilution
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
2.4.14 Biogeochemical changes

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
3.1.1.4 Storm surges
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

TABLE 1 (Cont.)

- 3.1.2.3 Sea level changes (rise/fall)
- 3.1.2.4 Storm surges
- 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
- 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

3.3 Hydrology
- 3.3.1 Soil moisture and evaporation
- 3.3.2 Near-surface runoff processes
  - 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
- 3.3.3 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 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

TABLE 1 (Cont.)

- 3.3.5.3 Successional 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
- 3.3.7.1 Water exchange
- 3.3.7.2 Effects of sea level change

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

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 Effects of vegetation
- 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 variation
- 3.5.8.5 Effects of vegetation
- 3.5.8.6 Effects of estuarine development
- 3.5.8.7 Effects of sea-level change

TABLE 1 (Cont.)

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 Human Exposure

3.6.1 External
- 3.6.1.1 Land
- 3.6.1.2 Sediments
- 3.6.1.3 Water bodies

3.6.2 Ingestion
- 3.6.2.1 Drinking water
- 3.6.2.2 Agricultural crops
- 3.6.2.3 Domestic animal products
- 3.6.2.4 Wild plants
- 3.6.2.5 Wild animals
- 3.6.2.6 Soils and sediments

3.6.3 Inhalation
- 3.6.3.1 Soils and sediments
- 3.6.3.2 Gases and vapours (indoor)
- 3.6.3.3 Gases and vapours (outdoor)
- 3.6.3.4 Biotic material
- 3.6.3.5 Salt particles

4. <u>Short-Circuit Pathways Related to Human Activities</u>

4.1 Related to repository construction

4.1.1 Investigation borehole seal
- 4.1.1.1 Failure
- 4.1.1.2 Degradation

4.1.2 Shaft or access tunnel seal

TABLE 1 (Cont.)

4.1.2.1 Failure
4.1.2.2 Degradation
4.1.3 Subsidence
4.1.3.1 Fault/fracture induction

4.2 Post-closure
4.2.1 Deliberate recovery of wastes or associated materials
4.2.2 Malicious intrusion
4.2.3 Exploratory drilling
4.2.4 Exploitation drilling
4.2.5 Geothermal energy production
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

TABLE 1 (Cont.)

APPENDIX A

COMMENTS BY THE SECRETARIAT ON FACTORS/PHENOMENA TO BE CONSIDERED

Comments are listed by item number from Table 1.

1.1.1 Structural and container metal corrosion

Implications for gas production are addressed under item 1.2. So the main consideration here is the physical integrity of the containers. Because physical integrity cannot be guaranteed for more than a few hundred years, safety cases are likely to be influenced only marginally by how these processes are represented. It may be sufficient to aggregate all the underlying processes into a single measure of the accessibility of the wastes to near-field pore waters. Alternatively, it may be appropriate to neglect physical containment and assume ready access of pore waters from the time of closure. Use of vented containers, or compaction of low level waste drums, with breaching of their physical integrity, might also encourage this approach.

1.1.2 Physical degradation of concrete

Intact structural concretes can have a very low hydraulic conductivity. Thus, tunnel liners might be the limiting factor in controlling the moisture content of the repository (item 1.5.1) and in determining groundwater flow in unsaturated conditions (item 1.5.2). However, day joints and other localised features may be of greater importance initially. Backfill materials may be designed to enhance hydraulic conductivities, to ensure that chemical controls on solubility and sorption (items 1.6.5.7 and 1.6.5.8) are optimised. Modelling of the physical degradation of concrete may be more important for determining the characteristics of surfaces present in the long-term than for determining initial changes in hydraulic conductivity. However, the early release and transport of gases (item 1.2.6) may be strongly conditioned by these changes in physical properties.

1.1.3 Chemical degradation of concrete

This is regarded as being of major importance in determining the temporal evolution of the properties of the near-field and hence of controls on solubility and sorption (items 1.6.5.7 and 1.6.5.8). Some assessment models assume a well-mixed 'soup' of materials in the near-field, but this is difficult to justify and a more comprehensive approach is probably required if influential biases are to be avoided.

1.1.4 Degradation of wastes

The degradation of wastes is strongly linked with gas production (items 1.2.1, 1.2.2 and 1.2.4). It partly determines radionuclide concentrations in the near-field, which are controlled by solubility and sorption constraints (items 1.6.5.7 and 1.6.5.8), but, in turn, it influences those constraints by the production of complexes and colloids (items 1.1.4.3 and 1.1.4.4). Organic wastes form a suitable substrate for microbial growth, which has a wide variety of implications (items 1.1.4.5, 1.1.4.6, 1.2.1.8, 1.2.2). Mechanistic modelling of waste degradation would seem to be an important component of radiological assessment studies.

1.2 Gas production, transport and flammability

Representation of gas production and transport is now regarded as an essential component of post-closure radiological safety assessments. Both corrosion and microbial degradation need to be considered. There has generally been a presumption that gases will be produced in bulk and will have to be removed from the near-field. This is not proven, nor are the likely evolution rates well established. Thus, it is reasonable to direct attention to the modelling of gas evolution rates, since very low rates would minimise the significance of this pathway and associated factors/phenomena (e.g. item 1.5.2.2). Low rates of gas production could imply low rates of microbial activity. This could be advantageous (low rates of build-up of organic products which enhance solubility/sorption) or disadvantageous (low rates of degradation of such complexes).

Because of the very different rates of corrosion of different metals, the division of item 1.2.1 into sub-components appears to be required. It is an open question whether Magnox and aluminium components might be completely corroded prior to repository closure.

It is likely that metal corrosion and microbial degradation should be studied in a detailed mechanistic model and that the outputs from such a model should be used to condition the assessment approach.

It is not clear that gas generation from concrete (item 1.2.3) is of significance relative to the other gas production processes.

The potential radiological impact of active gases should undoubtedly be considered in assessments. However, H-3 may virtually completely decay prior to release to the biosphere. Thus, more attention should be directed to C-14, I-129 and Sn-126 labelled gases, notably methylated forms. [C-14]O_2 is likely to react strongly with cementitious materials in the near-field and may, therefore, be of limited significance.

Because of their short half-lives, Rn-222 and Rn-220 will only be of significance in the context of uranium, thorium and radium having migrated from the repository to the near-surface environment.

The toxicity of gases (item 1.2.5) is irrelevant to radiological assessment studies, though of interest in its own right.

It is possible that the repository could be engineered to ensure ready transport of gas through and out of the structure. However, limited dissolution in the far-field and a low relative permeability of argillaceous formations could lead to substantial over-pressurisation effects. Thus, transport phenomena (item 1.2.6) need to be considered in some detail.

Flammability (item 1.2.7) could influence the physical integrity of the near-field and its chemical properties. It is potentially of importance during repository operation or shortly after closure, when substantial amounts of oxygen are present. It is, therefore, unlikely to be a problem for more than 50 - 100 years post-closure. Flammability at the surface is a hazard in its own right, but this is irrelevant to radiological assessment studies.

However, burning of gases at the surface is one form of chemical transformation which could change their radiotoxicity. This is likely to be of minor significance compared with the transforming effects of biogeochemical processes in the far-field and in the biosphere (e.g. in soils and sediments).

1.3 Radiation phenomena

Radioactive decay and ingrowth (item 1.3.1) need to be included in all components of the assessment models. Virtually all uranium disposed is likely to be U_{nat} or tails-depleted, so criticality (item 1.3.2) should not be a problem. Similarly, other fissile material should be present only at low concentrations. Overall, risks of criticality should be minimal, given appropriate operational controls on the materials disposed.

1.4 Mechanical effects

These probably need to be studied in detailed models to derive inputs to models for physical degradation of the repository environment (item 1.1.2). Of the items listed, 1.4.4 appears to be the one most likely to condition long-term transport paths, though fracturing (item 1.4.6) could determine preferential groundwater flow paths through the repository and hence influence radionuclide solubility and sorption.

1.5 Hydrological effects

At closure, parts of the repository could well be unsaturated and gas generation (item 1.2) could maintain this unsaturated condition. This will determine the early contact of groundwaters with wastes, corrosion rates and microbial degradation rates. Timescales of 10^2 to 10^4 years are possible for unsaturated conditions, so they should be included in radiological assessment studies.

Nevertheless, groundwater flow in saturated conditions (item 1.5.3) remains the norm and the bulk of assessment studies can probably be undertaken under this assumption.

Because a variety of chemically active substances may enter the near-field (item 1.5.4), affecting radionuclide solubility and sorption, this matter should be addressed in assessments. This may be possible simply by modifying the parameter values or distributions used in assessment models to take account of these effects.

1.6 Thermal effects

Elastic and non-elastic responses (items 1.6.1 and 1.6.2) might well be considered in the modelling discussed under item 1.4. The implications of fracture changes (item 1.6.3) are also discussed under item 1.4. Hydrological changes (item 1.6.4) are relevant to thermally induced groundwater movement (item 2.4.13.1) and can be studied using detailed groundwater models. More generally, temperature should be considered a controlling variable in chemical and microbial modelling (items 1.6.5 and 1.6.6).

2.1.1 Meteorite impact

On a timescale of 10^6 years, the cumulative probability of gross disruption of the repository by a meteorite impact is thought to be $\sim 10^{-6}$. Indirect effects (e.g. ground fracturing) may occur from smaller and more widely distributed impacts and be more likely. However, these constitute limited changes to the far-field and can probably be neglected in comparison with seismically-induced effects (item 2.2.6).

2.2.1 Regional tectonic

Over the next 10^6 years, at the Harwell site, such effects are likely to be of limited significance and can probably be ignored.

2.2.2 Magmatic

As for item 2.2.1.

2.2.3 Metamorphism

As for item 2.2.1.

2.2.4 Diagenesis

As for item 2.2.1.

2.2.5 Diapirism

Not applicable at Harwell.

2.2.6 Seismicity

Relatively low levels of natural seismicity (item 2.2.6.3) are anticipated. As physical integrity of the repository is only of relevance on timescales of a few hundred years, effects of natural seismicity are thought to be of minor significance. On longer timescales, the primary effects are likely to be changes in rock properties due to faulting/fracturing (item 2.2.7).

Repository-induced seismicity might be of relevance on short timescales and could reasonably be considered in the context of the detailed modelling described under item 1.4.

2.2.7 Faulting/fracturing

This could change groundwater flow and radionuclide transport paths. The likelihood of such effects and their possible influence on the groundwater flow regime needs to be assessed.

2.2.8 Major incision

This is potentially of considerable importance. The likelihood and magnitude of major incisions should be assessed.

2.2.9 Weathering

Weathered zones tens of metres deep can occur in presently or previously exposed rocks. The flow and transport properties of existing weathered zones and the likely future evolution of these zones should be taken into account in assessment studies. Weathering in the vicinity of the repository due to ingress of air during repository construction/operation may have to be taken into account.

2.2.10 Effects of natural gases

It is not clear whether pockets of natural gas would be present in the vicinity of a repository at Harwell, or what effects such gases would have on the radiological impact of the facility. Effects of such gases can probably be neglected.

2.2.11 Geothermal effects

These can probably be neglected at Harwell, except in so far as the repository constitutes a geothermal anomaly (item 1.6).

2.3.1 Variations in groundwater recharge

These will be caused by climatic changes (item 3.1), geomorphological changes (item 3.2) and changes in vegetation cover (item 3.4.1). They should be derived from environmental change modelling (see item 3.1).

2.3.2 Groundwater losses

Groundwater losses have to be taken into account in hydrogeological models. Their implications, in terms of radionuclide discharge, are considered elsewhere (items 3.5.3, 3.5.4, 3.5.5 and 3.5.6).

2.3.3 Rock property changes

These may occur as a consequence of seismicity (item 2.2.6), chemical effects, or microbiological effects. However, the various strata have been influenced by these factors for very long periods prior to repository construction and may have reached a quasi-equilibrium state. For this reason, future changes, except for those induced by larger seismic events, may not have to be taken into account.

2.3.4 Groundwater flow

In the various strata at Harwell, Darcy flow (item 2.3.4.1) is likely to occur. Fracture flow (item 2.3.4.4) could be of relevance in the chalk. Unsaturated flow is mainly of relevance in the context of the near-field (see item 1.5).

2.3.5 Salinity

Though deeper groundwaters may be somewhat saline (e.g. in the Great Oolite), it is not clear that this has any significant influence on local or regional hydrology).

2.3.6 Variations in groundwater temperature

Except in respect of repository associated variations (item 1.6.4), variations in groundwater temperature are not considered to be a major determinant of local or regional hydrology (see also item 2.4.13.2).

2.4 Transport and geochemical

Advection (item 2.4.1), diffusion (item 2.4.2) and hydrodynamic dispersion (item 2.4.3) should be included in assessment studies. It is not likely that matrix diffusion (item 2.4.2.2) or surface diffusion (item 2.4.2.3) are relevant in this context. Solubility constraints (item 2.4.4) are much less relevant in the far-field than in the near-field and a reasonable initial approach might be to assume that far-field transport is not solubility limited. In contrast, far-field sorption (item 2.4.5) is typically an important factor in radiological safety assessments and all the items listed require careful consideration.

Fracture mineralisation (item 2.4.6) seems a factor that could reasonably be neglected in the context of the Harwell site. However, organic and inorganic colloid transport require consideration (items 2.4.7 and 2.4.8). The effect may be primarily to modify radionuclide transport velocities, either increasing or decreasing them, depending upon radionuclide affinity for the colloids, the stability of the associations and the intrinsic mobility of the colloids.

It is not clear whether transport of radionuclides bound to microbes (item 2.4.9) is possible or significant. Pore sizes would seem to preclude this as a possibility in the various argillaceous strata.

Isotopic dilution (item 2.4.10) may be of relevance for C-14, taking into account amounts of organic material and carbonate minerals present in the various strata.

Both gas transport (item 2.4.11) and gas-induced groundwater transport (item 2.4.12) require consideration (but see also item 1.2).

Thermally induced groundwater transport (item 2.4.13) was discussed under item 1.6.

It is not clear that there are any biogeochemical changes (item 2.4.14) that need to be considered, other than those implied in the other items discussed.

3.1 Climatology

Changes in climate influence deep hydrogeology (item 2.3), erosional processes (item 3.2), near-surface hydrology (item 3.3) and ecological development (item

3.4). There is a general recognition that the effects of climate should be included in post-closure radiological assessment studies.
In the context of transient greenhouse gas induced warming at the Harwell site, changes in precipitation (item 3.1.1.1) and temperature (item 3.1.1.2) are primary measures, with ecological effects (item 3.1.1.5) and potential evaporation (item 3.1.1.6) being the major derived measures. All of these require consideration. In contrast, sea level rise (item 3.1.1.3) and storm surges (item 3.1.1.4) are of little interest.

Similarly, in glacial/interglacial cycling (item 3.1.2), attention should be given to precipitation (item 3.1.2.1), temperature (item 3.1.2.2), ecological effects (item 3.1.2.5), frozen ground phenomena (items 3.1.2.6 and 3.1.2.7), glacial effects (items 3.1.2.8 and 3.1.2.9) and potential evaporation (item 3.1.2.10). Storm surges (item 3.1.1.4) are not considered to be of relevance, but sea-level falls under periglacial/glacial conditions may be an important control on river incision (item 3.2.4.1).

The possibility of an exit from glacial/interglacial cycling (item 3.1.3) over the next 10^6 years cannot be rejected out of hand. Some consideration of its implications should be included.

3.2 Geomorphology

Both generalised and localised denudation (items 3.2.1 and 3.2.2) can affect local hydrogeology and near-surface hydrology (item 3.3). Denudation (items 3.2.1 and 3.2.2), sediment redistribution (item 3.2.3) and river incision/sedimentation as influenced by sea-level change (item 3.2.4.1) can affect substantially the distribution of radionuclides in the environment. Coastal erosion (item 3.2.4.2) is irrelevant in this context.

3.3 Hydrology

The surface hydrological regime is of primary importance in determining radionuclide dilution in the biosphere. Self-consistency is important, so a full water balance should be developed for assessment modelling. Thus, soil moisture and evaporation (item 3.3.1) should be considered, as should near-surface runoff processes (item 3.3.2), groundwater recharge (item 3.3.3) and freshwater surface flow characteristics (item 3.3.4). Lake formation/sedimentation (item 3.3.4.4) and effects of sea level change on site hydrology (item 3.3.4.5) are probably of limited importance. In the context of determining critical group doses and risks, estuarine characteristics (item 3.3.5), coastal waters (item 3.3.6) and ocean waters (item 3.3.7) can, almost certainly, be ignored.

3.4 Ecological development

Attention should be concentrated on the various types of terrestrial ecosystem (item 3.4.1). In the context of determining critical group doses and risks, developments of estuarine (item 3.4.2), coastal (item 3.4.3) and oceanic systems (item 3.4.4) can be ignored.

3.5 Radionuclide transport

Erosive transport (item 3.5.1) is almost certainly important on the long timescales of relevance in post-closure radiological assessments. In the context of an inland site, the various processes associated with groundwater discharges to soils (item 3.5.2) all need to be considered. Similarly, at Harwell, groundwater discharges to wells or springs (item 3.5.3) and to freshwaters (item 3.5.4) require consideration. Discharges to estuaries (item 3.5.5) and coastal waters (item 3.5.6) can be assumed not to occur.

The various processes of radionuclide transport in surface water bodies (item 3.5.7) all need to be considered. Furthermore, the long timescales involved suggest that fluvial system development (item 3.5.7.5) should be considered explicitly. For evaluating critical group doses and risks, there is probably little need to consider radionuclide transport in estuarine (item 3.5.8) or coastal (item 3.5.9) waters.

Again, given an inland site, plant (item 3.5.10) and animal (item 3.5.11) transport processes require consideration. Many of these are included, as a matter of course, in biosphere models, but vapour uptake by plants (item 3.5.10.3), cycling processes (items 3.5.10.7 and 3.5.11.4) and effects of animal relocation and migration (item 3.5.11.5), are less often incorporated in such models and require evaluation as to their likely significance. Biogeochemical cycling processes may be of particular importance in determining the long-term retention of radionuclides in soils.

3.6 Human exposure

All the listed pathways are of relevance, except salt particles (item 3.6.3.5), which are primarily of concern in sea-to-land transfers.

4.1 Short-circuit pathways related to repository construction

Seal failures post-closure (items 4.1.1 and 4.1.2) are a potentially important short-circuit route that requires investigation in the context of both groundwaters and gas-mediated pathways. Subsidence, with fault/fracture induction (item 4.1.3) needs to be considered in the context of the associated near-field effects (item 1.4.4.1) and repository induced seismicity (item 2.2.6.1).

4.2 Post-closure short circuit pathways

These primarily relate to intrusion into the repository. It is general practice to exclude intentional intrusions (items 4.2.1 and 4.2.2) from consideration. Exploratory and exploitation drilling (items 4.2.3 and 4.2.4) require consideration, but geothermal energy production (item 4.2.5) can, almost certainly, be excluded from consideration. The various excavations of underground space (items 4.2.6, 4.2.7, 4.2.8 and 4.2.9) require consideration, possibly in generic scoping terms. It might be argued that archaeologists (item 4.2.10) would rapidly recognise the type of facility into which they were intruding and that this would, therefore, constitute a deliberate intrusion, but this matter of early recognition is debatable. The implications of injection of liquid wastes (item 4.2.11), possibly leading to radionuclide mobilisation, need consideration. Groundwater abstraction (item 4.2.12) from the radionuclide plume, though not from the repository host stratum, is a serious possibility. It is difficult to believe that underground weapons testing (item 4.2.13) would take place in the area, since more remote sites and more suitable geological contexts would, almost certainly, be available.

DISTRIBUTION

K M Clayton
T D Davies
F P Glasser
J Higgo
A D Horrill
J Knill
C C Naish
M L Parry
J H Rees
E Tufton
J West
H S Wheater

M C Thorne
B G J Thompson
T J Sumerling

EG(90)P3

HMIP Expert Group on Post-Closure Radiological Assessment

M C Thorne

Electrowatt Engineering Services (UK) Ltd
Grandford House
16 Carfax
Horsham
West Sussex
RH12 1UP

May 1990

1. **REMINDER**

A response to Briefing Note 2 [EG(90)P2] was requested by 30th April 1990. So far only 4 responses have been received. Other responses are requested as soon as possible, so that the final briefing note, relating to aggregation of phenomena and ranking of approaches to assessment, can be finalised and distributed.

2. **NOTICE OF MEETING**

For the final stage of work, a round table meeting will be required, preferably before 15th June 1990. The secretariat would appreciate it if members of the Expert Group would complete the attached form relating to availability over the period and return it as soon as possible. The meeting will last one day and will take place in London.

3. **MEMBERSHIP**

An updated membership list is attached.

EXPERT GROUP AVAILABILITY

NAME:

DATE	DAY	AVAILABLE (Y/N)
18/6	Monday	
19/6	Tuesday	
20/6	Wednesday	
21/6	Thursday	
22/6	Friday	
25/6	Monday	
26/6	Tuesday	
27/6	Wednesday	
28/6	Thursday	
29/6	Friday	

Earliest acceptable start time:

Latest acceptable finish time:

To be returned to:

Dr M C Thorne
Electrowatt Engineering Services (UK) Ltd
Grandford House
16 Carfax
Horsham
West Sussex
RH12 1UP

<u>HMIP Expert Group on Post-Closure Radiological Protection</u>

Membership:

Professor K M Clayton
School of Environmental Sciences
University of East Anglia
Norwich NR4 7TJ

Dr C C Naish
Corrosion Technology Group
Materials Development Division
B393 Harwell Laboratory
Oxfordshire OX11 ORA

Dr T D Davies
Climatic Research Unit
School of Environmental Sciences
University of East Anglia
Norwich NR4 7TJ

Professor M L Parry
Atmospheric Impacts Research Group
Department of Geography
University of Birmingham
PO Box 363
Birmingham B15 2TT

Professor F P Glasser
Department of Chemistry
University of Aberdeen
Meaton Walk
Old Aberdeen AB9 2UE

Dr J H Rees
AEA Safety and Reliability
Building E6/116
Culham Laboratory
Abingdon
Oxfordshire OX14 3DB

Ms J Higgo
British Geological Survey
Nicker Hill
Keyworth
Nottingham RG12 5GG

Mr E Tufton
Ove Arup & Partners
13 Fitzroy Street
London W1P 6BA

Dr A D Horrill
Institute of Terrestrial Ecology
Merlewood Research Station
Grange-over-Sands
Cumbria LA11 6JU

Dr J West
British Geological Survey
Nicker Hill
Keyworth
Nottingham RG12 5GG

Professor J Knill
Natural Environment Research Council
Polaris House
North Star Avenue
Swindon
Wiltshire SN2 1DU

Dr H S Wheater
Imperial College
Department of Civil Engineering
Prince Consort Road
London SW7 2BU

Secretariat:

Dr M C Thorne
Electrowatt Engineering Services (UK) Ltd
Grandford House
16 Carfax
Horsham
West Sussex RH12 1UP

Correspondence should be copied for information to:

Dr B G J Thompson
Her Majesty's Inspectorate of Pollution
Room A5.33
Romney House
43 Marsham Street
London SW1P 3PY

Mr T J Sumerling
INTERA-ECL
Chiltern House
45 Station Road
Henley-on-Thames
Oxfordshire RG9 1AT

DISTRIBUTION

K M Clayton
T D Davies
F P Glasser
J Higgo
A D Horrill
J Knill
C C Naish
M L Parry
J H Rees
E Tufton
J West
H S Wheater

M C Thorne
B G J Thompson
T J Sumerling

EG(90)P4

HMIP EXPERT GROUP ON POST-CLOSURE RADIOLOGICAL ASSESSMENT: BRIEFING NOTE 4

M C Thorne

Electrowatt Engineering Services (UK) Ltd
Grandford House
16 Carfax
Horsham
West Sussex
RH12 1UP

June 1990

1. INTRODUCTION

In a previous Briefing Note [EG(90)P2], members of the Expert Group were requested to:

a) Identify those factors/phenomena that should be excluded from consideration on the grounds of negligible impact;

b) Identify those factors/phenomena which will undoubtedly be of significance in post-closure radiological assessments, or which will have to be included in order to evaluate their significance;

c) Identify groups of factors/phenomena that could be considered together in the assessment process, because of similarities in their implications.

This note comprises a compilation of replies received and briefing notes for the proposed meeting of the Expert Group.

2. COMPILATION OF REPLIES RECEIVED

In this compilation, extraneous matter in the replies has been deleted and minor editorial corrections have been made. Otherwise, they are as received. Reference should also be made to EG(90)P2, where the various table entries are defined.

2.1 F P GLASSER

1. Timescale

I accept that the "10^6 yr" study period should be accepted in principle, but subject to the proviso that, on present knowledge, predictions become fuzzy in the range 10^4 - 10^5 years and even fuzzier (if you permit me the word) in 10^5 - 10^6 years.

2. Temperature

Since I last wrote, it is becoming increasingly evident that the repository will experience a high temperature excursion owing to the inclusion of heat generating wastes. Creation of a thermal plume - spatial as well as temporal - does seem to me to have a profound effect on assumptions which we make. These assumptions will be based mainly on isothermal experiments, and the most important isotherm will be in the range 18° - 25°C. However, almost all aspects of the near-field will be affected if temperatures attain, say, 75° - 80°C for a decade. Almost all aspects of 1.1 and 1.2 will be affected; it is specifically mentioned in 1.2.2.5 but more generally in 1.6. I am not concerned primarily about the balance of the listing, but how we are to undertake an assessment, bearing in mind the limited data available.

There is, however, a secondary consideration. Each topic in 1.1 - 1.5 could be affected by temperature excursions, and this should be reflected in 1.6. At present, not all factors are so listed, eg mechanical effects (creep may increase), radiation phenomena (rate of irradiation will remain unaffected but lattice damage may decay more rapidly, etc).

2.2 C C NAISH

For the purposes of this note I shall concentrate on my area of expertise, corrosion, and its implications for other related near field phenomena; eg gas evolution. Before trying to answer the requirements for stage 2, I will briefly review the relevant corrosion modes, time periods, etc, as I believe this will help in deciding what part corrosion plays in the broader scheme of things.

Present NIREX corrosion studies are aimed at providing information on the rate of metal penetration to give, in the case of metallic containers, the percentage area penetrated at a given time. This information, together with whether a container is vented or not, leach rates, etc, should allow a rate of radioactive release into the near field to be calculated. Studies suggest that containment metal will be present for up to 1000 years but that significant container penetration will occur in the order of 100 to 300 years from repository closure.

Initial corrosion failure will be due to localised corrosion, although the percentage of a given container's area penetrated by this form of corrosion will probably be insignificant, especially in the case of a vented container, which in some ways can be viewed as having failed from day one. The eventual bulk failure and final disappearance of metal containment will be by general anaerobic corrosion, from both inside and outside the container. This mode of failure will apply to both stainless steel and carbon steel containers.

Hydrogen gas evolution will accompany anaerobic corrosion of all metals. In addition, it is possible that the more active metals, aluminium and Magnox, will produce significant hydrogen whilst the surroundings are still aerobic. This would be caused by these wastes (which are immobilised in a cement matrix which will be relatively dry and possibly cracked) being exposed, on repository closure and saturation, to groundwater which may be saline and warm. This could initiate rapid corrosion of exposed metal with an associated burst of hydrogen which could further stress and crack the matrix material.

The carbon steel containers in the repository will be covered with a Haematite rust film. This will have a local influence on Eh and hold it at around 150 mV positive of the equilibrium hydrogen potential. Anaerobic corrosion will produce hydrogen gas, this will impose an Eh at or below the hydrogen potential as long as catalytic surfaces are available on which it can react. The kinetics of the Haematite to Magnetite reaction do not appear to be at all fast. For carbon steel there may, therefore, be a delay between oxygen depletion (following repository closure) and hydrogen evolution.

Apart from the metals discussed above, other metals mentioned in waste inventories are present in such small quantities and/or are so slow reacting as to be of no significance to the present study. (This is my belief: I have not seen an inventory list to confirm.)

Turning to the requirements for stage 2 of the assessment:

Corrosion will be the most significant in the period from closure to 1000 years into repository life. After this time, the steels and active metals will probably have fully reacted and any other, more corrosion resistant materials, will be present in small quantities and be so benign as to exert no influence.

The consequences of corrosion could persist for a much longer period. These would include such things as hydrogen gas evolution (and subsequent effects on the other near field barriers) and the influence on near field chemistry of the corrosion products.

All steels can probably be treated similarly, although the active metals may require different treatment for the reasons outlined in the discussion above. I believe it quite unlikely that Magnox, and to a lesser extent, aluminium will be completely corroded by the time repository closure occurs. The corrosion rates observed in cemented Magnox wastes under storage type conditions and the potential for cracking make me believe the possibility of a pulse of gas generation from re-initiating corrosion on these metals needs to be examined. (This point is to be addressed in a research programme funded by DoE.)

Stress corrosion cracking, whilst compromising retrievability, is unlikely to cause a significant area of container to be lost, it may well, therefore, be excluded from consideration in this assessment.

Similarly localised corrosion will only cause a relatively small area of container to be penetrated before anaerobic corrosion conditions halt any further localised corrosion activity.

Unlike the common case of aerobic corrosion of structural reinforcement in concrete, the rate of anaerobic corrosion of steels and the volume of the corrosion product produced, compared with the corroded metal volume, will probably not cause significant cracking of the backfill material.

The corrosion product may well produce some local effect on the Eh, as will the hydrogen produced by corrosion, assuming it finds a surface on which it can react.

The most important consequence of the presence in the repository of large amounts of metal, with relatively large surface area to weight ratios, is most likely the hydrogen gas produced by the corrosion process and its effect on repository integrity, both directly structural (pressurisation and cracking) and the accelerated movement of water through the cracks, voids and cement pores.

2.3 J J W HIGGO

1. Near Field

The only place that sorption and solubility in the near-field appear is under the heading "Thermal Effects". Temperature does affect sorption and solubility, but there is no heading in the near field section where sorption and solubility are evaluated. Has the near field been defined? Normally it is taken as the disturbed zone, ie the zone of increased temperature and, of course, the zone containing backfill. It is not clear from the background information provided whether a backfill (eg cement or bentonite) is to be included in the assessment. The backfill can be a significant barrier and I am inclined to think that the near field deserves a section equivalent to the far field "2.4 Transport and Geochemical".

2.4 Transport and geochemical

I agree with all the comments by the secretariat apart from the statement that matrix diffusion can be neglected. Surely this depends on the flow rate?

Additional Comments

2.4.5.1/2. In the far-field radionuclide concentrations are normally very low and Henry's Law is obeyed over the concentration range of interest, ie the distribution coefficient (K_d) is constant. Only if there is a high concentration of stable element in the waste (caesium in vitrified waste is an example; I do not know if there are any elements in ILW and LLW that fall into this category) will it be necessary to consider isotherms. If there is a high concentration of a particular element in groundwater, then the K_d

(although different) will remain constant because the increase in concentration will be negligible.

<u>In the near field</u> isotherms may be important.

2.4.5.3/4. Over a time scale of 10^6 years, it is very difficult to know what is reversible and what is irreversible. Strictly speaking only a chemical reaction will result in irreversible "sorption". The problem is that the kinetics of sorption and desorption are likely to be different. Can the models handle this?

2.4.10. Do you mean isotopic dilution or isotopic exchange? ^{14}C may exchange with the carbon in organic material and carbonates. ^{36}Cl may exchange with the stable chloride in clays. If there is a discharge into estuaries or the sea, then ^{129}I will be available for incorporation into the food chain. However, because of the large quantity of iodine in the marine biosphere, isotopic dilution will result in a negligible dose to man (Baxter and Aston, <u>Radioactive Waste Management and the Nuclear Fuel Cycle,</u> 1982 pp. 47-55). Presumably the same applies to ^{36}Cl.

2.4 <u>J WEST</u>

1. <u>Near Field</u>

1.1 <u>Chemical/Physical Degradation</u>

1.1.1 Structural and container metal corrosion

Obviously the use of canisters will only ensure waste isolation for a few hundred years and they cannot be expected to remain intact for the envisaged period of 10^6 y. With this in mind, I am of the opinion that it would be worth assuming for the purpose of the radiological assessment, that the canisters fail immediately and that the waste is immediately exposed to groundwater flow. However, I do not think that the mode of corrosion should be ignored completely, as this may prove to be an 'over conservative' assumption.

1.1.2 and 1.1.3 Physical and chemical degradation of concrete

I feel that these two aspects of concrete degradation are very closely linked and it may be extremely difficult to tease out the relative importance of the processes involved (I could be very wrong here as I am no expert in concretes). The process of concrete degradation and its effects are long term and may extend to 10^6 y. However, before this time the concrete will have failed physically. Timescales are extremely difficult to judge and can only be assessed conservatively on the basis of an appropriate interpretation of hydrogeological information.

1.1.4 Degradation of wastes

Degradation of wastes will lead to the production of gases (1.2) and complexing agents and colloids. These products will influence sorption processes and radionuclide solubility. The waste and degradation products are all prone to microbial attack (particularly organic wastes) and their presence should be seen as a catalyst. The microbes themselves should also be viewed as 'organic colloids', as their behaviour can be colloidal. On the timescales considered, the purely chemical degradation of the wastes will take place at a rate which can be calculated by existing models. Microbial acceleration of degradation will be a significant perturbation and will be related to factors in 1.2.2.

1.2 Gas Production, Transport and Flammability

Gas production is an important area which requires modelling of rate of production. This may not be possible without experimental work. Low rates of gas production do not necessarily imply low microbial activities, but could also indicate low microbial numbers. Microbes could attack the structural container and waste steel, producing gases (with different microbial functional groups acting as the environment changes). Microbial corrosion is a well documented phenomenon and cannot be ruled out. Similar functional groups will also attack the concrete, producing acids and ultimately hydrogen sulphide. Microbial degradation of both inorganic and organic wastes will produce electron donors and acceptors, feeding complex interactions between microbial groups and giving rise to production of CO_2, methane, H_2S, etc. These interactions and processes are also controlled by environmental factors (1.2.2.5, 1.1.1.6, 1.2.2.13) and by the availability of energy and nutrients (1.2.2.12). Some work has been carried out in the production of gases by microbes, with simple mechanistic models developed.

The movement of gases from the repository must be considered. Explosions etc. may occur in the first few hundred years after repository sealing when oxygen is present. If gas is not removed, then physical disruption of repository materials may occur with subsequent release of gases (radioactive and explosive). This sort of failure could happen at any time with many implications depending on the scale of damage to the repository.

1.4 Mechanical Effects

The physical disruption caused by excessive gas production must be included in detailed models.

1.5 Hydrological Effects

It is anticipated that waste will remain unsaturated for the first part of the repository's life. However, it is most likely that the waste will be damp (condensation etc.) through storage and that it will remain damp even if compressed. Such dampness will enhance microbial activity prior to and after waste emplacement. Such an effect will last until the microbial populations reach their optimum levels for the environment.

1.6 Thermal Effects

Thermal effects will have considerable controlling influence on microbial activity (and hence biodegradation rates, by-product formation). These effects will extend throughout the lifetime of the repository.

2. FAR FIELD

2.1 - 2.3 I do not think I can usefully comment on these topics.

2.4 Transport and Geochemical

A huge subject and I feel competent only to comment on the influence of microbes. This will depend on the amount of nutrients etc. present in the far field but, intuitively, it would seem reasonably to suggest that this will be minimal unless supply rates change drastically (e.g. by sudden failure of repository releasing a surge of biodegradation by-products). Transport of radionuclides bound to microbes cannot be ruled out, given the pore sizes of host rocks (since starved microbes can be 0.3 μm diameter) although at Harwell movement would be hampered.

2.5 J H REES

Comments were produced in tabular form and are reproduced directly (Table 1). The relationship between gas generation and its consequences was illustrated graphically (Figure 1).

2.6 K M CLAYTON

2.2.1 through 2.2.5. Comments agreed.

2.2.6 and 2.2.7. The separation of seismicity from faulting/fracturing may need consideration. Does 2.2.7 mean simply the existing configuration of faults and fractures (joints) at the site, or does it also include changes over time. If the latter, since they are only likely to be changed by seismicity (or by the excavation itself), is it best to consider the change under the 2.2.7 heading or under 2.2.6? I am not sure if the logic of this is already established and described for us.

2.2.8. On the timescale of 10^6 years this is agreed to be important. The River Thames as the local base-level is of most significance, but the possibility of a glaciation more extensive than any hitherto must also be covered. The site, at the foot of the north-facing Chalk escarpment, is one where glacial erosion could be considerable.

2.2.9. The existing statement is agreed. However, this may be the best place to consider the possibility of solutional cavities developing within the Chalk and the underlying Jurassic limestones, with the possibility of solution-induced collapse. Such phenomena as the pipes found in the Chalk show the scale of the problem, which is likely to be relatively small, but should not be ignored.

2.3.1. Comment agreed. The most important effect is likely to be in the short-term and to be the severe reduction in groundwater recharge as a consequence of greenhouse gas-induced warming.

2.2.3. Agreed, subject only to the addition of solution, included already under 2.2.9 above.

2.3.4. Comment agreed, but note that fracture flow will certainly be relevant in the Chalk and probably in the underlying Jurassic limestones should they later be incorporated in the flow field.

2.3.5. Comment agreed.

2.3.6. Comment agreed.

3.1. Comment agreed, subject to the following. Line 7/8 - potential evaporation should be potential evapotranspiration. As already noted under 2.3.2, this is likely to change dramatically in the short term.

At the end of the second paragraph, river incision at this site is most unlikely to be influenced by sea-level. Instead two factors will operate, changes in river behaviour with changes in climate and vegetation influencing discharge and sediment yield, and tectonic uplift. The latter has not been important in the past million years (though some uplift has probably occurred) and we should not expect the situation to change in the modelled future. If it does, it falls into the unexpected category like seismicity.

The implications of an exit from glacial/interglacial cycling are to reduce the chance that erosion will affect this site.

3.2. I would remove the reference to sea-level change. It is relevant at many sites, but not at Harwell. See comments on reasons for change in river behaviour under 3.1 above.

3.3. Comment agreed, especially the exclusions at the end.

4.2. Within this comment, I would again note further groundwater extraction. If groundwater supplies reduce with greenhouse warming, we may expect one reaction to be the deepening of boreholes and extraction from greater depths, which could affect groundwater movement through and away from the repository.

2.7 H S WHEATER

OVERVIEW

This response is primarily directed to hydrological considerations in post-closure assessment, but it can reasonably be argued that hydrology is of central importance to the assessment, since it determines the moisture states, water pathways and water fluxes which govern diffusive, advective and dispersive transport of radionuclides in the liquid phase.

Hydrological factors are included in the near field (1.5), the far field (2.3) and the biosphere (3.3.), and it should be emphasised that the hydrology of the near field is determined by the hydrology of the far field, which, in turn, is a function of biosphere hydrological processes. It is, therefore, not possible to assess 1.5 in isolation from 2.3 and 3.3.

A first-order influence diagram, expressing the primary controls on hydrology and hence radionuclide transport, is included at Fig. 2. In the short term (10^1 years), geomorphology (3.2) and ecological development (3.4) can be regarded as in quasi steady-state, and the hydrology of the biosphere (3.3) is determined by short-term variability in climatology (3.1). It can be noted that runoff processes occur on a timescale of 10^{-4} years, and that certain biosphere transport pathways (3.5) can only be fully described on this timescale. Variability in far-field hydrology (2.3) is primarily determined by groundwater recharge from the biosphere, commonly represented on a timescale of 10^{-1} to 10^{-2} years, but may also be influenced by longer-term variability in boundary conditions such as river, lake or sea levels. As noted above, near-field hydrology (1.5) is determined by 2.3 and in the absence of direct surface connection could probably be characterised on a time-scale of 10^0 years upwards.

As the timeframe is expanded from the short-term, the overall system response becomes progressively more complex, due to feedback controls. For timescales of 10^2 to 10^3 year upwards, geomorphology (3.2) becomes a variable, determined by climatology (3.1), subject to structural geological controls. In the presence of climate change, ecological development (3.4) may vary significantly, adding to the direct effects of climate change, as part of a complex integrated biogeochemical system. Far field and near field hydrology will in turn respond to biosphere changes, and it should be noted that relatively subtle biosphere changes may cause significant modification to far field hydrology. Groundwater recharge occurs, under current climatic conditions, as a result of relatively small differences between precipitation and evaporation and is strongly dependent on their relative seasonal distribution. In addition to biosphere influences, the far and near fields will also be subject to geological changes (2.2) on the longer timescales.

In a discussion of primary influences, human activities should also be included, and not necessarily in the context of "short-circuit pathways" (4). There are many direct and indirect ways in which social and economic development and agricultural policy can influence the hydrology of the biosphere and the far field. Urbanisation is an extreme example of land use change and the hydrological consequences can be dramatic. Primary effects include increased flood frequency, reduced low flows and reduced groundwater recharge, although all of these may be mitigated by secondary effects, such as provision of storage ponds, effluent discharge of imported water supplies and groundwater recharge from leaky water services or septic tanks. More subtle land use changes, for example due to changing agricultural policy, may also be of significance, although it may be considered that in the long term such effects are likely to be minor in comparison with climate-induced change.

Also of major concern is the future management of water resources. At present there is concern within the Thames catchment that projected resource demand is approaching the reliable yield of existing sources. On the timescale of 10^1 to 10^2 years, climate change and gradual economic growth are likely to exacerbate existing problems and one can foresee progressive exploitation of deeper groundwater sources and much more active management of shallow groundwater in conjunctive use schemes, with induced or injected winter recharge and ephemeral streams increasingly maintained by pumped groundwater. Significant changes to groundwater fluxes and flow paths could be envisaged, with obvious implications for far field radionuclide transport.

In summary, this overview has attempted to demonstrate that near field, far field and biosphere hydrology cannot be regarded as independent, that, on all but the shortest timescales, complex feedback mechanisms apply and that human influences may be of major importance.

DETAILED COMMENTARY

Near-field

1.5 <u>Hydrological Effects</u>

1.5.1. The near field will inevitably be dewatered for construction and changes in material properties due to stress relief may be expected. Given the geological situation, return to saturated conditions will be expected, and the time scale could be relatively short (10^0 - 10^1 years) if stress relief increases fissure/macropore flow, or considerably longer if clay properties remain unchanged.

1.5.2. Unsaturated flow will be at least one to two orders of magnitude slower than saturated flow, and given the probable duration of unsaturated conditions is unlikely to be a significant liquid phase pathway. However, the existence of unsaturated conditions is important in terms of the physical and chemical environment of the near field, affecting chemical/physical degradation (1.1) and gas production (1.2). Gas transport (1.2.6) will be strongly affected by the liquid-filled porosity and would have to be evaluated in the context of two-phase flow.

1.5.3. Saturated groundwater flow is likely to be of major significance for radionuclide transport.

1.5.4. Transport of chemically active substances into the near-field is probable, particularly inorganic ions. Microbes are more likely to be introduced through construction activities; the influx of humic and fulvic acids, organic complexes and colloids is possible. Assessment will be required.

1.6 <u>Thermal Effects</u>

1.6.4. Thermal effects are likely to influence unsaturated and saturated flows, primarily through density and viscosity. Two-phase flow is particularly sensitive to relative density, viscosity and surface tension effects.

1.6.1/1.6.2/1.6.3/1.6.5/1.6.6. All items included will need to be assessed.

1.6.7?? The extent to which thermal effects are likely to propagate through the far-field and into the biosphere should be assessed; biosphere processes will be sensitive to temperature change.

Far-field

2.3 Hydrological

The far-field groundwater system responds to flux and pressure-potential boundary conditions, subject to material properties. The dependence on biosphere hydrology (3.3) has been discussed earlier, and the principal biosphere interactions are the fluxes defined by 2.3.1 and 2.3.2. Variability is likely to be severe, and, if greenhouse warming is currently occurring, the timescale of variability could be as short as 10^1 years. The system will be less sensitive to the pressure potential boundary condition variability that can be expected due to climate change, but on timescales of 10^3 years upwards, changes, e.g. in sea level, may be sufficient to significantly affect the far field groundwater flows. This cannot be neglected, even for the Harwell site, since the lower aquifer systems are likely to have boundary conditions outside the defined area of the "Background Information" note which will in the long term respond to sea level change. However, saline interface effects (2.3.5.2) due to the coastal boundary are unlikely to be significant in modifying far-field flows. Likewise evidence does not suggest that observed salinity effects within the defined area are sufficient to warrant the formal inclusion of density-dependence in groundwater assessment (2.3.5.1, 2.3.5.3).

Rock property changes (2.3.3) are likely to occur on the timescales of geological change (2.2), and porosity (2.3.3.1) and permeability (2.3.3.2) will need to be treated independently. The role of microbial pore blocking (2.3.3.3) is uncertain, but should be assessed. Channel formation (2.3.3.4) due to solution effects and preferential weathering is likely to be one of the more rapid structural changes (10^2 years).

With respect to groundwater flow (2.3.4), both Darcy (2.3.4.1) and non-Darcy flow (2.3.4.2) will need to be assessed. In particular, the chalk is well known for the occurrence of fractures in determining flow properties (2.3.4.4), and although the occurrence of fractures is primarily related to structural geological features, it is likely that they will be further developed by solution (2.3.4.5). A dual porosity representation will be essential for such media. Flow in the clay deposits is conventionally represented by Darcy flow. However, it should be noted that materials such as clays encompass a wide range of pore sizes, and that flow will predominantly take place in the larger pores. The effects of chemical transfer between relatively mobile porewater and relatively immobile pore water may be of significance, even in materials which are conventionally represented by Darcy flow. A general assumption of intergranular flow (2.3.4.3) for such media may be an oversimplification. As noted in the context of the near-field, unsaturated flow (2.3.4.6) is unlikely to be of significance within the far-field for the Harwell site.

Natural variations in groundwater temperature (2.3.6) would not seem to be significant for this site. However, as noted earlier, temperature effects propagating from the near-field should be quantified.

2.4 Transport and Geochemical

The primary transport models are advection (2.4.1), diffusion (2.4.2) and hydrodynamic dispersion (2.4.3), and all require full assessment. Given the long timescales of assessment, bulk diffusion may be an adequate representation (2.4.2.1). However, from the comments above, it can be seen that matrix diffusion (2.4.2.2) may be of relevance to initial propagation. Surface diffusion (2.4.2.3) is unlikely to be significant.

Sorption effects (2.4.5) will be of major significance and all of the 2.4.5 sub-headings will require consideration.

With respect to solubility constraints (2.4.4), I agree with the Secretariat that given emergence from the near-field, solubility is unlikely to be a limiting consideration in the far-field.

Fracture mineralisation (2.4.6) is likely to be of greater significance for the underlying strata than for the primary transport pathways and could probably be neglected. Colloid transport (2.4.7/2.4.8) requires consideration. Microbe transport effects (2.4.9) could occur, particularly if macropores are present in the clay deposits, but the significance will be dependent on the presence of a suitable population.

Both gas transport (2.4.11) and gas-induced groundwater transport (2.4.12) require assessment. Thermally-induced transport (2.4.13) is only likely to be of significance for repository-induced effects (2.4.13.1), as indicated earlier.

Other biogeochemical effects are unlikely to be important in the far-field, but will be of major importance in the biosphere.

Biosphere

General comments on the interdependence of biosphere processes have been included in the overview section.

3.1 <u>Climatology</u>

It is assumed that the relative timing of 3.1.1, 3.1.2 and 3.1.3 will be treated by other members of the group. Precipitation (3.1.1.1/3.1.2.1), temperature (3.1.1.2/3.1.2.2) and potential evaporation (3.1.1.6/3.1.2.10) are highly significant determinants of hydrological response.

Sea level changes (3.1.1.3/3.1.2.3) are unlikely to be of significance in the short-term. In the longer term (10^3 years) river morphological change will be influenced by sea level change and, if significant (>10 m) rise occurs, this may have a direct effect on upstream river levels which in turn would affect biosphere-groundwater interactions. As noted earlier, sea level change can influence deep groundwater flows in the long term.

Storm surges (3.1.1.4/3.1.2.4) are unlikely to affect the defined area unless major sea level rise occurs.

Ecological effects (3.1.1.5/3.1.2.5) are likely to be of significance, and as noted earlier, relatively subtle changes in land use may have significant effects on groundwater recharge, as well as surface flows.

Seasonally frozen ground (3.1.2.6) can have a significant impact on low frequency flood events (>50 year return period) within the present climate. Such events are important for sediment transport and morphological development. More extreme changes (3.1.2.8/9/10) will obviously have greater impact.

3.2 Geomorphology

It is assumed that detailed discussion will be provided by other members of the group. The general interaction between climate, geomorphology and hydrology and an indication of timescales is included in the overview.

3.3 Hydrology

In general, soil moisture and evaporation processes (3.3.1) determine groundwater recharge (3.3.3) and are thus of major significance for far-field and near-field hydrology. They also define the hydrological environment for vegetation, and hence are of major importance in determining ecological change (3.4).

Near-surface runoff processes (3.3.2) generate streamflow, but are highly non-linear and strongly influenced by soil moisture state. The mode of runoff generation will also influence the extent to which groundwater recharge occurs. In general, high antecedent soil moisture conditions will induce rapid response pathways and direct a greater proportion of precipitation to streamflow. It should be noted that the subdivisions 3.3.2.1-5, although general, have been primarily developed from observation of small upland humid catchments. Hence, some care is necessary to interpret the existing situation (under present climate). For example, for areas of chalk outcrop, groundwater-stream interactions are extremely important, but are not normally considered to be return flow, which is normally associated with variable source area response. It would be helpful to include an additional category of stream-aquifer interaction (a new 3.3, or 3.2.2.6?) to cover this point and also to represent the possible contribution of streamflow to groundwater recharge. In areas with clay soils, agricultural activity in general and field drainage in particular are major influences on hydrological response. This could be represented within the definitions of interflow and macropore flow, but it can be seen that the subdivisions should be assessed in a flexible manner for lowland response under present and alternative climates.

Of the surface flow characteristics (3.3.4), 3.3.4.1 and 3.3.4.2 represent the short term dynamic response (10^{-4} to 10^{-3} years) which generates fluvial transport of radionuclides (3.5.1.1, 3.5.7.1, 3.5.7.2 and 3.5.7.3). Meander migration (3.3.4.3) and lake formation (3.3.4.4) are both forms of geomorphological response which will be significant on longer timescales (10^{2} to 10^{3} years upwards). As discussed above, sea level change (3.3.4.5) will influence this geomorphological development and may, if large rises occur, have direct effects on river flows, and hence 3.3.4.1 and 3.3.4.2, and aquifer/stream interactions.

Estuarine flows (3.3.5) will not affect fluvial processes, and are only of relevance with respect to the subsequent fate of radionuclides after transport within the fluvial system. The same applies to 3.3.6 and 3.3.7 (coastal and ocean waters).

3.4 Ecological Development

As discussed earlier, terrestrial ecological development (3.4.1) is dependent on hydrology and climatology and is an important aspect of the response of the integrated biosphere system. Estuarine, coastal and ocean systems (3.4.2/3/4), as described above, are only relevant for post-fluvial transport.

3.5 Radionuclide Transport

As noted earlier, on the longer timescales, geomorphological development is an important influence, and fluvial, aeolian and glacial processes (3.5.1.1/2/3) require assessment with respect to radionuclide transport. Coastal erosion (3.5.1.4) will be of significance only for radionuclides transported to the coast by fluvial processes, or transport in the deeper aquifers to a coastal location (3.5.5/6).

The groundwater discharges 3.5.2-3.5.6 are all potentially relevant. The latter two (estuaries and coastal waters) only apply to long distance transport in the deeper aquifers, but cannot be excluded for the timescales of interest until the boundary conditions for the deeper aquifers have been defined.

All of the surface water transport processes (3.5.7) are relevant. However, the effects of vegetation (3.5.7.4) are just one aspect of biological influences which can be highly significant in terms of physical mixing and chemical processes within bed sediments. It would be appropriate to broaden 3.5.7.4 accordingly.

Estuarine and coastal processes (3.5.8/9), as discussed above, are only of importance if fluvial and groundwater transport processes provide significant throughput of radionuclides.

The role of plants (3.5.10) is complex. Instantaneous root uptake can be seen to be dependent on hydrology, soil chemistry and plant chemistry. However, net uptake is dependent on chemical cycling (3.5.10.7), which includes internal translocation (3.5.10.4), canopy washoff and leaching (3.5.10.5) and leaf-fall and senescence (3.5.10.6) and also soil chemical processes such as weathering and ion exchange. On the longer-term (10^3 years) soil development will itself reflect hydrological, vegetation and geological influences.

Once again, a long term perspective indicates complex interdependence of processes, all of which require consideration.

In addition to root uptake, surface deposition and vapour uptake (3.5.10.2/3) are part of the normal biogeochemical cycle for vegetation and will require assessment.

Short-Circuit Pathways Related to Human Activities

4.2 includes a range of direct effects which could lead to post-closure short-circuits, all of which require consideration. However, as described in the introductory overview, a wide range of human activities can influence biosphere and far-field hydrology and hence affect post-closure assessment. Thus, groundwater abstraction from the radionuclide plume is an important possible direct short-circuit. However, it is highly probable that changes in the management of groundwater resources will affect groundwater flow patterns and hence modify transport pathways, i.e. an indirect effect. Similarly near surface mineral extraction (e.g. gravels) is quite likely to affect surface water groundwater interactions, as well as evaporation, and this would be more probable than direct mineral extraction from a contaminated area. Changes in land-use and land-use management, in response to social change, agricultural practice and recreational needs (and influenced by climate change) are highly likely to modify hydrological response.

Several examples have been presented to illustrate that the indirect effects of human activity have a much greater probability of influencing post-closure transport than direct effects, and require assessment.

3. MAJOR ITEMS AND INTER-RELATIONSHIPS

On the basis of material presented in EG(90)P2 and in Section 2 above, it is possible to:

a) Eliminate factors/phenomena from consideration;

b) Identify factors/phenomena that can be considered separately;

c) Identify factors/phenomena that should be considered together and display the major relationships between them.

3.1 ELIMINATION OF FACTORS/PHENOMENA

Table 2 summarises the factors/phenomena that could reasonably be neglected in an assessment. For convenience, to provide a basis for subsequent discussion, Table 3 summarises remaining factors/phenomena to the third level of indexing.

3.2 FACTORS/PHENOMENA THAT SHOULD BE CONSIDERED SEPARATELY

Amongst the factors/phenomena listed in Table 3, a few are unlikely and/or involve gross disruption of the repository. It is suggested that these factors/phenomena should be considered separately from the main assessment in 'what if?' or scoping calculations. The entries to which this applies are meteorite impact (item 2.1.1), major incision (item 2.2.8), and some short-circuit pathways related to post-closure intrusion (items 4.2.4, 4.2.6, 4.2.7, 4.2.8, 4.2.9, 4.2.10, 4.2.11). Other short-circuit pathways (items 4.2.3 and 4.2.12) are likely to occur in the long-term and are associated with only minor perturbations to the repository system.

The position with short-circuit pathways related to repository construction (item 4.1) is less clear. These can be considered a normal part of repository evolution, or it can be argued that these should be engineered not to occur, or to be of negligible radiological significance if they do occur.

3.3 INTER-RELATIONSHIPS BETWEEN FACTORS/PHENOMENA

Two members of the Expert Group constructed partial influence diagrams showing relationships between the various factors listed (Figures 1 and 2). Figure 3 is a more comprehensive influence diagram, based on Table 3, which attempts to show broader classes of relationships. A brief discussion of the various inter-relationships is provided below.

a) Chemical and physical degradation in the near-field controls both the rate of gas production and its transport local to the repository. Conversely, the presence of gas can act as a control on chemical degradation and over-pressurisation may be associated with physical degradation.

b) Gas production in the near-field can alter the local hydrological regime, notably through pressurisation and prevention of resaturation. It can also have effects on geosphere hydrology.

c) Radionuclides can be transported in the gas phase in the geosphere.

d) Hydrology, in terms of resaturation and water flow rates,can be a determinant of rates of chemical and physical degradation of the near-field. However, the degree of degradation can also affect the hydrology.

e) Mechanical effects may be induced by geological changes and can influence physical degradation.

f) Thermal effects include increased temperatures which induce stresses, modify rates of chemical and physical degradation and induce buoyant flows in both the near-field and the geosphere.

g) Geosphere hydrology is a major determinant of near-field hydrology.

h) Geological changes, e.g. in rock permeability, affect the hydrological regime, which, in turn, controls radionuclide transport in the geosphere.

i) Climate influences both surface and groundwater hydrology, though it could be argued that the control of groundwater hydrology is exercised via the surface water component. There is, in any event, a close relationship between surface and groundwater hydrology.

j) Climate and changes of climate also influence denudation processes and changes in the nature of the land surface modify the surface hydrological regime.

k) Ecological development is partly determined by climate, surface hydrology and land surface characteristics. However, reciprocally, surface hydrology and changes in land surface characteristics are influenced by vegetation cover.

l) Radionuclide transport in the biosphere is proximally determined by geomorphological, hydrological and ecological factors.

m) Human behaviour is a determinant, and is also governed by, climate change, landform development, surface hydrology and ecological development. In conjunction with radionuclide distribution and transport in the biosphere, human behaviour determines the radiation exposures received.

4. MEETING AGENDA

Given the work undertaken to date, and summarised in this and previous briefing notes, it is proposed that the Expert Group meeting should address the following points.

a) Should any of the factors/phenomena eliminated from consideration be re-introduced and should any new factors/phenomena be introduced?

b) What are the minimum combinations of factors/phenomena that should be included in an assessment study?

c) What additions to those minimum combinations could most enhance the quality of the assessment?

d) What relative weight should be attached to results derived from assessment studies undertaken on the basis of different combinations of factors/phenomena proposed under (b) and (c).

In respect of (b) and (c), one might argue that a reasonable minimal assessment basis is to:

i) Neglect the details of chemical/physical degradation in the near-field and consider it as a well-mixed, saturated quasi-equilibrium chemical system;

ii) Neglect effects of gas generation;

iii) Neglect repository-induced thermal effects;

iv) Ignore changes in structural geology and treat the existing geology as a combination of homogeneous porous media;

v) Assume radionuclides are transported in the far-field in ionic form;

vi) Presume glacial/interglacial cycling continues with similar characteristics to those exhibited over the last 5 10^5 years;

vii) Neglect geomorphological change;

viii) Impose surface hydrological and vegetational characteristics from analogue regions appropriate to the climatic conditions pertaining at the time;

ix) Neglect all pathways other than those mediated by groundwater;

x) Neglect human-induced perturbations to the repository and its environment.

The next stage would be to determine which of these restrictions on the assessment the Expert Group would find it most desirable to relax.

Written responses to this note would be useful, especially from any members of the Expert Group unable to attend the proposed meeting. Such responses will be tabled at that meeting and will form an additional basis for discussion.

Section	Topic	Priority in Assessment [a]	Justification	Linked Sections [d]		
1.2.1 Hydrogen by Metal Corrosion						
1.2.1.1	Structural Steel	-	Low/medium depending on detailed design	-	-	-
1.2.1.2	Container Steel	H [b]	Substantial quantity, much of it of high specific surface area	1.2.1.3 1.2.2.9	1.2.1.8 1.2.4.1	1.6.5.4
1.2.1.3	Waste Steel	H [b]	Large quantities in LLW	1.2.1.2 1.2.2.9	1.2.1.8 1.2.4.1	3.6.3.2 1.6.5.4
1.2.1.4	Waste Magnox	L	Small H_2 - generating potential	-	-	-
1.2.1.5	Waste Aluminium	L	Small H_2 - generating potential; much may corroded before repository closure.	-	-	-
1.2.1.6	Waste Zircaloy	L	Small H_2 - generating potential, low corrosion rate	-	-	-
1.2.1.7	Waste other metals	L	Small H_2 - generating potential	-	-	-
1.2.1.8	Effects of microbial growth on concrete	H(?) [b]	Uncertain; could increase rate of steel corrosion by lowering pH	1.2.1.2 1.2.2.9	1.2.1.3 1.2.4.1	1.6.5.4
1.2.2	CH_4 and CO_2 by Microbial Degradation					
1.2.2.1	Cellulosics	H [c]	Particularly in compacts of LLW	1.2.2.4 1.2.4.2	1.2.2.5 1.6.5.4	1.2.2.9 1.2.2.10
1.2.2.2	Other susceptible organic materials	L	Small gas - generating potential	-	-	-
1.2.2.3	Aerobic degradation	L	Short aerobic period expected following closure	-	-	-

TABLE 1

Response of J H Rees to EG(90)P2

Section	Topic	Priority in Assessment[a]	Justification	Linked	Sections[d]	
1.2.2.4	Anaerobic degradation	H[c]	Main part of degradative process	1.2.2.1 1.2.4.2	1.2.2.5 1.6.5.4	1.2.2.9 1.2.2.10
1.2.2.5	Effects of temperature	H(?)[c]	Uncertain, could be major	1.2.2.1 1.2.4.2	1.2.2.4 1.6.5.4	1.2.2.9 1.2.2.10
1.2.2.6	Effects of lithostatic pressure	L	Current evidence suggests will be a minor factor	-	-	-
1.2.2.7	Effects of microbial growth on properties of concrete	L	Compacts of LLW will be at intermediate pH over much of degradation period	-	-	-
1.2.2.8	Effects of biofilms	L	(as for 1.2.2.7)	-	-	-
1.2.2.9	Effects of H_2 from metal corrision	H[b]	Could stop microbial gas formation	1.2.2.1 1.2.4.2	1.2.2.4 1.6.5.4	1.2.2.5 1.2.2.10
1.2.2.10	Inhibition due to the presence of toxic materials	H(?)	Uncharacterised, could be substantial	1.2.2.1 1.2.2.9	1.2.2.4 1.2.4.2	1.2.2.5 1.6.5.4
1.2.2.11	Carbonate/bicarbonate exchange with concrete	L	Affects up to half gas produced (ie not CH_4), not a large perturbation	-	-	-
1.2.2.12	Energy and nutrient control of metabolism	-	Low/medium priority with Harwell ground-waters	-	-	-
1.2.2.13	Effects of radiation on microbial populations	L	Gases formed mainly in LLW	-	-	-
1.2.3	Gas generation from concrete	L	Radiolysis unimportant c.f corrosion and microbial effects	-	-	-

TABLE 1 (Cont.)

Section	Topic	Priority in Assessment [a]	Justification	Linked Sections [d]
1.2.4	Active Gases			
1.2.4.1	Tritiated H_2	H(?) [b]	Important if rapid transport pathways available eg. silty layers in clay	1.2.1.2 1.2.1.3 1.2.1.8 1.2.2.9 1.6.5.4
1.2.4.2	Active CH_4 and CO_2	H [c]	Particulary $^{14}CH_4$ - ^{14}C longlived	1.2.2.1 1.2.2.4 1.2.2.5 1.2.2.9 1.6.5.4 1.2.2.10
1.2.4.3	Other active gases	L	Current studies suggest these will not significantly affect radiological safety	- - -
1.2.5	Toxic Gases	L	Non-radiological	- - -
1.2.6	Transport			
1.2.6.1	In the waste container	L	Irregular waste shapes suggest that gas will be able to find migration pathways in containers	- - -
1.2.6.2	In Vault between containers	H [b]		1.2.6.3 1.2.6.4 2.4.12
1.2.6.3	Between Vaults	H [b]	Pressurisation could lead to cracking and acceleration of water flows	1.2.6.2 1.2.6.4 2.4.12
1.2.6.4	Shafts and Adits	H [b]	Much gas could escape in zones of disturbed geology	1.2.6.2 1.2.6.3
1.2.6.5	Far field	H [b]	Not clear whether clay would hold up gas movement - depends on presence of high permeability strata	1.5.2.2 2.4.11.1 2.4.11.2 2.4.12
1.2.7	Flammability			
1.2.7.1	Fires	L	Non-radiological	- - -
1.2.7.2	Explosions	L	Non-radiological	- - -

TABLE 1 (Cont.)

Section	Topic	Priority in Assessment [a]	Justification	Linked Sections [d]
1.5.2	Groundwater Flow (Unsaturated)			
1.5.2.2	Due to gas production	H [b]	Gas could accelerate water flow	1.2.6.5 2.4.11.1 2.4.11.2 2.4.12
1.6.5	Thermal Effects/Chemical			
1.6.5.4	Gas Production	H [b]	Could affect corrosion and microbes	1.2.1.2 1.2.1.3 1.2.1.8 1.2.2.5 1.2.2.10
2.2.10	Effects of Natural Gas	L	Amounts unlikely to be significant	- - -
2.4.11	Gas Transport			
2.4.11.1	Solution	H [b]	Which is the more important will depend on the presence of highly permeable strate in the clay.	1.2.6.5 1.5.2.2 2.4.11.2 2.4.12
2.4.11.2	Gas phase	H [b]		1.2.6.5 1.5.2.2 2.4.11.1 2.4.12
2.4.12	Gas-induced Groundwater Transport	H [b]	Could accelerate water flows	1.2.6.5 1.5.2.2 2.4.11.1 2.4.11.2
3.6.3	Inhalation			
3.6.3.2	Gases and Vapours (indoors)	H	Any radiological effects much likely to be higher indoors	1.2.6.5 etc
3.6.3.3	Gases and Vapours (outdoors)	L		- - -

NOTES

a H = High L = Low
b Duration of effect up to 10^4 years, assumed to start around the time of repository closure
c Duration of effect up to 10^3 years, assumed to start around the time of repository closure
d Only close links are shown.

TABLE 1 (Cont.)

ITEM	DESCRIPTION	JUSTIFICATION
1.1.1.1	Metal corrosion: localised	CCN
1.1.1.4	Stress corrosion: localised	CCN
1.2.1.4	Waste Magnox	JHR (Questioned by CCN)
1.2.1.5	Waste aluminium	JHR (Questioned by CCN)
1.2.1.6	Waste Zircaloy	CCN/JHR
1.2.1.7	Waste other metals	CCN/JHR
1.2.2.2	CH_4 and CO_2 production from non-cellulosics	JHR
1.2.2.3	Aerobic degradation	JHR
1.2.2.6	Effects of lithostatic pressure	JHR
1.2.2.7	Effects of microbial growth on properties of concrete	JHR
1.2.2.8	Effects of biofilms	JHR
1.2.2.11	Carbonate/bicarbonate exchange with concrete	JHR
1.2.2.13	Effects of radiation on microbial populations	JHR
1.2.3	Gas generation from concrete	S/JHR
1.2.4.3	Other active gases	JHR
1.2.5	Toxic gases	S/JHR
1.2.6.1	Transport in the waste container	JHR
1.2.7	Flammability	JHR
1.3.2	Nuclear criticality	S
2.2.1	Regional tectonic effects	S/KMC
2.2.2	Magmatic effects	S/KMC
2.2.3	Metamorphism	S/KMC
2.2.4	Diagenesis	S/KMC
2.2.5	Diapirism	S/KMC
2.2.10	Effects of natural gases	S/JHR
2.2.11	Geothermal effects	S
2.3.5	Salinity	S/KMC
2.3.6	Variations in groundwater temperature	S/KMC
2.4.2.3	Surface diffusion	S
2.4.4	Geosphere solubility constraints	S/HSW
2.4.6	Fracture mineralisation	S
2.4.13.2	Natural thermally induced groundwater transport	S (implied)
2.4.14	Biogeochemical changes	S
3.1.1.3	Sea level rise	S/KMC (Questioned by HSW)
3.1.1.4	Storm surges	S/KMC
3.1.2.3	Sea level changes	S/KMC
3.1.2.4	Storm surges	S/KMC

TABLE 2

Factors/Phenomena That Could Reasonably Be Neglected

ITEM	DESCRIPTION	JUSTIFICATION
3.2.2.4	Coastal denudation	S/KMC
3.2.4	Effects of sea-level change	KMC
3.3.4.4	Lake formation/sedimentation	S/KMC (Questioned by HSW)
3.3.4.5	Effects of sea level change	S/KMC (Questioned by HSW)
3.3.5	Surface flow characteristics (estuarine)	S/KMC
3.3.6	Surface flow characteristics (coastal waters)	S/KMC
3.3.7	Surface flow characteristics (ocean waters)	S/KMC
3.4.2	Ecological development (estuarine)	S
3.4.3	Ecological development (coastal)	S
3.4.4	Ecological development (oceanic)	S
3.5.1.4	Erosive coastal transport	S/KMC (implied)
3.5.5	Groundwater discharge to coastal waters	S
3.5.6	Groundwater discharge to coastal estuaries	S
3.5.8	Radionuclide transport in estuaries	S
3.5.9	Radionuclide transport in coastal waters	S
3.6.3.3	Inhalation of gases and vapours outdoors	JHR
3.6.3.5	Inhalation of salt particles	S
4.2.1	Deliberate recovery of wastes or associated materials	S
4.2.2	Malicious intrusion	S
4.2.5	Geothermal energy production	S
4.2.13	Underground weapons' testing	S

Note: S relates to comments by the secretariat in EG(90)P2. Other entries are initials of Expert Group members and relate to comments provided in Section 2.

TABLE 2 (Cont.)

1. NEAR-FIELD

1.1 Chemical/Physical Degradation

1.1.1 Structural and container metal corrosion
1.1.2 Physical degradation of concrete
1.1.3 Chemical degradation of concrete
1.1.4 Degradation of wastes

1.2 Gas Production, Transport and Flammability

1.2.1 Hydrogen by metal corrosion
1.2.2 Methane and carbon dioxide by microbial degradation
1.2.4 Active gases
1.2.6 Transport

1.3 Radiation Phenomena

1.3.1 Radioactive decay and ingrowth

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
1.4.5 Rock creek
1.4.6 Fracturing

1.5 Hydrological Effects

1.5.1 Changes in moisture content
1.5.2 Groundwater flow (unsaturated conditions)
1.5.3 Groundwater flow (saturated conditions)
1.5.4 Transport of chemically active substances into the near-field

1.6 Thermal Effects

1.6.1 Differential elastic response
1.6.2 Non-elastic response
1.6.3 Fracture changes
1.6.4 Hydrological changes
1.6.5 Chemical changes
1.6.6 Microbiological effects

TABLE 3

Factors/Phenomena Requiring Consideration

2. FAR-FIELD

2.1 Extra-terrestrial

2.1.1 Meteorite impact

2.2 Geological

2.2.6 Seismicity
2.2.7 Faulting/fracturing
2.2.8 Major incision
2.2.9 Weathering
2.2.11 Geothermal effects

2.3 Hydrological

2.3.1 Variations in groundwater recharge
2.3.2 Groundwater losses (direct evaporation, springflow)
2.3.3 Rock property changes
2.3.4 Groundwater flow

2.4 Transport and Geochemical

2.4.1 Advection
2.4.2 Diffusion
2.4.3 Hydrodynamic dispersion
2.4.5 Sorption
2.4.7 Organic colloid transport
2.4.8 Inorganic colloid transport
2.4.9 Transport of radionuclides bound to microbes
2.4.10 Isotopic dilution
2.4.11 Gas transport
2.4.12 Gas-induced groundwater transport
2.4.13 Thermally-induced groundwater transport

3. BIOSPHERE

3.1 Climatology

3.1.1 Transient greenhouse-induced warming
3.1.2 Glacial/interglacial cycling
3.1.3 Exit from glacial/interglacial cycling

3.2 Geomorphology

3.2.1 Generalised denudation
3.2.2 Localised denudation
3.2.3 Sediment redistribution

TABLE 3 (Cont.)

3.3 Hydrology

3.3.1 Soil moisture and evapotranspiration
3.3.2 Near-surface runoff processes
3.3.3 Groundwater recharge
3.3.4 Surface flow characteristics (freshwater)

3.4 Ecological Development

3.4.1 Terrestrial

3.5 Radionuclide Transport

3.5.1 Erosive
3.5.2 Groundwater discharge to soils
3.5.3 Groundwater discharge to wells or springs
3.5.4 Groundwater discharge to freshwaters
3.5.7 In surface water bodies
3.5.10 In plants
3.5.11 In animals

3.6 Human Exposure

3.6.1 External
3.6.2 Ingestion
3.6.3 Inhalation

4. SHORT-CIRCUIT PATHWAYS RELATED TO HUMAN ACTIVITIES

4.1 Related to Repository Construction

4.1.1 Investigation borehole seal failure
4.1.2 Shaft or access tunnel seal failure
4.1.3 Subsidence

4.2 Post-closure

4.2.3 Exploratory drilling
4.2.4 Exploitation drilling
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

FIGURE 1

RELATIONSHIP BETWEEN GAS GENERATION AND ITS CONSEQUENCES

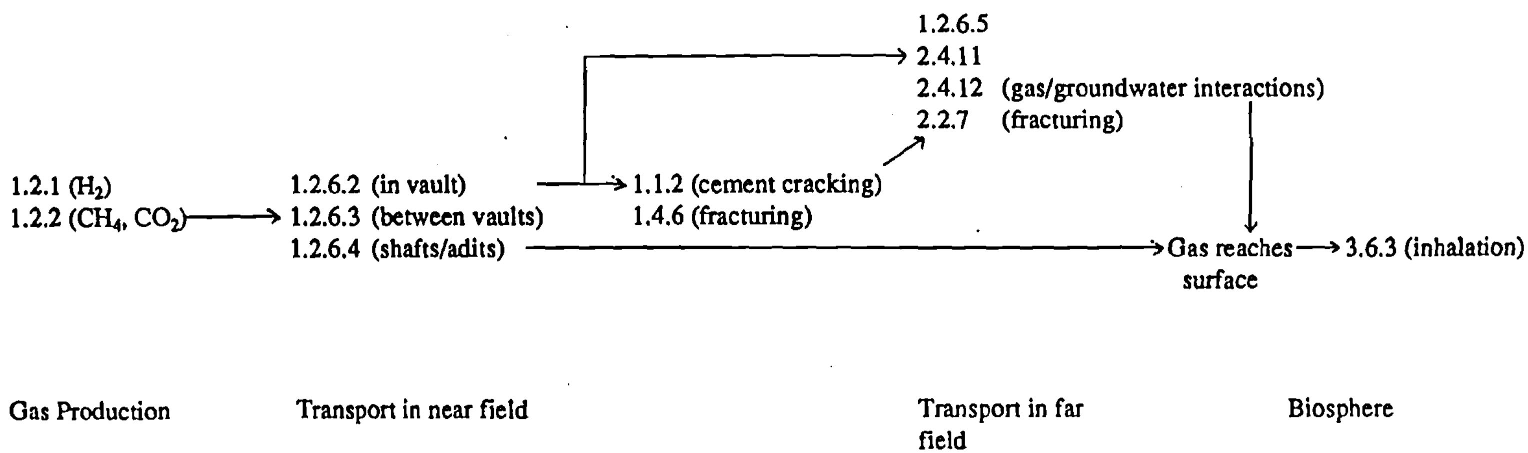


Figure 2. Influence Diagram Provided by H S Wheater.

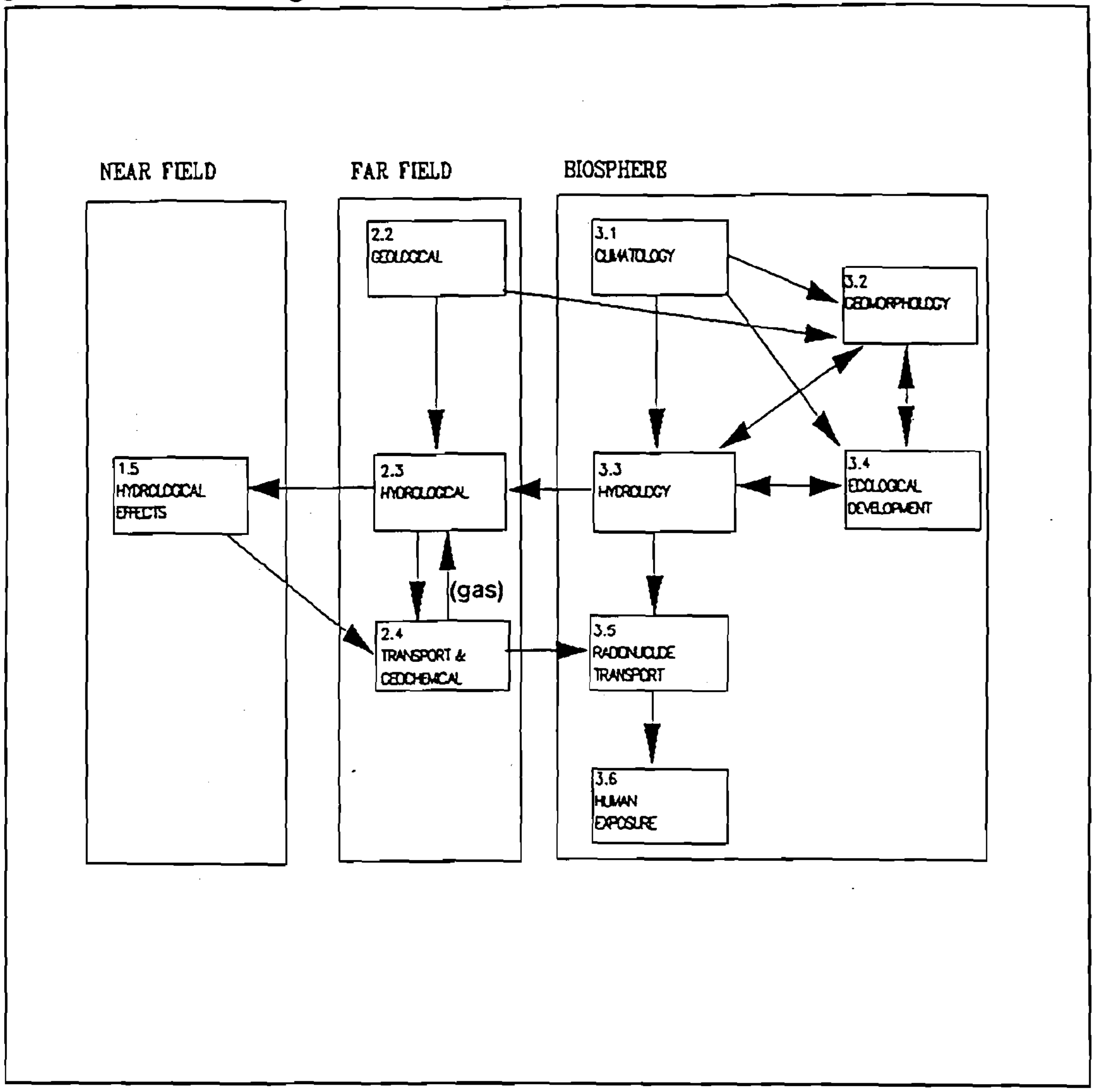
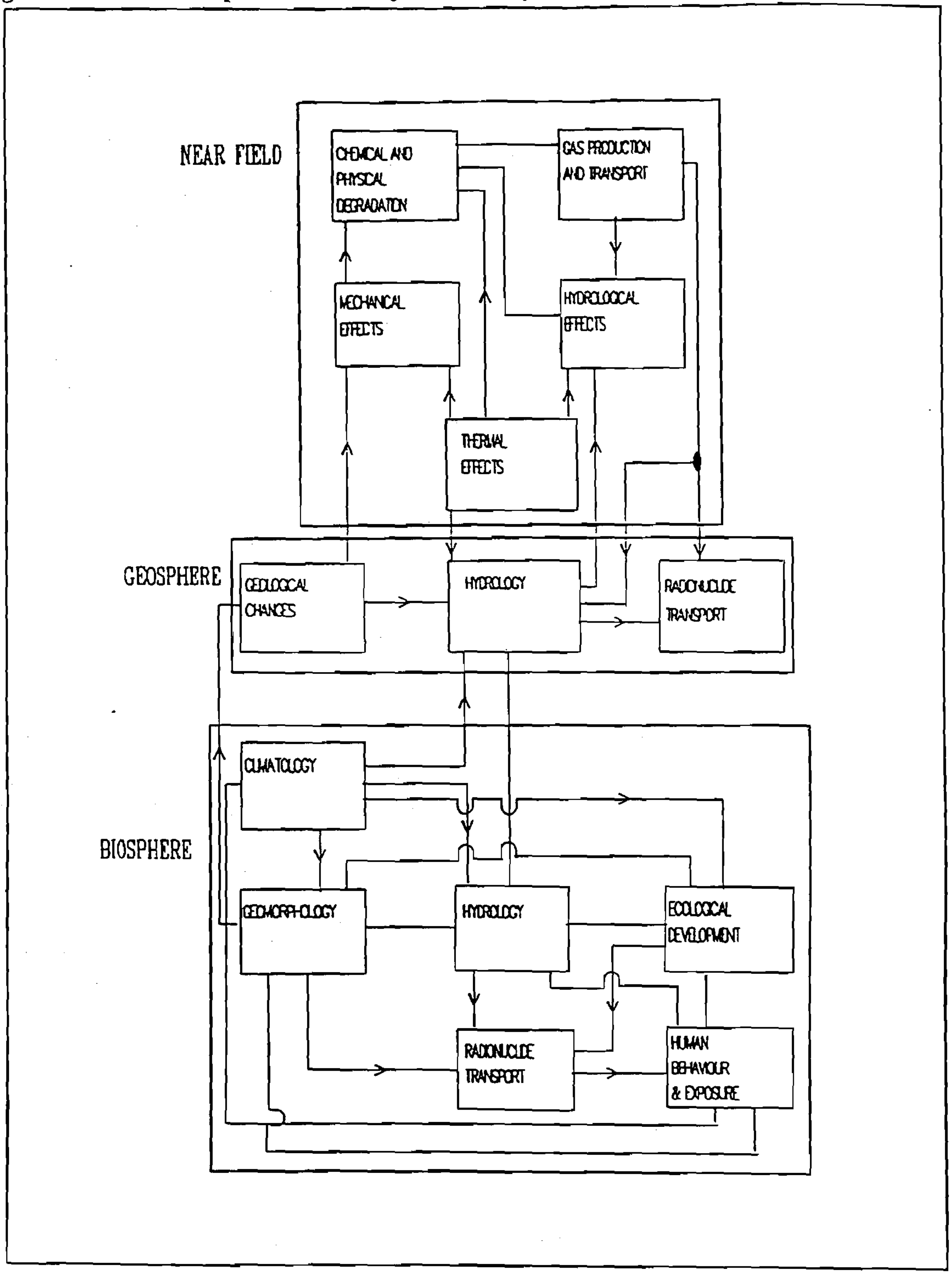


Figure 3. Relationships between Major Factors / Phenomena.



Lines indicate bi-directional flow unless marked otherwise.

DRAFT-FOR-COMMENT

ELECTROWATT
CONSULTING ENGINEERS AND SCIENTISTS

Grandford House, 16 Carfax, Horsham, West Sussex, RH12 1UP
Telephone: (0403) 50131, Telefax 59175, Telex 877960 elwatt g

Branch Office: Standford House, Garrett Field, Science Park South, Birchwood, Warrington, Cheshire, WA3 7BH. Telephone: (0925) 827757, Telefax 824498, Telex 877960 ELWATT G

MINUTES OF MEETING	
Project: HMIP Expert Group on Post-Closure Radiological Protection	EWE Project No. 2636
Venue: Room P3.151A, 2 Marsham Street, London	Date of Meeting 26th June 1990
Purpose of Meeting: To discuss Briefing Note EG(90)P4	

Attendance:

M C Thorne	(Electrowatt) (Chairman)
I Teasdale	(Electrowatt) (Secretary)
J Higgo	(BGS)
J West	(BGS)
B G J Thompson	(HMIP)
E Tufton	(Ove Arup)
H S Wheater	(Imperial College)

Apologies for Absence:

Apologies were received from K M Clayton, T D Davies, F P Glasser, J Knill, J H Rees and C C Naish

Distribution: Members of Expert Group
B G J Thompson
T J Sumerling

EWE File: 2636 Minutes issued by: Ian Teasdale — Date: 16 July 1990

MINUTES OF MEETING	ACTION
MCT began by reviewing the agenda, suggesting that the meeting begin by discussing the factors that could reasonably be neglected (Table 2 EG(90)P4) to see if any should be reintroduced before proceeding to define the minimum requirement for an assessment (including updating the influence diagram). He noted that due to absences the committee could not discuss all aspects fully.	
BGJT thanked everyone for coming on behalf of HMIP.	
1. <u>DISCUSSION OF EG(90)P4, TABLE 2</u>	
1.1.1.1 Metal corrosion - localised: General view (ET, JW) was that we could ignore this unless we have a long lived near field barrier (e.g. Zircaloy canister). It was noted that carbon steel canisters will add metal (hence gas) to the system. JW asked has repository been defined yet and MCT explained the Dry Run 3 conceptualisation. It was agreed that this process should be omitted (along with Crevice Corrosion).	
1.1.1.4 Stress corrosion - localised: omission agreed by everyone.	
1.2.1.4 Waste Magnox - J H Rees had expressed the opinion that it would all be corroded by the time that repository fails. ET agreed that swarf would have corroded but MCT thought that ends of fuel elements might be a problem. MCT felt that this should be omitted but would contact JHR by letter on this (also aluminium and Zircaloy wastes).	MCT
1.2.2.2 CH_4 and CO_2 production from non-cellulosics - JW thought that by-products might be a problem and it should be considered from point of view of organic complexation rather than gas.	
1.2.2.3 Aerobic degradation - Aerobes begin degradation. Although it is not clear whether this topic should be considered on it own account, it shouldn't be omitted (JW). It was agreed that it should be a supplementary topic for consideration.	
1.2.2.6 Effects of lithostatic pressure - Theoretical limit for sulphur bacteria is 250 atm (JW). Pressure in vault would be 20 - 60 atm. Microbe community would survive these pressures and	

MINUTES OF MEETING	ACTION

evolve toward optimal utilisation of these conditions over the period considered, hence this process was reinstated.

1.2.2.7 Microbes and properties of concrete. Although microbes can withstand high pH it was queried whether there was enough nutrients for them to grow and make by-products. Agreed to neglect.

Points were made that although 1.2.2.3-8 are not considered there, they may have an effect on 1.1.4 (degradation of waste). JH noted that hydrology should be considered as it may affect pressure and hence microbe growth.

1.2.2.11 Carbonate/bicarbonate exchange with concrete - Agreed that it doesn't affect microbes but belongs under 1.2.6 (transport).

1.2.2.13 Radiation and microbes - can be ignored (MCT).

1.2.3 Gas generation from concrete - can be ignored (MCT).

1.2.4.3 Other active gases - MCT noted that I-129, Sn-126 and Se-79 may form methylated compounds and be transported. JH questioned stability. Thought to be speculative and might reasonable be omitted.

1.2.5 Toxic gas - Agreed that this should be omitted as the requirement is to perform a radiological assessment.

1.2.6.1 Transport in the waste containers - agreed to omit.

1.2.7 Flammability - agreed to omit.

1.3.2 Nuclear criticality - *thought to be totally implausible* (MCT), agreed to omit.

It was noted that there was no real expert on far-field geological effects present.

2.2.1 Regional tectonic - this was re-introduced on the basis that over 10^6 years many initiating events will occur (e.g. ice ages).

ELECTROWATT
CONSULTING ENGINEERS AND SCIENTISTS

MINUTES OF MEETING	ACTION
A brief discussion resulted in agreement on the omission of 2.2.2, 2.2.3, 2.2.4, 2.2.5, 2.2.10 and 2.2.11 although it was suggested that geothermal effects could be made more explicit in 2.3.6 [2.3.5 (salinity) was accidentally not discussed].	
2.4.2.3 Surface Diffusion - JH supported the idea that this should just be included in normal diffusion (omitted).	
2.4.4 Geosphere solubility constraints - MCT (devil's advocate) suggested that gross change of chemistry (e.g. chalk → clay or salinity in corallian) could render it important. HW suggested that it was conservative to omit it. ET pointed out that 2.4.4.7 was important and could not be omitted. JH said that sorption was more important but a high concentration of Ca^{2+} could affect solubility. Omitted after some discussion.	
2.4.6 Fracture mineralisation - doesn't apply to Harwell. ET asked whether it would not occur in hard clay. Action on JH to investigate. Pending.	JH
2.4.13.2 Natural thermally induced groundwater flow - negligible but repository induced thermal flow needs investigation.	
2.4.14 Biochemical changes - omit as 2.4.5.7 already includes it.	
3.1.1.3 Sea level change (greenhouse warming) - HSW questioned this based on magnitude of rise. MCT suggested a maximum of 5 m (Harwell is 60 m OD) hence omit.	
3.1.1.4 Storms (greenhouse warming) - omitted.	
3.1.2.3 Sea level change (glacial cycling) - MCT will write to KMC	MCT
3.1.2.4 Storms (glacial cycling) - omitted.	
3.2.2.4 Localised denudation (coastal) - MCT will write to KMC	MCT
3.2.4 Effects of sea level change - MCT will write to KMC	MCT
3.3.4.4 Lake formation/sedimentation - Lakes could form easily and accumulate radionuclides. HSW pointed out that they are	

MINUTES OF MEETING	ACTION
subject to human control. MCT to include in letter to KMC. Reinstated.	MCT
3.3.4.5 Effects of sea level (hydrology) - reinstated.	
3.3.5 Surface flow characteristics (estuarine). Can be important for risk calculation but if we concentrate on local groups we need not model it. HW pointed out that estuarine sediments can accumulate radionuclides and can later be used for various human activities, notably after drainage and land reclamation. MCT discussed the effects of an ice free world, with sea levels 60 - 70 m A.O.D. Reinstate this process.	
3.3.6 Surface flow (coastal). This ought to be considered for different climate states.	
3.3.7 Surface flow (oceanic) - omitted.	
Ecological development for estuarine and coastal processes was reinstated for the same reasons as above, whilst for oceanic processes it was agreed that it could be ignored.	
Erosive coastal transport, groundwater discharge to estuaries and coastal waters, and radionuclide transport in estuaries and coastal waters were all reinstated.	
3.6.3.3 Inhalation of gases outdoors - general agreement to omit it.	
3.6.3.5 Inhalation of salt particles - Whilst you can obtain a heavy salt load (HSW), MCT considered it to be a second order process and it was omitted.	
The omission of various human intrusion types (i.e. deliberate recovery, malicious intrusion, geothermal energy production and underground weapons testing) was agreed upon. JH noted that they couldn't be modelled in any case.	
The topic of new factors to be introduced was considered. HW discussed the increase of urbanisation and management of water resources (artificial recharge etc.) as the world warms. This whole issue of such planning was not considered, although construction of underground towns was (neither was recreation policy or agricultural policy). It was noted	

that global warming (which is human induced) reduces recharge and increases usage. This results in the management of the groundwater cycle becoming more sophisticated (e.g. artificial recharge in N. London). This will move the hydrogeological cycle quicker and deeper hence the assumption the deep aquifers aren't used is wrong, as they could be used for make-up water. JW saw no reason not to use deeper aquifers, especially as MCT pointed out that aquifer water is not saline up dip of Harwell. It was noted that desalination could also concentrate nuclides. It was agreed that this should be investigated.

MCT suggested to BGJT that a varied selection of lifestyles other than subsistence should be included.

2. DEFINING A MINIMUM ASSESSMENT

It was proposed that the meeting work through EG(90)P2, Table 1.

1.1 Near-field basis was suggested to be a homogeneous well-mixed chemical soup, as in STRAW2, hence ignore 1.1.1 and 1.1.2 but not 1.1.3 or 1.1.4.

1.1.2 JH said that we should include degradation as we cannot ignore gas generated from it which leads to flow effects, over-pressurisation (physical damage) and biochemical effects.

It was suggested the repository induced thermal effects be included. Some figures for temperatures rises in DR3 were quoted from Vol. 3, Chap. 6.

LLW	Centre of tunnel	5°C	(consequence of backfill hydration)
	Periphery of tunnel	4.2°C	
	25 m from tunnel	1.7°C	
ILW	Centre of tunnel	25°C	(20°C from decay/5°C from hydration)
	Periphery of tunnel	23°C	
	25 m from tunnel	2.1°C	

ET pointed out that a group of tunnels would give a higher thermal peak at a later time. Consequences that must be considered are convective

MINUTES OF MEETING	ACTION

flow and interaction with gas generation. It was assumed that microbial and chemical consequences could be neglected.

1.1.1 We can neglect local metal corrosion as a control on waste being exposed to groundwaters but not with respect to H_2 generation. (1.2).

1.1.2 Contact between waste and groundwater due to cracks in concrete (ET). With respect to 1.2.2.4 it was noted by ET that such reactions are expansive and will affect host geology. Also crack and pore blockage (1.1.2.2 and 1.1.2.3) by clay particles may occur. The conclusion was to ignore concrete barrier degradation, but not resultant chemistry or stress fields.

1.1.3 Chemical degradation requires contact water changing. Also buffer provided by concrete will leach away and we should consider timescale for this outside the assessment.

1.1.4 Waste degradation to a well mixed system is fast and will not be seen ($\tau < 10^4$ y). Gas and heat production may shorten the time scale for migration and require the inclusion of 1.1.3 and 1.1.4. The important sub-sections we thought to be 1.1.3.1, 1.1.3.3, 1.1.4.1 and 1.1.4.2. 1.1.4.7 was though not important whilst the others should be considered outside the assessment.

The final conclusion is that items in 1.1 should go to external study in an assessment.

1.2.1 Included in assessment: sub-items 1, 2, 3, 4, 5 and 6 (MCT to contact J H Rees on last three).

Not included: sub-items 7 and 8 (8 should be included in 1.2.6 instead).

1.2.2 Included in assessment: sub-items 1, 4, 10 and 12.

Not included: sub-items 2, 3, 5, 6, 8, 9, 11, 13 (7, 8 and 11 should be moved to 1.2.6).

9 was thought to be second order and 5 and 6 may have to be reintroduced at a future date.

ELECTROWATT
CONSULTING ENGINEERS AND SCIENTISTS

MINUTES OF MEETING	ACTION
1.2.3 Gas generation from concrete need not be considered.	
1.2.4 Active gases should be the subject of scoping calculations. MCT suggested that other methylated gases be considered too.	
1.2.5 Toxic gases need not be considered.	
1.2.6 The effect of transport should be considered for gases.	
1.2.7 Flammability need not be considered.	
1.3 For radiation phenomena: decay and ingrowth (1.3.1) should be included whilst criticality (1.3.2) need not.	
1.4 The important mechanical effect from gas production is the stress field (1.4.2) and should be the subject of supplementary study (related to 1.4.4 - ET). Other effects can be omitted.	
1.5 ET pointed out that the hydrological effects are governed by the properties of the host rock. Dewatering will occur mainly from large pores and fractures, and due to stress-related effects. Resaturation will occur on a timescale of decades. Water content in repository will be high (from pumped backfill). Readily agreed to include groundwater flow (saturated and unsaturated) (1.5.2 and 1.5.3) and to omit change in moisture content (1.5.1).	
Some discussion followed concerning transport of chemically active substances. JW said that 1.5.4.3 would be important if incoming water contained sulphate. ET thought that incoming water would not be pure, but pointed out that as we were struggling to think of scenarios they must be secondary effects. HSW thought it dangerous to ignore inorganic ions. JH suggested that humic and fulvic acids will precipitate internally (blocking pores) and not be transported. HSW noted that this would reduce flow. Conclusion was that MCT should look at background chemistry, but ignoring 1.5.4.4 and 1.5.4.5.	MCT
1.6 Thermal effects. The discussion began with chemical effects. Sorption and solubility where highlighted for special study (1.6.5.7 and 1.6.5.8) whilst speciation (1.6.5.9) should be studied	

outside the assessment, as it would help define sorption. Most of the other effects were considered under other headings.

Thermal hydrological changes (1.6.4) should be included in an assessment, whilst microbiological consequences were deemed to be second order.

The remaining processes (1.6.1, 1.6.2 and 1.6.3) should be the subject of a separate geotechnical study.

JH noted that transport out of vault was not included, so a new section 1.7 was added with topics solubility, sorption and speciation.

2.1 The effect of a meteorite impact (2.1.1) has been shown to be small by MCT (cumulative probability of a large crater 3 - 7 x 10^{-6}) hence it can be ignored.

2.2 It was noted that no geologist was present and further consultation may be necessary. Regional tectonic effects (2.2.1) should be included due to large consequence and proximity to N. Sea basin (JH). 2.2.6 (seismicity) should be included in a pre-study to see how it could affect repository, as should 2.2.7 (faulting and fracturing).

HSW thought that weathering should be modelled as it affects conductivity and dispersion. Remaining processes can be ignored (MCT pointed out, for 2.2.8, that a major incision would lead to massive dilution).

2.3 The effects of groundwater recharge (2.3.1) and losses (2.3.2) must be included in the hydrology model.

Changes in rock properties (porosity and permeability) should be considered especially with respect to ice-loading (ET) and pore-structure/dispersion (HSW).

Microbial pore blocking (2.3.3.3) is important (JW) if sufficient nutrient is available (CO_2 may be utilised, but process is controlled by N and P). 2.2.3.4 can be subsumed under weathering (2.2.9).

MINUTES OF MEETING

ACTION

2.3.4 HSW stated that we must include non-Darcy flow especially if release is via the chalk. HSW also discussed the problem of assuming homogeneity, saying that much progress had been made in describing heterogeneity and this must be considered. Unsaturated flow should be considered for the biosphere, but not necessarily for the geosphere.

2.3.5 Salinity can be ignored, although it might be important at the end of an interglacial cycle.

2.3.6 Variations in groundwater temperature need only be considered in so far as induced by repository (not natural variation).

2.4 The three main transport processes should be included: advection (2.3.1), diffusion (2.4.2) and dispersion (2.4.3) whilst solubility constraints (2.4.4) can be ignored.

2.4.5.1 Linear sorption should be modelled.

2.4.5.2 JH pointed out that there is no need to consider non-linear effects (this could be explored outside assessment).

2.4.5.3 JH said that we should keep reversible but not irreversible (2.4.5.4) sorption. Typically laboratory K_d values are underestimates of total K_d due to the limited timescales, which render the processes observed effectively irreversible. Generally, in-diffusion measurements are preferred over batch studies.

2.4.5.5 HSW noted that changing recharge of aquifers can change Eh and pH, hence boundary conditions can affect geochemistry.

2.4.5.7 The effects of complexing agents is important (also 2.4.5.8 and 2.4.5.9) as they can remain stable through to biosphere.

2.4.5.10 JH noted that colloids don't move in laboratory studies hence we can ignore this process in comparison with transport of complexes (2.4.5.7).

2.4.5.12 Although significant this topic should be put into external models and the consequences folded into the assessment.

MINUTES OF MEETING		ACTION
2.4.5.13	Effects of microbes on sorption is a topic for research which may need to be included later.	
2.4.6	Resolve to seek wider advice on fracture mineralisation.	MCT
2.4.7	Both organic and inorganic (2.4.8) colloid transport were discussed under sorption (2.4.5.10) but people will ask questions on this topic.	
2.4.9	Microbial transport of radionuclides has been covered elsewhere. Action on JW to look at work done by oil industry on transport of starved microbes through rock.	JW
2.4.10	Isotope dilution which is significant for C-14, Cl-36 and I-129 has already been covered under sorption (isotope exchange).	
2.4.11	Gas transport should be included, although it is very case dependent.	
2.4.12	Gas induced groundwater transport should be included.	
2.4.13	Repository induced thermally induced groundwater transport should be included, 2.4.13.2 can be ignored.	
2.4.14	All biogeochemical processes have already been considered.	
3.1.1	Transient greenhouse gas induced warming effects should be considered except for 3.1.1.3 and 3.1.1.4. Action on MCT to write to Horrill and Parry for advice on ecological effects.	MCT
3.1.2	All of the glacial/interglacial cycling processes should be included except sea level rise and storm surges.	
3.1.3	If this occurs it would be important: MCT to write to T D Davies for advice.	MCT
3.2.1	Generalised denudation (except aeolian) should be considered.	
3.2.2	Local denudation (except coastal) should be considered.	
3.2.3	Sediment redistribution to be included.	

MINUTES OF MEETING	ACTION

3.2.4 Effects of sea level change on geomorphology should be included.

Referring to the minimum assessment on pg. 19 of EG(90)P4 it was noted that item (vi) should include global warming and effects from the end of glacial/interglacial cycling. Also that item (vii) is not acceptable and that (viii) could possibly extend to cover dynamics. Item (ix) must be corrected to include gas transport although it could be considered as a separate pathway (recognising potential interaction with groundwater).

3.3 HSW noted that interaction between surface flow and groundwater is important (also effects from agricultural policies). It was agreed to rename 3.3.2 as Surface Hydrology and that development and application of a detailed model outside the assessment would be appropriate. All the processes affecting hydrology were to be included except effects of sea level change on estuarine flow (3.3.5.4) and coastal waters (3.3.6.3) and we can ignore factors relating to ocean waters (3.3.7).

3.4 Ecological development (hydrology) should be included except for oceans (3.4.4).

3.5.1 Erosive radionuclide transport should consider fluvial (3.5.1.1) and glacial (3.5.1.3) ignore aeolian (3.5.1.2) and note that coastal (3.5.1.4) was second order.

3.5.2 Groundwater discharge to soil to be included except volatilisation (3.5.2.4) which is second order.

Other groundwater discharge processes (3.5.3, 3.5.4, 3.5.5 and 3.5.6) should be included, although deep groundwater flows to coastal waters could be the subject of a scoping study (HSW).

3.5.8 Estuary effects are important especially salinity variation (3.5.8.4) (JH).

3.5.9 Include all effects for coastal waters, except effects of coastal erosion (3.5.9.6) and effects of sea-level change (3.5.9.7).

MINUTES OF MEETING	ACTION
3.5.10 MCT made the point that present assessments contain a simple representation of the effects of all the listed processes. Hence transport by plants is included implicitly as is transport by animals (3.5.11).	
3.6.1 Human exposure by all external pathways should be included.	
3.6.2 Human exposure by ingestion should be included (except wild plants (3.6.2.4) and animals (3.6.2.5).	
3.6.3 Inhalation of soils (3.6.3.1) and gases (3.6.3.2) should be considered - other processes can be ignored.	
4.1 ET pointed out that access shafts are an integral part of repository and flow pathways up them should be investigated (although maybe not as part of the main assessment).	
4.2 For post-closure short circuit pathways we have already excluded 1, 2, 5 and 13. We should now include 3 and 12 and exclude 10 and 11. It would be possible to define a dose for the remainder (4, 6, 7, 8 and 9) given a limited number of assumptions.	
HSW discussed some possible scenarios e.g. agricultural change, urban development, managed groundwater and raised the question, "should we stick with our current climatic conditions and critical groups or try to define more appropriate bases for the future".	
To recap on items in minimal assessment (p. 19 EG(90)P4).	
i) Yes we can neglect details of structural/physical degradation although we should consider secondary processes from concrete degradation.	
ii) Cannot neglect effects of gas generation (only neglect gas transport).	
iii) Cannot neglect repository induced thermal effects.	
iv) We cannot ignore non-Darcy flow and the assumption of homogeneity is wrong. We should perform supplementary studies for changes in structural geology.	

MINUTES OF MEETING	ACTION
v) Assume transport is in ionic form (with complexation as a secondary process).	
vi) Assumption of glacial/interglacial cycling is valid (however, we could consider greenhouse warming and end of cycling as secondary processes).	
vii) Geomorphological change should be considered (except aeolian erosion).	
viii) Agreed, although maybe we should use more analogue lifestyles.	
ix) Agreed, but gas transport should be considered separately.	

EG(90)P6

HMIP Expert Group on Post-Closure Radiological Assessment: Briefing Note 6

M C Thorne

Electrowatt Engineering Services (UK) Ltd
Grandford House
16 Carfax
Horsham
West Sussex
RH12 1UP

September 1990

1. INTRODUCTION

This briefing note is intended to provide a basis for discussion at the next meeting of the Expert Group. It covers:

- Administrative details for the meeting;
- Previously issued material that will be required;
- Supplementary information recently received;
- Agenda;
- Supplementary guidance in relation to the agenda items.

2. ADMINISTRATIVE DETAILS

Venue: Department of the Environment, 2 Marsham Street
Room P3/136
Please go to the North Tower, Entrance 5.

Date: 25th September 1990

Time: 10:30 to 17:00

An overhead projector will be available, if members of the group wish to illustrate particular points with visual material.

3. PREVIOUSLY ISSUED MATERIAL

Relevant documents for this meeting comprise:

EG(90)P2 - Issued April 1990
EG(90)P4 - Issued June 1990
Minutes of a meeting of the group which took place on 26th June 1990, dated 16th July 1990 and distributed August 1990.

4. SUPPLEMENTARY INFORMATION

At the last meeting of the group, various matters arose that were to be dealt with by correspondence. The various replies received are reproduced below.

4.1 GAS EVOLUTION FROM MAGNOX WASTES

The following information was received from J H Rees.

The current view on this point is that gas evolution from cemented Magnox wastes in a repository is a low priority area in assessing any hazards due to gas evolution. The main reason is that the scope for hydrogen generation from Magnox - about 10^7 m^3 in total - is about 2 orders of magnitude below that for the various steels present in ILW and LLW [1].

The assessment of a corrosion lifetime of 10^4 years for Magnox is based on work carried out for the storage of the cemented fuel cladding before disposal [2]. Compared with an average corrosion time for waste steel of say, 10^3 years, this implies that the rate of evolution of hydrogen from steels would be one thousand times the rate of formation from Magnox. Incidentally, it seems unlikely that more than a small proportion of the Magnox will have corroded before disposal.

Under disposal conditions, two additional factors may affect the corrosion rate:

(a) The temperature will be above ambient and may reach 80°C, say.

(b) Groundwater entering vaults will eventually contact the Magnox.

Breakaway of the passivating layer could occur with an enhancement in the rate of corrosion. Even if this does happen, the effect will need to be very marked indeed in order to rival, let alone exceed, the production of hydrogen from steels:

(a) The higher temperature may also increase the rate of corrosion of steel.

(b) A different passivating layer may form after some relatively rapid corrosion of the Magnox.

(c) Good contact with water needs to be maintained. Bubbles of hydrogen on the surface may in themselves prevent this, and the canister and grout may limit the availability of water for relatively rapid corrosion.

In summary, hydrogen generation from Magnox seems to merit only a low priority in hazard assessments. A small amount of work in this area is planned in the Nirex research programme this financial year to examine the merit of this conclusion.

In respect of corrosion of aluminium, I think that the very high rates of initial corrosion on waste immobilisation [2] (which seems to be followed by the formation of a passivating layer) could account for the 0.5 mm-thickness of the main waste stream, MTR fuel cladding [1]. It seems likely that the amount of aluminium in wastes will be much less than the mass of Magnox.

References

1. J H Rees, Gas Evolution and Migration in Repositories: Current Status May 1989. NSS/G112.

2. J H Rees and W R Rodwell, Gas Evolution and Migration in Repositories: Current Status May 1988. NSS/G104.

4.2 EFFECTS OF SEA-LEVEL CHANGE AND RELATED MATTERS

The following material was received from K M Clayton.

Sea-level. I do not believe there is any way that sea-level can affect the river above the Goring Gap, unless of course it were to rise high enough (>40 m) to flood through the Gap. I accept that there are river terraces above Goring Gap, and that some of these have been linked with various interglacial sea-levels, but they were caused by climatic changes, not by changes in sea-level affecting the river upstream. Even the downcutting associated with the two buried channels at Tilbury did not reach west of Central London, whilst such terraces as the Boyn Hill below London which may be affected by sea-level (and in that sense be thalassostatic terraces) show no estuarine/tidal influence except below London. Further, studies of streams and rivers behind mill dams and reservoirs in the USA and elsewhere show that the influence of a raised base-level extends a very modest distance upstream, being largely accommodated in channel adjustments, rather than a change of slope. Thus, I can see no possible influence from stable, low, or high sea-levels within the range encountered during the last million years.

Downstream transportation of radionuclides. This I accept can occur and these may well be concentrated in the estuarine region at the time. The location of that will indeed depend on the position of sea-level at the time.

Lake/formation and sedimentation. The only lakes I would expect to form in this area would either be ox-bow lakes from meander cut-offs and possibly thawed pingos following periglacial conditions. These small lakes should be allowed for, but will be uncommon and short lived.

The exception, of course, is if the area is reached by an ice-sheet, but the various possibilities then including lakes are no doubt best considered under the glaciation heading.

4.3 ECOLOGICAL CHANGES DUE TO GREENHOUSE WARMING AND/OR GLACIAL/INTERGLACIAL CYCLING

The following material, received from A D Horrill, focuses upon West Cumbria, but the principles are more generally applicable.

One has to assume that we are dealing with a fixed location, e.g. West Cumbria, because either of the two changes envisaged really correspond to a latitudinal shifting of the earth's climatic belts. We are therefore asking what changes will take place in relation to the present situation.

There is also the question of Man's interference. It is very unlikely that Man is going to stand by and let these changes take place without a considerable amount of intervention. There is really no "natural vegetation" of any type left in much of the British Isles. Even in the remoter parts of Scotland there are severe modifications due to sheep grazing.

a) Greenhouse Warming

If there is a warming effect and a climatic amelioration then the character of an area such as Cumbria could change dramatically. If rainfall decreased the formation of peat on the uplands would cease. There is a possibility that oxidation of the present material could take place maybe yielding a much more rocky soil. Hence the water holding capacity would be reduced and any rainfall subject to rapid drainage and further possible erosion.

The better land, subject to agriculture, could become more amenable to arable farming and (if above the new sea level) the shift would be away from dairying and meat production. The implications for man might be that in this scenario diet may move more towards the vegetarian side as plants become easier to grow.

On the natural vegetation side, the changes could be too fast for existing vegetation to migrate. The more drought sensitive species in the present flora could therefore die off and be replaced by opportunistic invasive species, possibly annuals, with a high turnover rate in each generation. The woodland situation, if permitted by Man, would swing towards the dry deciduous type of woodland found in southern Europe.

To sum up then, if warming lead to a lower rainfall, vegetational changes could lead to more rapid runoff and perhaps even erosion. Peat formation in many upland areas could cease due to lack of moisture. There could be a swing towards more agricultural land use. Species present now could die out and be replaced by more invasive types and woodland become more deciduous.

b) Interglacial Cycling

In contrast to the above scenario, I assume that precipitation will increase and temperatures will drop. In this case, the climate of an area such as Cumbria will become even more unsuitable for any type of arable farming and livestock rearing and the harvesting of natural animal populations become the only possible land use.

Natural vegetation will tend towards that of the northern latitudes and initially Pine or Birch forest become the climax vegetation. With a further decline in the climate, dwarf shrubs and tundra conditions could develop as is found in much of northern Europe.

The implications for Man's diet in this case could be the reverse to that outlined above and a much greater dependence develop on meat and other animal products.

Although the amount of precipitation will increase, the retention may also increase. There could be larger amounts held in permanent snow or even glaciers, if the temperature drop is large enough. There will certainly be an increase in the retention of water by organic soils as the peaty layers build up, and woodland areas will prevent rapid runoff and erosion.

Roughly then Man's diet could become much more dependent on animal products under these conditions. The countryside will be less amenable to any farming but some types of animal husbandry may persist. The vegetation will become more retentive of precipitation and possibly this will even out the supply to ground water systems.

4.4 GREENHOUSE GAS EFFECTS LEADING TO TERMINATION OF GLACIAL/INTERGLACIAL CYCLING

The following is a slightly edited version of material supplied by T D Davies.

Our current feeling at the Climatic Research Unit is that Tom Wigley's guess of a 10% probability of exiting from glacial/interglacial cycling is an overestimate. This opinion is strongly based on results from A Berger's work, which will be summarised in a forthcoming NSS report, where he suggests that the glacial cycle will be moderated, but not eliminated, by greenhouse gas warming.

5. AGENDA

1. Chairman's Introduction

2. Review of Work to Date

   2.1 Comprehensive List of Factors and Phenomena

   2.2 Elimination of Factors and Phenomena

   2.3 Characteristics of a Minimal Assessment

   2.4 Preferred Enhancements of a Minimal Assessment

3. Ranking of Factors and Phenomena

   3.1 Additions to the Minimal Assessment

   3.2 Subtractions from the Minimal Assessment

4. Confidence in Assessment Results

   4.1 Minimal Relative to Ideal Assessments

   4.2 Augmented Related to Ideal Assessments

   4.3 Impoverished Relative to Ideal Assessments

5. Requirements for Further Work

   5.1 Underlying Research

   5.2 Model Development

   5.3 Data Acquisition

6. GUIDANCE ON THE AGENDA

6.1 COMPREHENSIVE LIST OF FACTORS AND PHENOMENA

During the exercise, various suggestions have been made with respect to this list. A finalised version is included as Table 1, which also incorporates brief comments derived from earlier guidance notes and minutes, and an indication of which factors and phenomena have been generally accepted as not requiring further consideration.

Initially, a few minutes will be devoted to reviewing this list and the exclusions, concentrating on the very few debatable items.

6.2 CHARACTERISTICS OF MINIMAL AND AUGMENTED ASSESSMENTS

The characteristics of the Minimal Assessment were defined in the Minutes of the Meeting of 26th June 1990 and are summarised in Table 2. There will be a brief discussion as to whether this is the final view of the Group as to what constitutes a minimum adequate assessment.

Following this, the Minimal Assessment will be reviewed against Table 1 to agree a limited number (4 or 5) preferred enhancements. These enhancements will be used singly or in combination to define several potential Augmented Assessments.

6.3 RANKINGS OF FACTORS AND PHENOMENA

The aim of this agenda item is to form an ordered sequence of preferred approaches to assessment. The Minimal Assessment forms a reference case. It is taken to be an assessment which is generally adequate, but which contains limited biases and unresolved issues. The first step will be to rank order the various Augmented Assessments defined under agenda item 2.4. However, even the Minimal Assessment implies a substantial programme of work and would stretch the present generation of models to, or beyond, their limits. Thus, an equally important agenda item is to identify and rank order those items which could be dropped from the Minimal Assessment, recognising that substantial and significant biases may, as a consequence, be introduced into the results obtained.

Thus, the output from agenda, item 3 is a ranked list of approaches to assessment, centred on the Minimal Assessment.

6.4 CONFIDENCE IN ASSESSMENT RESULTS

For the purpose of this exercise, we define the principal output from an assessment as the maximum of the expectation value of annual individual risk (taken over all futures) at any time over the next 10^6 years. We also take it to be acceptable to estimate the risk to an accuracy of plus or minus one order of magnitude. It is emphasised that these rules are adopted for the purpose of this exercise and do not necessarily constitute a statement of HMIP policy or intentions in respect of actual assessments.

Given the structured list developed under agenda item 3, the aim of agenda item 4 is to address the question:

> 'How confident are we that, given the appropriate models and data, each of the assessment procedures proposed would give an estimate of risk within an order of magnitude of the true value?'

It is emphasised that, in each case, we assume that the models and data available are fit-for-purpose. Uncertainties and biases due to limitations in conceptual models, mathematical models and underlying data are not being addressed at this meeting.

The above question will be addressed in three stages.

a) The adequacy of the Minimal Assessment procedure.
b) The degree to which it can be improved by augmentation.
c) The degree to which it would be degraded by impoverishment.

It is recognised that individuals will find it difficult to make semi-quantitative judgements of this nature without extended time for reflection (and even, perhaps, some calculation). Thus, views obtained at the meeting will be regarded as provisional and subject to modification by correspondence. Nevertheless, it is emphasised that an attempt to quantify our confidence in assessment methodologies is an essential pre-requisite for judging the adequacy and comprehensiveness of the approaches adopted by the industry and by the authorising Departments.

6.5 REQUIREMENTS FOR FUTURE WORK

The work undertaken by the Expert Group to date supplemented by the formation of a ranked set of assessment methodologies, provides a very useful basis for discussing research and development priorities in support of assessments. It is proposed that this topic be addressed briefly at the end of the meeting. However, time will be too limited for this matter to be covered in detail, so the main aim will be to provide a basis for subsequent correspondence.

Item	Description	Inc.	Comments
1.	Near-field	√	General area important
1.1	Chemical/physical degradation	√	General area important
1.1.1	Structural and container metal corrosion	√	Short-term barrier degradation; relevant to gas production
1.1.1.1	Metal corrosion: localised	x	Minutes
1.1.1.2	Metal corrosion: bulk	√	See 1.1.1
1.1.1.3	Metal corrosion: crevice	x	Minutes
1.1.1.4	Stress corrosion	x	Minutes
1.1.2	Physical degradation of concrete	√	Short-term barrier degradation; relevant to chemical conditioning
1.1.2.1	Cracking	√	Water penetration and characteristics
1.1.2.2	Sealing of Cracks	√	As 1.1.2.1
1.1.2.3	Pore blockage	√	As 1.1.2.1
1.1.2.4	Alkali-aggregate reaction	√	Possibility of occurrence needs investigation
1.1.2.5	Cement-sulphate reaction	√	As 1.1.2.4
1.1.3	Chemical degradation of concrete	√	Major control on near-field chemistry
1.1.3.1	Changes in pore water composition, pH, Eh	√	See 1.1.3
1.1.3.2	Exchange capacity exceeded	√	Possibly not an independent item (Secretariat)
1.1.3.3	Alkali-aggregate reaction	√	See 1.1.2.4
1.1.3.4	Cement-sulphate reaction	√	See 1.1.2.5
1.1.4	Degradation of wastes	√	Major control on source term
1.1.4.1	Metal corrosion	√	Major component
1.1.4.2	Leaching	√	Important process
1.1.4.3	Complex formation	√	Potential major control on solubility and sorption
1.1.4.4	Colloid formation	√	As 1.1.4.3
1.1.4.5	Microbial degradation of organic waste	√	Important process
1.1.4.6	Microbial corrosion	√	Potentially important modifying factor
1.1.4.7	Radiolysis	√	Probably secondary consideration (Secretariat)
1.2	Gas production, transport and flammability	√	Major potential pathway
1.2.1	Hydrogen by metal corrosion	√	Major component
1.2.1.1	Structural steel	√	Major item

TABLE 1

Factors and Phenomena Considered

Item	Description	Inc.	Comments
1.2.1.2	Container steel	√	Major item
1.2.1.3	Waste steel	√	Major item
1.2.1.4	Waste Magnox	x	EG(90)P4, Minutes, This note
1.2.1.5	Waste aluminium	x	EG(90)P4, Minutes, This note
1.2.1.6	Waste Zircaloy	x	EG(90)P4
1.2.1.7	Waste other metals	x	EG(90)P4
1.2.1.8	Effects of microbial growth on concrete	√	Potentially important modifier of local chemical regime and directly relevant to gas production
1.2.2	Methane and carbon dioxide by microbial degradation	√	Major components
1.2.2.1	Cellulosics	√	Major item
1.2.2.2	Other susceptable organic materials	x	Minor source of gas, but relevant to organic complexation (item 1.1.4.3)
1.2.2.3	Aerobic degradation	√	Not important in own right, but partly defines initial conditions for anaerobic degradation, see Minutes
1.2.2.4	Anaerobic degradation	√	Long-term regime
1.2.2.5	Effects of temperature	√	Effects on metabolic activity and chemical degradation of cellulose (Secretariat)
1.2.2.6	Effects of lithostatic pressure	√	Supplementary modifying factor (see Minutes), partly determined by hydrology
1.2.2.7	Effects of microbial growth on properties of concrete	x	EG(90)P4, Minutes
1.2.2.8	Effects of biofilms	x	EG(90)P4
1.2.2.9	Effects of hydrogen from metal corrosion	√	Microbial utilisation (Secretariat)
1.2.2.10	Inhibition due to the presence of toxic materials	√	Secondary factor
1.2.2.11	Carbonate/bicarbonate exchange with concrete	x	Included in transport (item 1.2.6)
1.2.2.12	Energy and nutrient control of metabolism	√	Primary control
1.2.2.13	Effects of radiation on microbial populations	x	EG(90)P4
1.2.3	Gas generation from concrete	x	EG(90)P4
1.2.4	Active gases	√	Major item
1.2.4.1	Tritiated hydrogen	√	Major component
1.2.4.2	Active methane and carbon dioxide	√	Major component
1.2.4.3	Other active gases	x	EG(90)P4, Minutes

TABLE 1 (Cont.)

Item	Description	Inc.	Comments
1.2.5	Toxic gases	x	EG(90)P4, Minutes
1.2.6	Transport	√	Major item
1.2.6.1	In the waste container	x	EG(90)P4, Minutes
1.2.6.2	In the vault between containers	√	Secondary factor (Secretariat)
1.2.6.3	Between vaults	√	Significant in pressure build-up
1.2.6.4	In the near-field, including vicinity of shafts and adits	√	Depressurisation, routes to surface
1.2.6.5	Into and through far-field	√	As 1.2.6.4
1.2.7	Flammability	x	EG(90)P4, Minutes
1.3	Radiation phenomena	√	Fundamental processes
1.3.1	Radioactive decay and ingrowth	√	Fundamental processes
1.3.2	Nuclear criticality	x	EG(90)P4, Minutes
1.4	Mechanical effects	√	Generally, topics in this area can be studied by detailed modelling outside the assessment proper c.f. EG(90)P2
1.4.1	Canister or container movement	√	
1.4.2	Changes in 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	√	Major control on source term
1.5.1	Changes in moisture content	√	Secondary effect at early times (but see 1.5.2.2)
1.5.1.1	Due to dewatering	√	As 1.5.1
1.5.1.2	Due to stress relief	√	As 1.5.1 (but see 1.5.2.2)
1.5.2	Groundwater flow (unsaturated)	√	As 1.5.1
1.5.2.1	Initial	√	As 1.5.1
1.5.2.2	Due to gas production	√	Could feasibly significantly extend unsaturated period
1.5.3	Groundwater flow (saturated)	√	Major control on source term
1.5.4	Transport of chemically active substances into the near-field	√	Modifiers of solubility and sorption
1.5.4.1	Inorganic ions	√	As 1.5.4
1.5.4.2	Humic and fulvic acids	√	As 1.5.4
1.5.4.3	Microbes	√	As 1.5.4 (c.f. Minutes, page 11)
1.5.4.4	Organic complexes	√	As 1.5.4
1.5.4.5	Colloids	√	As 1.5.4

TABLE 1 (Cont.)

Item	Description	Inc.	Comments
1.6	Thermal effects	√	It was generally agreed that this main topic and all its subtopics require consideration (c.f. Minutes)
1.6.1	Differential elastic response	√	c.f. 1.4
1.6.2	Non-elastic response	√	c.f. 1.4
1.6.3	Fracture changes	√	c.f. 1.4
1.6.3.1	Aperture	√	c.f. 1.4
1.6.3.2	Length	√	c.f. 1.4
1.6.4	Hydrological changes	√	Secondary effect (Secretariat)
1.6.4.1	Fluid pressure	√	
1.6.4.2	Density	√	Mainly a far-field concern
1.6.4.3	Viscosity	√	
1.6.5	Chemical changes	√	Thought to be the major item of 1.6 (c.f. Minutes)
1.6.5.1	Metal corrosion	√	Secondary effect
1.6.5.2	Concrete degradation	√	Secondary effect
1.6.5.3	Waste degradation	√	Secondary effect
1.6.5.4	Gas production	√	Secondary effect
1.6.5.5	Complex formation	√	Secondary effect
1.6.5.6	Colloid production	√	Secondary effect
1.6.5.7	Solubility	√	Primary effect (Minutes)
1.6.5.8	Sorption	√	Primary effect (Minutes)
1.6.5.9	Species equilibrium	√	Studied outside assessment to define sorption (Minutes)
1.6.6	Microbial effects	√	Secondary (Minutes)
1.6.6.1	Cellulose degradation	√	Secondary effect
1.6.6.2	Microbial activity	√	Secondary effect
1.6.6.3	Microbial product reactions	√	Secondary effect
1.7	Transport out of the repository	√	Major new entry (Minutes)
1.7.1	Solubility	√	Minutes
1.7.2	Sorption	√	Minutes
2.	Far-field	√	General area important
2.1	Extra-terrestrial	√	Secondary (Minutes)
2.1.1	Meteorite impact	√	Secondary (Minutes)
2.2	Geological	√	General area important
2.2.1	Regional tectonic	√	Marginal (compare EG(90)P4 and Minutes). Not justified listing sub-items separately
2.2.2	Magmatic	x	EG(90)P4, Minutes
2.2.3	Metamorphism	x	EG(90)P4, Minutes
2.2.4	Diagenesis	x	EG(90)P4, Minutes
2.2.5	Diapirism	x	EG(90)P4, Minutes

TABLE 1 (Cont.)

Item	Description	Inc.	Comments
2.2.6	Seismicity	√	Secondary (Secretariat)
2.2.6.1	Repository induced	√	As 2.2.6
2.2.6.2	Externally induced	√	As 2.2.6
2.2.6.3	Natural	√	As 2.2.6
2.2.7	Faulting/fracturing	√	Related to 2.2.6
2.2.7.1	Activation	√	Secondary (Secretariat)
2.2.7.2	Generation	x	Debatable with current UK levels of seismicity (Secretariat)
2.2.7.3	Change of properties	√	Secondary (Secretariat)
2.2.8	Major incision	√	Secondary (Minutes)
2.2.9	Weathering	√	Secondary in far-field (Secretariat)
2.3	Hydrological	√	General area important
2.3.1	Variation in groundwater recharge	√	Major control
2.3.2	Groundwater losses	√	Major control
2.3.3	Rock property changes	√	Secondary (c.f. 2.2.6, 2.2.7 and 2.2.9)
2.3.3.1	Porosity	√	As 2.3.3
2.3.3.2	Permeability	√	As 2.3.3
2.3.3.3	Microbial pore blocking	√	Theoretical possibility
2.3.3.4	Channel formation, closure	√	Related to 2.2.6, 2.2.7, 2.2.9
2.3.4	Groundwater flow	√	Major process
2.3.4.1	Darcy flow	√	Usual basis
2.3.4.2	Non-Darcy flow	√	Minutes, p.10
2.3.4.3	Intergranular (matrix)	√	Secondary (Secretariat)
2.3.4.4	Fracture	√	Especially in Chalk (Minutes)
2.3.4.5	Effects of solution channels	√	Secondary (Secretariat)
2.3.4.6	Unsaturated	√	Possibly not required for geosphere (Minutes, p.10)
2.3.5	Salinity	x	EG(90)P4
2.3.6	Variations in groundwater temperature	x	Excluding repository induced effects (see 2.4.13)
2.4	Transport and geochemical	√	General area important
2.4.1	Advection	√	Major process
2.4.2	Diffusion	√	Major process for near-stagnant groundwater
2.4.2.1	Bulk	√	As 2.4.2
2.4.2.2	Matrix	√	Effects on retardation, secondary (Secretariat)
2.4.2.3	Surface	x	EG(90)P4, Minutes
2.4.3	Hydrodynamic dispersion	√	Major process

TABLE 1 (Cont.)

Item	Description	Inc.	Comments
2.4.4	Solubility constraints	x	EG(90)P4, Minutes - This was a major, debated decision
2.4.5	Sorption	√	Major process, all the sub-heads require consideration, though not all need necessarily be included in an assessment (Minutes)
2.4.5.1	Linear	√	Might be omitted (Minutes)
2.4.5.2	Non-linear	√	
2.4.5.3	Reversible	√	Might be omitted (Minutes
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	√	Probably of much less importance than complexation (Minutes)
2.4.5.11	Effects of colloids formed in the near-field	√	As 2.4.5.10
2.4.5.12	Effects of major ions migrating from the near-field	√	Explore in external models and fold into assessment (Minutes)
2.4.5.13	Effects of microbial activity	√	Research topic (Minutes)
2.4.6	Fracture mineralisation	x	Minutes, query arises with respect to hard clays
2.4.7	Organic colloid transport	√	See 2.4.5.10, Marginal process (Secretariat)
2.4.7.1	Porous media	√	See 2.4.7
2.4.7.2	Fractured media	√	See 2.4.7
2.4.7.3	Effects of pH and Eh	√	See 2.4.7
2.4.7.4	Effects of ionic Strength	√	See 2.4.7
2.4.8	Inorganic colloid transport	√	Comments as for 2.4.7
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	√	Marginal, but possible for starved microbes (Minutes)

TABLE 1 (Cont.)

2.4.10	Isotopic exchange	√	Contribution to sorption (Minutes)
2.4.11	Gas transport	√	Potentially important transport pathway
2.4.11.1	Solution	√	Marginal amount and importance (Secretariat)
2.4.11.2	Gas phase	√	Major process
2.4.12	Gas-induced groundwater transport	√	Potentially significant (Secretariat)
2.4.13	Thermally induced groundwater transport	√	Potentially significant
2.4.13.1	Repository induced	√	Minutes
2.4.13.2	Naturally induced	x	EG(90)P4, Minutes
2.4.14	Biogeochemical changes	x	EG(90)P4, Minutes (c.f. 2.4.5.7)
3.	Biosphere	√	General area important
3.1	Climatology	√	General area important
3.1.1	Transient greenhouse gas induced warming	√	Minutes
3.1.1.1	Precipitation	√	Minutes
3.1.1.2	Temperature	√	Minutes
3.1.1.3	Sea level rise	x	Minutes
3.1.1.4	Storm surges	x	Minutes
3.1.1.5	Ecological effects	√	Minutes, This note
3.1.1.6	Potential evaporation	√	Minutes; derived quantity (Secretariat)
3.1.2	Glacial/interglacial cycling	√	Minutes
3.1.2.1	Precipitation	√	Minutes
3.1.2.2	Temperature	√	Minutes
3.1.2.3	Sea level fall	√	Rise excluded (Minutes); fall not important locally (This note)
3.1.2.4	Storm surges	x	EG(90)P4, Minutes
3.1.2.5	Ecological effects	√	Minutes, This note
3.1.2.6	Seasonally frozen ground	√	Minutes
3.1.2.7	Permanently frozen ground	√	Minutes
3.1.2.8	Glaciation	√	Minutes
3.1.2.9	Deglaciation	√	Minutes
3.1.2.10	Potential evaporation	√	Minutes; derived quantity (Secretariat)
3.1.3	Exit from glacial/interglacial cycling	√	Unlikely, but not excluded (This note)
3.1.3.1	Greenhouse-gas induced	√	Most likely cause
3.1.3.2	Other causes	√	Possible on 10^6 - 10^7 y timescale (Secretariat)

TABLE 1 (Cont.)

Item	Description	Inc.	Comments
3.2	Geomorphology	√	General area important
3.2.1	Generalised denudation	√	Minutes
3.2.1.1	Fluvial	√	Minutes
3.2.1.2	Aeolian	√	Marginal (Minutes)
3.2.1.3	Glacial	√	Minutes
3.2.2	Localised denudation	√	Minutes
3.2.2.1	Fluvial (valley incision)	√	Minutes, This note
3.2.2.2	Fluvial (weathering/mass movement)	√	Minutes
3.2.2.3	Glacial	√	Minutes
3.2.2.4	Coastal	x	EG(90)P4, Minutes, This note
3.2.3	Sediment redistribution	√	Minutes
3.2.3.1	Fluvial	√	Minutes
3.2.3.2	Aeolian	√	Minutes
3.2.3.3	Glacial	√	Minutes
3.2.4	Effects of sea level change	√	Marginal; effects only considerable distances downstream from site (This note)
3.2.4.1	River incision/sedimentation	√	As 3.2.4
3.2.4.2	Coastal erosion	x	As 3.2.2.4 (Secretariat)
3.3	Hydrology	√	General area important, virtually all sub-areas have to be incorporated for a coherent approach (Secretariat)
3.3.1	Soil moisture and evaporation	√	
3.3.2	Surface hydrology	√	Includes near-surface components (renamed) (Minutes)
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	√	New item; various overlaps in the interpretation of all the above items
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	√	Belongs more under geomorphology (Secretariat)
3.3.4.4	Lake formation/sedimentation	√	Marginal (This note)

TABLE 1 (Cont.)

Item	Description	Inc.	Comments
3.3.4.5	Effects of sea level change	√	Debated significance (EG(90)P4, Minutes, This note)
3.3.5	Surface flow characteristics (estuarine)	√	Marginal; only if there are substantial reconcentrating processes in the estuarine environment (Minutes)
3.3.5.1	Tidal cycling	√	As 3.3.5
3.3.5.2	Sediment transport	√	As 3.3.5
3.3.5.3	Successional development	√	As 3.3.5 (NB. This is in relation to hydrological factors, see also item 3.4.2)
3.3.5.4	Effects of sea level change	√	As 3.3.5
3.3.6	Coastal waters	√	Marginal (Minutes)
3.3.6.1	Tidal mixing	√	As 3.3.6
3.3.6.2	Residual current mixing	√	As 3.3.6
3.3.6.3	Effects of sea level change	√	As 3.3.6
3.3.7	Ocean waters	x	EG(90)P4, Minutes
3.4	Ecological development	√	General area important, included sub-items consistent with hydrology (Minutes)
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	√	Marginal, see 3.3.5
3.4.3	Coastal waters	√	Marginal, see 3.3.6
3.4.4	Oceans	x	
3.5	Radionuclide transport	√	General area important, sub-topics, follow assignment in previous headings
3.5.1	Erosive	√	
3.5.1.1	Fluvial	√	
3.5.1.2	Aeolian	√	
3.5.1.3	Glacial	√	
3.5.1.4	Coastal	√	Marginal (EG(90)P4, Minutes)
3.5.2	Groundwater discharge to soils	√	Potential major route of contamination (Secretariat), all components relevant
3.5.2.1	Advective	√	
3.5.2.2	Diffusive	√	
3.5.2.3	Biotic	√	

TABLE 1 (Cont.)

Item	Description	Inc.	Comments
3.5.2.4	Volatilisation	√	Specific radionuclides (Secretariat)
3.5.3	Groundwater discharge to wells or springs	√	Potential major route of contamination (Secretariat)
3.5.4	Groundwater discharge to freshwaters	√	As 3.5.3
3.5.5	Groundwater discharge to estuaries	√	Marginal (compare EG(90)P4 and Minutes)
3.5.6	Groundwater discharge to coastal waters	√	Marginal (compare EG(90)P4 and Minutes)
3.5.7	Surface water bodies	√	Defines initial redistribution, all sub-items potentially important (Secretariat)
3.5.7.1	Water flow	√	
3.5.7.2	Suspended sediments	√	
3.5.7.3	Bottom sediments	√	
3.5.7.4	Biogeochemical cycling	√	Generalised description
3.5.7.5	Effects of fluvial system development	√	
3.5.8	Estuaries	√	Marginal (compare EG(90)P4 and Minutes)
3.5.8.1	Water flow	√	As 3.5.8
3.5.8.2	Suspended sediments	√	As 3.5.8
3.5.8.3	Bottom sediments	√	As 3.5.8
3.5.8.4	Effects of salinity and pH variation	√	As 3.5.8; extended description
3.5.8.5	Biogeochemical cycling	√	As 3.5.8; generalised description
3.5.8.6	Effects of estuarine development	√	As 3.5.8
3.5.8.7	Effects of sea level change	√	As 3.5.8
3.5.9	Coastal waters	√	Marginal (compare EG(90)P4 and Minutes)
3.5.9.1	Water transport	√	As 3.5.9
3.5.9.2	Suspended sediment transport	√	As 3.5.9
3.5.9.3	Bottom sediment transport	√	As 3.5.9
3.5.9.4	Effects of sea-level change	√	As 3.5.9
3.5.9.5	Effects of estuarine development	√	As 3.5.9
3.5.9.6	Effects of coastal erosion	√	As 3.5.9
3.5.9.7	Effects of sea level change	√	As 3.5.9
3.5.10	Plants	√	Important that all items are represented either explicitly or in aggregated parameters (Minutes)
3.5.10.1	Root uptake	√	
3.5.10.2	Deposition on surfaces	√	

TABLE 1 (Cont.)

Item	Description	Inc.	Comments
3.5.10.3	Vapour uptake	√	Specific radionuclides
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 process	√	
3.5.11	Animals	√	As 3.5.10
3.5.11.1	Uptake by ingestion	√	
3.5.11.2	Uptake by inhalation	√	Generally less important than ingestion (Secretariat)
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	√	New area (Minutes)
3.6.1	Urbanisation	√	Minutes
3.6.2	Management of water resources	√	Minutes
3.6.3	Agricultural policy	√	Minutes
3.6.4	Recreation policy	√	Minutes
3.7	Human Exposure	√	Fundamental component, previously item 3.6, virtually all sub-items important and included in biosphere models (Minutes)
3.7.1	External	√	Minutes
3.7.1.1	Land	√	Minutes
3.7.1.2	Sediments	√	Minutes
3.7.1.3	Water bodies	√	Minutes
3.7.2	Ingestion	√	Minutes
3.7.2.1	Drinking water	√	Minutes
3.7.2.2	Agricultural crops	√	Minutes
3.7.2.3	Domestic animal products	√	Minutes
3.7.2.4	Wild plants	√	Marginal (Minutes)
3.7.2.5	Wild animals	√	Marginal (Minutes)
3.7.2.6	Soils and sediments	√	Minutes
3.7.3	Inhalation	√	Minutes
3.7.3.1	Soils and sediments	√	Minutes
3.7.3.2	Gases and vapours (indoors)	√	Minutes
3.7.3.3	Gases and vapours (outdoors)	x	Minutes
3.7.3.4	Biotic material	√	Marginal (Minutes)
3.7.3.5	Salt particles	x	EG(90)P4, Minutes
4.	Short-circuit pathways related to human activities	√	General area important

TABLE 1 (Cont.)

Item	Description	Inc.	Comments
4.1	Related to repository construction	√	Minutes (by inference)
4.1.1	Investigation borehole seal	√	Minutes (by inference)
4.1.1.1	Failure	√	Minutes (by inference)
4.1.1.2	Degradation	√	Minutes (by inference)
4.1.2	Shaft or access tunnel seal	√	Minutes (by inference)
4.1.2.1	Failure	√	Minutes (by inference)
4.1.2.2	Degradation	√	Minutes (by inference)
4.2	Post-closure	√	Minutes
4.2.1	Deliberate recovery of wastes or associated materials	x	EG(90)P4, Minutes
4.2.2	Malicious intrusion	x	EG(90)P4, Minutes
4.2.3	Exploratory drilling	√	Minutes
4.2.4	Exploitation drilling	√	Minutes
4.2.5	Geothermal energy production	x	EG(90)P4, Minutes
4.2.6	Resource mining	√	Minutes
4.2.7	Tunnelling	√	Minutes
4.2.8	Construction of underground storage/disposal facilities	√	Minutes
4.2.9	Construction of underground dwellings/shelters	√	Minutes
4.2.10	Archaeological investigations	√	Minutes
4.2.11	Injection of liquid wastes	√	Minutes
4.2.12	Groundwater abstraction	√	Minutes
4.2.13	Underground weapons' testing	x	EG(90)P4, Minutes

Notes: Minutes = Minutes of the meeting of 26th June 1990
Secretariat = Significant interpretation of the intentions of the Expert Group, or judgements by the Secretariat - requires careful scrutiny

TABLE 1 (Cont.)

a)	Neglect details of structural/physical degradation, but consider secondary processes from concrete degradation.	
	In: 1.1.3, 1.1.4	Out: 1.1.1, 1.1.2
b)	Gas generation in the repository must be included, but transport in the near field need not be included explicitly.	
	In: 1.2.1, 1.2.2, 1.2.4	Out: 1.2.3, 1.2.5, 1.2.6, 1.2.7
c)	Radiation phenomena must be included, but not criticality.	
	In: 1.3.1	Out: 1.3.2
d)	Mechanical effects of gas production on the stress field should be studied outside the assessment. All other mechanical effects can be neglected.	
	In: None	Out: 1.4.1, 1.4.2, 1.4.3, 1.4.4, 1.4.5, 1.4.6
e)	Groundwater flow in unsaturated and saturated conditions should be included for the near-field, but not initial changes in water content	
	In: 1.5.2, 1.5.3	Out: 1.5.1
f)	Neglect transport of chemically active substances into the near-field.	
	In: None	Out: 1.5.4
g)	Repository induced thermal effects cannot be neglected.	
	In: 1.6.4, 1.6.5	Out: 1.6.1, 1.6.2, 1.6.3 (but should be the subject of a special geotechnical study) 1.6.6
h)	Extra-terrestrial processes can be neglected.	
	In: None	Out: 2.1.1

TABLE 2

Characteristics of a Minimal Assessment

i) Regional tectonic effects, seismicity and the effects of faulting and fracturing should be included in supplementary studies outside the assessment. Weathering should be included.

In: 2.2.9

Out: 2.2.2, 2.2.3, 2.2.4, 2.2.5, 2.2.8, 2.2.10, 2.2.11
Supplementary study: 2.2.1, 2.2.6, 2.2.7

j) Far-field hydrological characteristics generally need to be included.

In: 2.3.1, 2.3.2, 2.3.3, 2.3.4

Out: 2.3.5, 2.3.6

k) Transport is assumed to be in ionic form (with complexation as a secondary process).

In: 2.4.1, 2.4.2, 2.4.3, 2.4.5, 2.4.11, 2.4.12, 2.4.13

Out: 2.4.4, 2.4.6, 2.4.7, 2.4.8, 2.4.9, 2.4.10, 2.4.14

l) Assume glacial/interglacial cycling, with greenhouse warming giving rise to an end of such cycling as a secondary consideration.

In: 3.1.1, 3.1.2, 3.1.3

Out: None

m) Geomorphological change should be included.

In: 3.2.1, 3.2.2, 3.2.3, 3.2.4

n) Surface hydrology needs to be included in a comprehensive and coherent way; development and application of a detailed model outside the assessment would be appropriate.

In: 3.3.1, 3.3.2, 3.3.3, 3.3.4, 3.3.5, 3.3.6

Out: 3.3.7

o) Effects of ecological development on hydrology should be included, except for oceans.

In: 3.4.1. 3.4.2, 3.4.3

Out: 3.4.4

p) Radionuclide transport processes in the environment should generally be included.

In: 3.5.1, 3.5.2, 3.5.3, 3.5.4, 3.5.5, 3.5.6, 3.5.7, 3.5.8, 3.5.9, 3.5.10, 3.5.11

Out: None

TABLE 2 (Cont.)

q) There should be a comprehensive treatment of human exposure pathways.

In: 3.7.1, 3.7.2, 3.7.3 — Out: None

r) Short-circuit pathways related to repository construction should be investigated, though not necessarily as part of the main assessment.

To be discussed: 4.1.1, 4.1.2

s) A limited number of short-circuit pathways should be included, others could, if necessary, be covered by scoping or scaling calculations.

In: 4.2.3, 4.2.12 — Out: 4.2.1, 4.2.2, 4.2.4, 4.2.5, 4.2.6, 4.2.7, 4.2.8, 4.2.9, 4.2.10, 4.2.11, 4.2.13

TABLE 2 (Cont.)

DISTRIBUTION

K M Clayton
T D Davies
F P Glasser
J Higgo
A D Horrill
J Knill
C C Naish
M L Parry
J H Rees
E Tufton
J West
H S Wheater

M C Thorne
B G J Thompson
T J Sumerling
J Taylor

C2086/TR/1
5-October 1990

YARD

OBSERVATIONS ON THE EXPERT GROUP MEETING OF 25TH SEPTEMBER 1990

Prepared by	:	J B Taylor
Prepared for	:	Dr M C Thorne
Version	:	1.0
Date	:	5 October 1990
Project Reference	:	C2086/TR/1

DISTRIBUTION	NO. OF COPIES
Dr M C Thorne	1
Dr B G J Thompson	1
Mr T J Sumerling	1
Project	1

YARD Limited - 233 High Holborn - London WC1V 7DJ

OBSERVATIONS ON THE EXPERT GROUP MEETING OF 25TH SEPTEMBER 1990

SUMMARY

This report presents the observations of the normative expert observer at the meeting of the Expert Group held on 25th September 1990. The procedure followed at the meeting is discussed in terms of potential biases which could enter into the deliberations and conclusions of the group. The meeting is considered, from a practical point of view, to have been conducted in such a way as to minimize the potential for bias to occur. A number of minor issues of concern are raised and practical recommendations for actions are suggested.

Author: J. B. Taylor .... 5th October 1990 ....
J B TAYLOR DATE

Checked by: Janet E. Chamley .... 5/10/90 ....
J CHAMLEY DATE

Approved by: David Bartholomew .... 5/10/90 ....
Dr D BARTHOLOMEW DATE

CONTENTS

1. INTRODUCTION

1.1 Background

The HMIP Expert Group on Post-Closure Radiological Assessment was set up to help define the calculations which should be undertaken in a comprehensive radiological assessment incorporating an uncertainty and bias audit. The Expert Group's work was undertaken in the context of the Dry Run 3 trial assessment.

In the period since January 1990 the Expert Group has been involved in the production of a comprehensive list of factors and phenomena and the definition of the characteristics of a Minimal Assessment through correspondence and meetings. The objectives of the meeting of the Expert Group on 25th September 1990 were:

1) to review the list of factors and phenomena

2) to review the characteristics of the Minimal Assessment

3) to establish a limited number of preferred enhancements to form Augmented Assessments

4) to produce a ranked list of approaches to assessment

5) to determine an initial quantitive view as to the confidence of the group that the assessment procedures proposed would give an estimate of risk within an order of magnitude of the true values.

These objectives were set out in a briefing role [ref 1] circulated to all participants of the Expert Group.

It was recognised that there was a requirement for a normative expert to attend the meeting to advise on procedural matters and to produce a report on the conduct the meeting for incorporation into the Dry Run 3 documentation. This report fulfils that requirement.

1.2 Scope of Report

The report presents the observations of the normative expert on the conduct of the meeting. It covers:

1) attendees and roles

2) procedural aspects and potential introduction of bias

3) use of facilities

4) suggestion for future actions.

Specifically excluded from this report are the rationale for the use of the Expert Group, the selection of the experts, a review of processes and procedures prior to the meeting, and technical issues discussed during the meeting. These issues should be covered by appropriate peer reviews.

Due to time constraints, the meeting did not achieve all objectives. Of those objectives listed in Section 1.1 above, objectives 1 and 2 were completed, considerable progress was achieved in relation to objective 4, but objectives 3 and 5 were not achieved. Some informal discussion on objective 5 took place. This report covers only those aspects actually discussed at the meeting.

2. ATTENDEES AND ROLES

The attendees can be grouped into four categories:

1) Chairman/generalist

2) Experts

3) Observers

4) Secretarial

The secretarial role was passive during the meeting (except in the important role of providing confirmation of earlier discussion) and is not discussed further.

In the formal parts of the meeting the two observers, the normative expert and Dr B G J Thompson, played no active role - with the exception of a single prompt regarding the need to draw specific attention to previous, explicitly noted, judgements on the part of the Secretariat to the Expert Group - so their contribution is also not discused further.

The roles of the chairman/generalist and experts are discussed below.

2.1 Chairman/Generalist

The role of the chairman of the meeting and that of the "generalist", i.e. the person charged with questioning the experts so as to elicit their expertise and to have overall awareness of the processes being discussed, were combined. In addition, due to the absence of some members of the Expert Group, the generalist had to input the views of the non-attendees.

The multi-natured aspects of this role were explicitly stated at the beginning of the meeting and were clearly sign-posted throughout so that little, if any, confusion arose over the nature of his input.

The generalist, of necessity, must have a broad understanding of all the issues likely to be covered during the meeting, together with a thorough knowledge of the background to the work being undertaken. To be able to combine this depth and breadth of understanding without involving someone intimately connected with ongoing studies is practically nearly impossible. It is thus necessary to accept that unconscious motivational bias can occur through the action of the generalist. This bias could probably only be detected by another suitably qualified generalist. In the specific instance of this meeting, given the knowledge of the generalist of the dangers of various types of bias and the general care taken to avoid them, it seems unlikely that any significant degree of unconscious motivational bias entered the discussions.

2.2 Experts

A wide range of experts was able to attend the meeting, though regrettably it was not possible to gather together the complete Expert Group. As such, in a number of technical areas there was no specialist present, whilst in others only one of the attendees had the required specialist knowledge. The result of this "missing" expertise was that some areas were subject to less debate than others. To ensure that no bias enters the conclusions of the Expert Group, those experts not present should be closely questioned in writing or by telephone and the results made available to the whole group before formal documentation of the decisions of the meeting.

An issue of importance in the use of experts is the degree of training necessary prior to their deliberations [2]. This training need to cover the background to the work they are to undertake, sensitization to potential introduction of the various kinds of bias, and specific training in any probabilistic or quantitive judgements which they might be required to make. In any practical exercise the costs of such training need to be offset against the benefits to be gained and the importance of the overall process.

From the informal discussion held on the issue of the quantitive assessment of the confidence in the proposed procedure, it was clear that those experts present were not fully aware of the process in which they were being asked to participate, nor, possibly as a result, were they confident in their ability to carry it out. Prior to attempting to carry out any further elicitation of their views on this matter, serious consideration should be given to the amount of information required to be given to the experts on the process itself.

The extent of training carried out with this Expert Group and the cost/benefits of training in future elicitation should be addressed in the peer review of the work of the Expert Group and borne in mind in any future expert elicitation.

3. PROCEDURAL ASPECTS

The processes performed during the meeting are considered under two headings:

1) Control of the meeting

2) Potential introduction of biases.

In considering the events of the meeting it is necessary to bear in mind the practical issues of the need to achieve a sufficiently good technical response from the experts on the objectives within the constraints of time and budget. As such, perfect adherence to a theoretical ideal to avoid bias is impractical. The purpose of this section is to record instances where there were actual or potential deviations from the ideal and to assess their likely impact on the conclusions reached.

3.1 Control of the Meeting

The objectives of the meeting were clearly set out in the briefing note [1] and were reiterated at the beginning of the meeting. With the benefits of hindsight it is possible to see that attempting to meet all the objectives in a single meeting was ambitious. This should be borne in mind when considering the time required for similar future discussion.

In general the meeting was well controlled, with appropriate breaks such that overlong periods of concentration were not required. Discussion was well focussed and the issues being debated were clear. Changes in the subject of debate were well sign-posted and after a period of discussion the points raised were usually well summarised and presented for explicit confirmation. Argument by rhetorical means was avoided on the rare occasion it was attempted through appropriate questioning of the expert.

As the meeting progressed and it became clear that it would not be possible to cover all the objectives, there was a slight tendency to ask "leading questions" or to attempt to force the discussion to a conclusion by posing a definitive question earlier than would have occurred at an earlier stage in the meeting. The extent of these negative points was however very small and is considered neither to have adversely affected the range of discussion nor to have introduced any significant bias.

3.2 Potential Introduction of Biases

The various types of biases which can occur during expert judgement meetings are well documented in the literature [e.g. references 2 and 3]. This section highlights a number of areas in which the potential for bias entered the discussion or was reduced through explicit action of the chairman.

Policy Issues and Assumptions

At several points in the meeting it was necessary for the chairman to remind the experts of important policy issues and assumptions which should have been underlying their judgements. Examples include the time period under consideration (10^6 years) and the fact that the work was being undertaken in consideration of the hypothetical Harwell site.

Since such intervention was deemed necessary by the chairman, it is possible that on some occasions judgements were made where these and similar policy issues or assumptions were not at the forefront of the experts minds. The full assumptions under which the exercise was carried out should, of course, have been documented. Following this meeting it would be prudent to check with the experts whether they wish to reconsider any of their views in the light of an explicit statement of the underlying assumptions.

Previous Judgements By the Secretariat

Judgements by the secretariat which had been made on the basis of earlier Expert Group discussions and correspondence were clearly indicated in the briefing note and reiterated during the meeting. The method of confirming that these judgements were acceptable to the experts was by asking for explicit dissent, rather than positive confirmation.

This method of obtaining confirmation leaves open the possibility that perceived lack of knowledge or certainty on the part of an expert would result in his or her not dissenting, even though it could be a debatable issue. Positive assent would be more likely to produce an open "I don't know" response. Equally, in the absence of some of the experts, those secretariat judgements in their specialist expertise area will need to be confirmed.

There will, of course, be the opportunity for the experts to comment on the record of the meeting, and their attention should be drawn once again to the points at which judgements had been made by the secretariat.

The Decomposition of the Factors and Phenomena

Only a single list of the factors and phenomena considered was prepared. Such decomposition lists contain much information regarding the decisions of the experts, and a single decomposition list implies a consensus position on the part of the Expert Group. It is possible that such consensus may have been forced or unwillingly accepted by some group members, whereas the possibility of keeping open two or more decompositions would have explicitly recorded any dissent from an otherwise consensus position, which could then have been the subject of further debate.

This approach is more costly, however, since it involves additional effort and administrative overheads.

It was not clear that all the experts had the same understanding of all the terms in use in the list. Ideally, to ensure that all are working to the same assumptions, a full glossary should have been prepared and issued to the experts.

Some amendments to the list were made during the meeting, both to points where there had been judgement by the secretariat and also in the actual decomposition. There is a danger in this, since the thought processes required to formulate a comprehensive list are distinctly different from those required to evaluate elements of the list. The need to switch from formulation to evaluation, and vice versa, may have led to a reduction in the evaluative capacity of the experts.

Changes to the list also raise a question of whether the list is fully complete. In practice, such amendments will always occur in any finite time period allowable for discussion, and the extent to which they interfered with the debate is considered small.

Modelling

The fact that the Expert Group's discussions are taking place in parallel with the modelling efforts, and hence the potential for conscious or unconscious motivational bias entering the discussion via the generalist, has already been mentioned (Section 2.1). It is not considered that any significant bias was introduced as a result of this, though this could only be confirmed by observation by a disinterested generalist.

Group Dynamics

As a group, the meeting functioned well, with no apparent suppression of view points and several instances of "devil's advocate" positions being taken so as deliberately to stretch the discussion. Differences in the personalities of the members of the Expert Group did not intrude adversely into the debate.

Availability Bias

In any such meeting, but especially when only one expert in a given field is available, there is the possibility of availability bias entering undetected. In practical terms it is difficult to avoid or account for this bias, expect through appropriate sensitization of the experts to its occurrence. Consideration should be given in a peer review of the Expert Group's work as to whether appropriate training was given in this area.

The Ranking Process

After establishing an agreed position regarding the characteristics of a minimal assessment, the experts were required to switch track and attempt to rank these characteristics. This was a psychologically difficult task, as evidenced by the questioning of the criteria to be used to rank the elements, and the clear difficulty of stating that a characteristic which had recently been identified as being required in a "minimal" assessment could be considered as "low" and hence potentially discarded.

Given the natural propensity to rank items more to the centre than to the extreme, and the desire not to rank characteristics "low" from the above point, it is likely that bias entered the ranking process, such that more of the characteristics have been accorded "high" or "medium" rankings than "low". The experts should be given the opportunity to revise their rankings, with an explicit statement of the criteria to be used in forming their judgement. Such an explicit statement should avoid potentially prejorative concepts such as "which characteristics would you throw away in the event of resource limitations?"

4. FACILITIES

The room and seating arrangements were adequate for the discussion. The chairman's position made it easy for effective control and the positioning of the experts permitted good communication. Due to the reduced number of participants the experts were somewhat grouped into "specialist" sub-groups, but this did not appear to detract from full discussion of the issues.

A viewfoil machine was available, but was used only very briefly after the main business of the meeting was concluded.

The briefing note prepared for the meeting gave the list of factors and phenomena together with their identifier in the structured list (Table 1, ref 1). This list presented a large amount of information very succinctly. Its effectiveness could perhaps have been improved by giving visual emphasis to the decomposition.

Since the list was modified during the early stages of the meeting and the revised list used in later stages, it would have been of benefit had some means been available to update the list for issue to the experts, rather than to rely on their having correctly amended their own copy. This could have been achieved through the rapid amendment and reprinting of the list on a laser printer during the meeting or through display of the revised list via a projected computer screen. In practice, the lack on a updated list did not appear to have any significant effect on the discussion, though it was necessary for the chairman to check and confirm the correct status of the list on several occasions.

Additional facilities such as tape recording the discussion to assist documentation would have been over-elaborate for this meeting.

5. SUMMARY AND RECOMMENDATIONS

The meeting covered a great deal of ground, even though it proved impossible to achieve all the objectives. It was well controlled and from a practical point of view the potential for the introduction of bias was limited. Ideally some improvements would have been possible and suggestions for practical ways forward are given in the recommendations below. The physical facilities provided for the meeting were adequate, though provision for more rapid updating of reference material would have been of some benefit.

It is recommended that:

1) note be taken of the potential for motivational bias in the generalist and that a suitably qualified observer should be present if practicable to detect such bias

2) positive confirmation of the secretariat's judgements should be sought at any such future meeting

3) policy and underlying assumptions be clarified with members of the Expert Group and that they should be given the opportunity to re-assess their decisions in the light of this clarification

4) the provisional decisions of the meeting be circulated to all the members of the Expert Group, with the attention of any non-attendees being explicitly drawn to points within their expertise for careful consideration

5) agreement on the definition of terms used be clarified through the issue of an Expert Group Glossary

6) the decisions on the ranking of the characteristics should be revisited by correspondence

7) particular attention should be paid in any peer review of the work of the Expert Group to the issue of training its members

8) consideration should be given, perhaps with the assistance of an information design consultant, to the visual impact of briefing material and the rapid presentation of the results of the deliberations

9) the methods of obtaining a quantitive measure of the confidence of the Group in the accuracy of the assessment proposed be examined very carefully.

REFERENCES

1. "HMIP Expert Group on Post Closure Radiological Assessment: Briefing Note 6", M C Thorne, September 1990.

2. "Elicitation and the Use of Expert Judgement in Performance Assessment for High-Level Radioactive Waste Repositories", NUREG/CR-5411, SAND 89-1821, Bonano EJ, et al, May 1990.

3. "Judgement Under Uncertainty: Heuristics and Biases", edited by Kahneman D, et al, Cambridge University Press, 1982.

ELECTROWATT
CONSULTING ENGINEERS AND SCIENTISTS

Grandford House, 16 Carfax, Horsham, West Sussex, RH12 1UP
Telephone: (0403) 50131, Telefax 59175, Telex 877960 elwatt g

Branch Office: Stanford House, Garrett Field, Science Park South, Birchwood, Warrington, Cheshire, WA3 7BH. Telephone: (0925) 827757, Telefax 824498, Telex 877960 ELWATT G

MINUTES OF MEETING	
Project: HMIP Expert Group on Post-Closure Radiological Protection	EWE Project No. 2636
Venue: Room P3/136, 2 Marsham Street	Date of Meeting 25.9.1990
Purpose of Meeting:	

Attendance:

M C Thorne (EWE) (Chairman)
I Teasdale (EWE) (Secretary)
F P Glasser (Aberdeen University)
C Naish (Harwell)
J H Rees (Culham Laboratory)
A D Horrill (ITE)
B G J Thompson (HMIP)
J Taylor (YARD)
J Higgo (BGS)
J West (BGS)
H S Wheater (Imp. College)
K M Clayton (UEA)

Apologies for Absence:

Received from T D Davies, E Tufton, J Knill, M L Parry and T J Sumerling

Distribution:

Attendees and apologies above.

EWE File: 2636	Minutes issued by: I Teasdale	Date: 28.9.90

MINUTES OF MEETING | ACTION

1. CHAIRMAN'S INTRODUCTION

MCT noted that this was the first full meeting of the expert group (in terms of numbers) and drew attention to the agenda and associated notes set out in EG(90)P6.

A reminder was issued for invoices to be submitted before the end of November.

2. REVIEW OF WORK TO DATE

2.1 COMPREHENSIVE LIST OF FACTORS AND PHENOMENA

The group worked through Table 1 in EG(90)P6. Comments and changes are noted under the appropriate sub-headings (with particular emphasis on those items subject to substantial interpretation by the Secretariat). All other items are unchanged.

1.2 Gas production, transport and flammability: FPG was unhappy with the conclusion that the corrosion rate for steel is 10 x that for Magnox (see EG(90)P6 p.5). JHR replied that these figures were not 'set in stone' and there were other factors that would accelerate corrosion in Magnox; however, the volume of steel is much greater than Magnox and hence steel would dominate any discussion. MCT asked about gas pulses from Magnox. CN replied that although surface area of Magnox is large it is well grouted. However, cement will crack leading to groundwater ingress. This together with temperature rise could give spatially and temporally localised peaks of hydrogen gas production. (The DoE is currently looking at this. BNFL data are not applicable.)

So, as a process, the group wished to include gas generation from Magnox with some thought as to its implications. FPG pushed 1.2.1.4 to be accorded a high priority.

The discussion also extended to gas from aluminium waste. It was generally agreed that it should remain out, because, most of it will corrode before it is put into repository, it will be coated in corrosion products, and also there is only a small volume of such waste relative to Magnox.

MINUTES OF MEETING	ACTION
1.2.2.3 JHR had doubts as to the importance of aerobic degradation in the long term. JW replied, confirming her previous view, stating that a long aerobic period would lead to more microbial breakdown products available to anaerobic bacteria with consequences for gas generation and radionuclide transport mediated by groundwater movement.	
1.2.2.6 FPG asked about temperature and pressure effects. MCT confirmed the previous minutes (pg 2 and 6) and stated that although the temperature could rise by 100°C at the centre of ILW vault, 25°C was normal (all temperatures in the minutes are rises above normal). FPG continued by asking about the depth of repository, as processes were very different for 300 m compared to 1000 m. MCT stated that Dry Run 3 relates to a depth of 200 - 300 m and it was generally agreed that 1.2.2.6 should be changed from a marginal tick to a cross.	
1.6 It was noted that this refers only to local thermal effects.	
1.7 It was noted that this is a new entry.	
2.1.1 KMC stated that meteorite impact would have other effects beyond radiological consequence.	
2.3 Hydrology was agreed to be important. FPG pointed out that data were uncertain. JH replied that the Harwell area has had more investigations than anywhere else. FPG highlighted that geology at Harwell is highly variable (both vertically and horizontally). HSW said that this had already been noted and also that it is not possible to separate hydrology from biosphere considerations.	
2.4.4 Solubility constraints in far-field transport has been previously deleted. JH asked whether its omission is due to dispersion precluding it. Its exclusion was upheld, unless a case can be found where solubility is lower in the far field than in the vault.	
2.4.6 JH pointed out that in clay you get fracture demineralisation where carbonate dissolves. This enhances transport and so must be included and the title altered to Fracture Surface Changes.	

MINUTES OF MEETING		ACTION
2.4.9	JW pointed out that in a low nutrient environment starved microbes will move because they are smaller and clay is potentially a low nutrient medium; hence this item is not marginal.	
2.4.11.1	JHR stated that pressurisation effects in unfractured rock can lead to a substantial proportion of transport being in solution, in which case this item would not be marginal.	
3.1	It was suggested that more basic meteorological parameters than temperature could be considered, e.g. radiation flux. KMC confirmed that glaciation should be considered even for Harwell.	
3.1.3	Although not discussed, there is advice from T D Davies (EG(90)P6 p.8) that we should not rule out an exit from glacial/interglacial cycling. KMC agreed that this would lead to a very different world. A 40 - 50 m rise in sea level could result if the Antarctic ice sheet melted; non-radiological consequences of this would almost certainly be more important than effects on the repository.	
3.2	KMC was unclear as to the difference between local and generalised denudation and requested clarification from the secretariat (this is to be continued by correspondence).	MCT
3.2.4	HSW questioned whether a change in sea level extends only a small distance upstream quoting the Colorado River where effects have been seen 55 miles upstream. This led to a discussion with KMC defending the view that river doesn't know what is happening downstream and any upstream changes are difficult to attribute to specific events.	KMC and HSW to clarify this
3.3.4.4	It was suggested that lake formation and its effects should be moved to man made effects (new heading 3.6.2.1).	
3.3.4.5	Sea level ought to be considered in terms of groundwater boundary conditions. KMC pointed out that the maximum sea-level rise of 5 m would not affect Harwell.	

MINUTES OF MEETING		ACTION
3.3.6	Interpretation of coastal waters heading needs to be bent to apply to Harwell. HSW pointed out effects of re-use of land after sea level drop. With reference to effects of sea level change FPG suggested that, despite current preoccupation with global warming, in the longer term UK is subsiding in the south. KMC countered by say that only Thames Basin is sinking. Over 100 - 500 years, global warming will dominate net sea level changes, whereas over the next 10,000 years net sea level will drop. At even longer times, geotectonic processes will dominate. MCT noted the effect of sediment flow into the North Sea as a contributor to, and compensation for, the general subsidence. Discussion of this subject was deferred.	
3.5.3	Groundwater discharge to wells was confirmed as important by HSW.	
3.5.11.2	ADH agreed with the secretariat's view.	
3.6	Planning considerations was introduced as a major new item after the last meeting. MCT suggested that this be taken as assuming that 20th Century technologies be continued over long term with some variations. HSW restated his case that these variations in groundwater management and agricultural policy could result in substantial hydrological perturbations. MCT asked whether substantial short term (10-20 years) variabilities should be reflected in the assessment procedure. He noted that, for the purpose of the group's deliberations, the post closure institutional management phase should be taken to be over but the likelihood of its consequences extending for some time should not be forgotten.	
3.7.2.5	There was general agreement that consumption of wild animals was of less significance than domesticated and that relocation/migration could be neglected. ADH pointed out that consumption of wild plants/animals may affect the Critical Group; hence in keeping with decisions on other topics it should be incorporated as a secondary study.	

MINUTES OF MEETING	ACTION

4.1.1 'Investigation borehole' should refer instead to any borehole.

4.2 This item was defined (MCT) as things that go wrong after the repository is completed and sealed.

JHR considered that the access shaft should be explicitly included in the list, not just for failure but also for surrounding stress relief phenomena.

2.3 CHARACTERISTICS OF A MINIMAL ASSESSMENT

The group worked through Table 2 in EG(90)P6.

a) FPG considered 'soup' model of vault inappropriate as it does not include any representation of physical processes, noting, in particular, that there are difficulties in modelling the effects of cracks in concrete. CN was also unhappy with soup model and would like to consider degradation of concrete. JHR (playing devil's advocate) said that this was at least a worst case as the physical barrier plays no part and also that the next level of vault modelling beyond a soup would be very complex. MCT wondered what effect a soup model would have on the sorption and solubility. FPG noted that alkali/aggregate reaction disappeared in the soup model, as it relates to structural cracking. It is assumed that in soup model leakage occurs from the time of repository closure governed by local chemistry - is this in fact a worst case? FPG made the point that if concrete is not part of the barrier why go to the expense of good quality concrete. MCT highlighted that the philosophy of deep geological disposal is that radionuclides should be held in geosphere for long enough to decay. MCT also tried to draw the distinction between concrete chemistry and concrete structural integrity reiterating the previous decision that the minimal assessment should include 1.1.3 but not 1.1.2.

   Possibilities for vault models are: physically based model, soup model or mixed model (comparing a soup model with more detailed studies). CN and JHR both hold that a more detailed model is required for a 10^3 - 10^4 year timescale.

b) JHR was worried about the exclusion of transport in or around access shafts hence 1.2.6.4 was included.

ELECTROWATT
CONSULTING ENGINEERS AND SCIENTISTS

MINUTES OF MEETING	ACTION
c) No comments.	
d) 1.4.6 fracturing effects in near field were included after some reference back to 1.1.2.	
e) Unsaturated flow is represented but not its chemistry (MCT replying to HSW accusation of inconsistency). JHR wanted 1.5.2 to be left out. It was omitted subject to further correspondence.	JHR
f) No comment.	
g) No comment.	
All of 1.7 is to be included in minimal assessment under transport out of repository.	
h) No comment.	
i) There was some discussion as to whether items should be under geology or geomorphology, especially major incision, which would only result from glaciation. Deep weathering caused some confusion about how it occurred and to what extent. KMC stated that it was very common. [It was suggested that it should be in DR3 glossary.] Conclusion is that 2.2.9 should be moved to general geomorphology.	
j) 2.3.3 There was a question as to whether rock property changes should be included. KMC pointed out that the characteristics of the chalk will undoubtedly change on a 10^6 y timescale.	
2.3.5 ADH asked whether saline effects should be included, as plutonium solubility (for instance) can vary tremendously. Conclusion is that it should be omitted subject to further correspondence.	
k) 2.4 Transport should be redefined as transport in aqueous form.	
2.4.5 Speciation and complexation should be considered (large organo-metallic complexes, e.g. humic materials, need separate consideration).	
2.4.6 This should be brought back to include demineralisation.	

MINUTES OF MEETING	ACTION

2.4.7 FPG suggested that organic colloids can affect transport of actinides. JH replied that it affects solubility rather than mobility. This should be in at some level.

2.4.8 JH pointed out that inorganic colloids are much 'stickier' (already much used by nuclear industry) and they retard transport rather than enhance it - should be included in a realistic assessment.

2.4.9 Transport bound to microbes was also re-included (JW).

2.4.12 JHR feels that the potential exists for gas induced groundwater transport, so that it should be included.

2.4.13 KMC felt that this could be left out.

l) Agreed to change end of glacial/interglacial cycling from a 'secondary consideration' to a 'low probability event with huge non-radiological consequences'.

3.1.3 Should this be changed to a secondary consideration?

BGJT asked why 3.1.1 (transient greenhouse effect) was retained. KMC replied that it could have a profound effect on groundwater although some components of 3.1.1 could be ignored e.g. storm surges.

FPG asked why there is a need to consider what processes lead to a change in head, when it is only necessary to estimate what happens to local heads under different conditions. MCT pointed out that consideration of the controlling processes is required in order to attach a degree of belief to the various possibilities. It was agreed to be a fair and interesting question.

m) 3.2.1.2 should be left out (KMC).

If a glaciation reaches Harwell then it will be a catastrophic event of far reaching implications, as well as being difficult to model, so it should be abstracted to a separate study.

MINUTES OF MEETING	ACTION
3.2.4 Following this morning's discussion this could be left out. Moved to out, conditional on a confirmatory exchange of letters between KMC and HSW.	KMC/HSW
n) 3.3.5 Should be taken out into a supplementary study.	
3.3.6 Should be taken out into a supplementary study.	
o) 3.4.2 Should be taken out into a supplementary study.	
3.4.3 Should be taken out into a supplementary study.	
3.4.1 Depends on whether you have shallow or deep rooted plants. Hence it should be split into 3.4.1.1 Shallow plants and 3.4.1.2 Deep plants (KMC). 3.6 will also have influence on this but is still an item in its own right (JHR).	
p) 3.5.1 Leave aeolian in, glacial special study, coastal supplementary study.	
3.5.5 Should be left out.	
3.5.6 Should be left out.	
3.5.7 Not clear what the difference is between this and 3.5.3 (just different aspects of the same process).	
3.5.8 Should go to supplementary study.	
3.5.9 Should go to supplementary study.	
3.5.10 and 3.5.11 These are the primary components of food chain model. ADH suggested that 3.5.10.7 can be left out if 3.5.10 is renamed soil/plant processes (inc. cycling).	
3.6 Planning should now be included in Table 2 but KMC wanted to change its title to 'Land Use' and move 'Management of Water Resources' (3.6.2) to the end as it can depend on the other headings.	
q) No comments.	

MINUTES OF MEETING	ACTION
r) Added a new title to short-circuit pathways (repository construction): that of damage around boreholes. These must all be included in the main assessment.	
s) The choice of 4.2.3 and 4.2.12 in particular to be included in the main assessment was done to represent direct and indirect pathways (MCT response to JHR). FPG suggested that one possibility is that scientists will use the facility as a test bed: MCT replied that if so then they should make their own safety arrangements.	
3. <u>RANKING OF FACTORS AND PHENOMENA</u>	
3.1 ADDITIONS TO THE MINIMAL ASSESSMENT	
This was omitted due to lack of time.	
3.2 SUBTRACTIONS FROM THE MINIMAL ASSESSMENT	
FPG thought that subtractions was too perjorative a word we should instead set priorities (low, medium or high). KMC pointed out that one way to simplify the assessment would be to shorten the timescale. There was some discussion of DoE policy: "calculate the maximum risk in any year to the most exposed individual". It was pointed out that one million years is a typical timescale found to be of relevance in assessment studies, which was why it was chosen for Dry Run 3.	
1.1.2 Low/medium	
1.1.3 High	
1.1.4 This is closely related to 1.1.3 and hence high (after much discussion). Noted that it can depend on timescale.	
1.2.1 High (but concentrate on 1.2.1.2 and 1.2.1.3). Note that for small times surface area dominates whereas for longer times volume considerations are important.	
1.2.2 High - JHR sees this as essential and agreed to provide supporting material by correspondence.	JHR
1.2.4 High [1.2.1, 1.2.2, and 1.2.4 can be seen as one single unit].	

	MINUTES OF MEETING	ACTION
1.2.4.6	Medium (approach E Tufton). FPG brought up the case of Mol where clay didn't re-close.	MCT
1.3.1	High	
1.4.6	Low/medium	
1.5.3	High	
1.6.4	Low	
1.6.5	Low	
2.2.8	This is coupled to glaciation.	
2.2.9	Moved to geomorphology.	
2.3.1	High	
2.3.2	High	
2.3.3	Medium (because of timescales compared with effectiveness of weathering).	
2.3.4	High [2.3.1 and 2.3.2 form a unit-boundary conditions on hydrology]	
2.4.4	High	
2.4.5	High	JH
2.4.6	Medium (subject to JH review) FPG noted that fractures in themselves would be important.	
2.4.7	Medium - organic colloids are not expected to move in intact clay but in fractures they would be expected to be transported.	
2.4.8	High	
2.4.9	Medium - tied up with fracture colloid transport.	
2.4.11	High - FPG pointed out that if you get a lot of gas then there is something wrong with the repository concept. Gas drives transport through fractures; if there are no fracture the gas leads to over-pressurisation and hence fractures.	
2.4.12	High [Two groups were identified 2.4.1 - 2.4.5 and 2.4.11 and 2.4.12].	
It was not possible to discuss (l) given the depleted group.		
3.2.1	High	
3.2.2	Low	
3.2.3	High/medium	

MINUTES OF MEETING	ACTION
Agreed (n), (o) and (p) should be left to secretariat to assign provisional values.	MCT
4.1.1 Medium (position of tunnels will determine effects). 4.1.2 Medium 4.1.3 (damage around boreholes) high/medium. [4.1.1 and 4.1.2 form another group.]	
If 4.2.3 and 4.2.12 were ignored, then the assessment would be seen as inadequate (further correspondence is necessary).	All
4. <u>CONFIDENCE IN ASSESSMENT RESULTS</u>	
From item 3, a well defined set of processes was identified for inclusion in an assessment. The question was then readdressed that, given the adequacy of models and data, what degree of belief would members of the group have that estimates of the maximum risk to an individual at any one time over the next 10^6 years would be within an order of magnitude of the true value.	
FPG noted that the data for human intrusion is always a guess.	
There was a general discussion of the difficulties of assigning a degree of belief to an overall assessment when individual members of the group had experience in only one area and also in the absence of recourse to modelling studies.	
As a way forward, the Delphi technique was suggested: initiated by distribution of a carefully worded questionnaire together with Table 2 and a summary of the discussion for comment. JT pointed out that the approach would have to be considered carefully as some of those to whom the questionnaire would be sent had participated in the discussion. There was also some discussion about how to solicit views from a limited number of experts.	
In terms of quantifying bias, BGJT suggested that a comparison of the scope and results of DR1, DR2, DR3 and the PACOMA exercise with the various levels of assessment derivable from the discussions under item 3.2 above, might provide a quantitative estimate of bias in relation to the comprehensiveness of the assessment procedure.	
BGJT thanked everyone for attending and the meeting closed at 4.55 pm.	

EG(90)P7

HMIP Expert Group on Post-Closure Radiological Assessment: Briefing Note 7

M C Thorne

Electrowatt Engineering Services (UK) Ltd
Grandford House
16 Carfax
Horsham
West Sussex
RH12 1UP

October 1990

1. INTRODUCTION

This briefing note analyses the implications of the various decisions made at the meeting of 25th September 1990 and provides a questionnaire designed to cover those matters which, because of limitations of time, could not be addressed adequately at that meeting. Responses to this note will be collated and analysed by the secretariat, with recourse to individual members of the Expert Group, as necessary, to generate the overall results and conclusions of the study. These results and conclusions will be made available to the members of the Expert Group for comment before they are finalised.

2. ANALYSIS OF DECISIONS

2.1 COMPREHENSIVE LIST OF FACTORS AND PHENOMENA

On the basis of the minutes of the meeting of 25th September 1990, Table 1 of EG(90)P6 has been updated. The revised version is presented as Table 1 of this note. In the previous version, various items were flagged as representing significant interpretation of the intentions of the Expert Group by the Secretariat. These items were carefully scrutinised at the meeting of 25th September 1990, so the flags have been removed from the revised list.

2.2 CHARACTERISTICS OF A MINIMAL ASSESSMENT

On the basis of the minutes of the meeting of 25th September 1990, Table 2 of EG(90)P6 has been updated. The revised version is presented as Table 2 of this note. This revised table is extended by inclusion of the Group's judgement of whether each item is of low, medium or high priority for inclusion in the minimal assessment.

The Group also identified linkages between items, which have been used to develop the assessment structure shown in Figure 1. There is a substantial amount of subjective judgement in this figure and in the associated Table 3, which sets out relationships at the tertiary level. As Figure 1 plus Table 3 define the structure of the minimal assessment, detailed review by members of the Expert Group is required.

The Group also set priorities for the various items shown in Figure 1. These can be used to define reduced assessment procedures. Thus, Figure 2 shows the procedure excluding low priority factors and phenomena, whereas Figure 3 shows the structure excluding low and medium priority factors and phenomena. In each case, where a factor or phenomenon is associated with two judgements of priority (e.g. L/M) the higher of the two has been used.

3. MATTERS ON WHICH RESPONSES ARE REQUIRED

3.1 INTERPRETATION OF DECISIONS

Members of the Group should scrutinise carefully Table 1 of this note to confirm that it represents their views. Dissenting opinions and points of expansion or clarification will be incorporated in the project documentation.

Table 2 should also be scrutinised carefully to ensure that it is an adequate representation of the views of members of the Group, noting particularly that some priorities have been assigned by the secretariat on the basis of general discussions rather than explicit statements by members of the Group. All responses to this table will be incorporated in the project documentation.

Tables 1 and 2, and the associated documentation, were used by the secretariat in drawing up Figures 1 to 3 and the associated Table 3. A significant amount of judgement was required in this exercise. Expert Group members are requested to scrutinise this material and suggest any amendments required. All responses will be incorporated in the project documentation.

3.2 EVALUATION OF ASSESSMENT ADEQUACY

Notwithstanding the above requests for responses to Tables 1 - 3 and Figures 1 - 3, this material should be considered as the reference basis for the final component of this exercise. In particular, Figures 1 - 3 illustrate three different levels of approach to assessment. The remaining item of work is to provide a view or views on the adequacy of each of these assessment procedures at the overall conceptual level, i.e. excluding consideration of the adequacy of the mathematical and computational models available for representing each of the factors and phenomena illustrated.

In the context of evaluating adequacy, members of the Group are reminded that the primary output from the assessment is the maximum annual individual risk over the period of assessment and that the timescale for the assessment is the first 10^6 years following closure of the repository.

Some further guidance is appropriate on the meaning of individual risk. Appendix A to this Briefing Note provides extracts from a report on this topic, which should be read prior to responding to the following questionnaire.

In items 6 and 8 of the following questionnaire, estimates of combined effects are requested. If you do not feel competent to comment at this level, estimates of effects of sub-sets or of single items will also be useful.

If you require further guidance on completing the questionnaire, please contact Dr M C Thorne (telephone 0403 50131).

Questionnaire

1. Are there any factors or phenomena excluded from the minimal assessment (Figure 1) which could render estimates of peak individual risk substantially in error?

2. What are these factors and/or phenomena?

3. What are your estimates of their probability of occurrence on the following timescales.

   $0 - 10^2$ years post-closure
   $10^2 - 10^3$ years post-closure
   $10^3 - 10^4$ years post-closure
   $10^4 - 10^5$ years post-closure
   $10^5 - 10^6$ years post-closure

   Note that these timescales increase as a geometric progression.

4. What are your estimates of their likely <u>separate</u> effects on the values of peak individual risk calculated from the minimal assessment?

   Limited (less than a factor of two)
   Moderate (less than a factor of ten)
   Severe (greater than a factor of ten)
   Unquantifiable without modelling studies
   Unquantifiable even with modelling studies

5. If several factors and/or phenomena are listed under item (2), are there any interactions between their various probabilities of occurrence and/or their likely effects on the results of the assessment?

6. As described in Section 2.2, the following components were excluded from the minimal assessment to produce the reduced assessment shown in Figure 2:

Item	Description
1.6.4	Thermally induced hydrological changes in the near-field
1.6.5	Thermally induced chemical changes in the near-field
3.2.2	Localised denudation
3.6.4	Recreation policy developments

   All of these are likely to occur. What is your estimate of the effects on calculated values of peak individual risk of their <u>combined</u> exclusion from the assessment?

   Limited (less than a factor of two)
   Moderate (less than a factor of ten)
   Severe (greater than a factor of ten)
   Unquantifiable without modelling studies

7. What were the main considerations you took into account in responding to item 6?

8. As described in Section 2.2, the following components were excluded from the minimal assessment to produce the reduced assessment shown in Figure 3:

Item	Description
1.1.2	Physical degradation of concrete
1.4.6	Fracturing in the near field
1.6.4	Thermally induced hydrological changes in the near-field
1.6.5	Thermally induced chemical changes in the near-field
2.3.3	Modification to far-field hydrology due to rock property changes
2.4.6	Fracture surface changes in the far-field, notably demineralisation
2.4.7	Organic colloid transport
2.4.9	Transport of radionuclides bound to microbes
3.1.1	Transient greenhouse gas induced warming
3.2.2	Localised denudation
3.6.4	Recreation policy developments
4.1.1	Short-circuit pathways relating to loss of integrity of borehole seals
4.1.2	Short-circuit pathways relating to loss of integrity of shaft or access tunnel seals

8a. What are your estimates of their probabilities of occurrence on the following timescales.

- $0 - 10^2$ years post-closure
- $10^2 - 10^3$ years post-closure
- $10^3 - 10^4$ years post-closure
- $10^4 - 10^5$ years post-closure
- $10^5 - 10^6$ years post-closure

Note that these timescales increase as a geometric progression.

8b. What are your estimates of the effects on calculated values of peak individual risk of their <u>combined</u> exclusion from the assessment?

- Limited (less than a factor of two)
- Moderate (less than a factor of ten)
- Severe (greater than a factor of ten)
- Unquantifiable without modelling studies

9. What were the main considerations you took into account in responding to item 8.

4. TIMESCALE

It would be appreciated if responses to this Briefing Note could be received by the secretariat no later than Friday 30th November 1990. These should comprise:

i) Explicit confirmation (or otherwise) of the adequacy of Table 1;
ii) Explicit confirmation of Table 2, or a list of required modifications;
iii) Comments on Figures 1 to 3 and the associated Table 3;
iv) Responses to all items included in the Questionnaire.

Item	Description	Inc.	Comments
1.	Near-field	√	General area important
1.1	Chemical/physical degradation	√	General area important
1.1.1	Structural and container metal corrosion	√	Short-term barrier degradation; relevant to gas production
1.1.1.1	Metal corrosion: localised	x	Minutes[1]
1.1.1.2	Metal corrosion: bulk	√	See 1.1.1
1.1.1.3	Metal corrosion: crevice	x	Minutes[1]
1.1.1.4	Stress corrosion	x	Minutes[1]
1.1.2	Physical degradation of concrete	√	Short-term barrier degradation; relevant to chemical conditioning
1.1.2.1	Cracking	√	Water penetration and characteristics
1.1.2.2	Sealing of Cracks	√	As 1.1.2.1
1.1.2.3	Pore blockage	√	As 1.1.2.1
1.1.2.4	Alkali-aggregate reaction	√	Possibility of occurrence needs investigation
1.1.2.5	Cement-sulphate reaction	√	As 1.1.2.4
1.1.3	Chemical degradation of concrete	√	Major control on near-field chemistry
1.1.3.1	Changes in pore water composition, pH, Eh	√	See 1.1.3
1.1.3.2	Exchange capacity exceeded	√	Possibly not an independent item
1.1.3.3	Alkali-aggregate reaction	√	See 1.1.2.4
1.1.3.4	Cement-sulphate reaction	√	See 1.1.2.5
1.1.4	Degradation of wastes	√	Major control on source term
1.1.4.1	Metal corrosion	√	Major component
1.1.4.2	Leaching	√	Important process
1.1.4.3	Complex formation	√	Potential major control on solubility and sorption
1.1.4.4	Colloid formation	√	As 1.1.4.3
1.1.4.5	Microbial degradation of organic waste	√	Important process
1.1.4.6	Microbial corrosion	√	Potentially important modifying factor
1.1.4.7	Radiolysis	√	Probably secondary consideration
1.2	Gas production, transport and flammability	√	Major potential pathway
1.2.1	Hydrogen by metal corrosion	√	Major component
1.2.1.1	Structural steel	√	Major item
1.2.1.2	Container steel	√	Major item
1.2.1.3	Waste steel	√	Major item

TABLE 1

Factors and Phenomena Considered

Item	Description	Inc.	Comments
1.2.1.4	Waste Magnox	√	EG(90)P4, Minutes[1], EG(90)P6, Minutes[2]
1.2.1.5	Waste aluminium	x	EG(90)P4, Minutes[1], EG(90)P6, Minutes[2]
1.2.1.6	Waste Zircaloy	x	EG(90)P4
1.2.1.7	Waste other metals	x	EG(90)P4
1.2.1.8	Effects of microbial growth on concrete	√	Potentially important modifier of local chemical regime and directly relevant to gas production
1.2.2	Methane and carbon dioxide by microbial degradation	√	Major components
1.2.2.1	Cellulosics	√	Major item
1.2.2.2	Other susceptible organic materials	x	Minor source of gas, but relevant to organic complexation (item 1.1.4.3)
1.2.2.3	Aerobic degradation	√	Not important in own right, but partly defines initial conditions for anaerobic degradation, see Minutes[1], Minutes[2]
1.2.2.4	Anaerobic degradation	√	Long-term regime
1.2.2.5	Effects of temperature	√	Effects on metabolic activity and chemical degradation of cellulose
1.2.2.6	Effects of lithostatic pressure	x	Supplementary modifying factor (see Minutes[1]), partly determined by hydrology, finally eliminated (Minutes[2])
1.2.2.7	Effects of microbial growth on properties of concrete	x	EG(90)P4, Minutes[1]
1.2.2.8	Effects of biofilms	x	EG(90)P4
1.2.2.9	Effects of hydrogen from metal corrosion	√	Microbial utilisation
1.2.2.10	Inhibition due to the presence of toxic materials	√	Secondary factor
1.2.2.11	Carbonate/bicarbonate exchange with concrete	x	Included in transport (item 1.2.6)
1.2.2.12	Energy and nutrient control of metabolism	√	Primary control
1.2.2.13	Effects of radiation on microbial populations	x	EG(90)P4
1.2.3	Gas generation from concrete	x	EG(90)P4
1.2.4	Active gases	√	Major item
1.2.4.1	Tritiated hydrogen	√	Major component
1.2.4.2	Active methane and carbon dioxide	√	Major component
1.2.4.3	Other active gases	x	EG(90)P4, Minutes[1]

TABLE 1 (Cont.)

Item	Description	Inc.	Comments
1.2.5	Toxic gases	x	EG(90)P4, Minutes[1]
1.2.6	Transport	√	Major item
1.2.6.1	In the waste container	x	EG(90)P4, Minutes[1]
1.2.6.2	In the vault between containers	√	Secondary factor
1.2.6.3	Between vaults	√	Significant in pressure build-up
1.2.6.4	In the near-field, including vicinity of shafts and adits	√	Depressurisation, routes to surface
1.2.6.5	Into and through far-field	√	As 1.2.6.4
1.2.7	Flammability	x	EG(90)P4, Minutes[1]
1.3	Radiation phenomena	√	Fundamental processes
1.3.1	Radioactive decay and ingrowth	√	Fundamental processes
1.3.2	Nuclear criticality	x	EG(90)P4, Minutes[1]
1.4	Mechanical effects	√	Generally, topics in this area can be studied by detailed modelling outside the assessment proper c.f. EG(90)P2
1.4.1	Canister or container movement	√	
1.4.2	Changes in 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	√	Major control on source term
1.5.1	Changes in moisture content	√	Secondary effect at early times (but see 1.5.2.2)
1.5.1.1	Due to dewatering	√	As 1.5.1
1.5.1.2	Due to stress relief	√	As 1.5.1 (but see 1.5.2.2)
1.5.2	Groundwater flow (unsaturated)	√	As 1.5.1
1.5.2.1	Initial	√	As 1.5.1
1.5.2.2	Due to gas production	√	Could feasibly significantly extend unsaturated period
1.5.3	Groundwater flow (saturated)	√	Major control on source term
1.5.4	Transport of chemically active substances into the near-field	√	Modifiers of solubility and sorption
1.5.4.1	Inorganic ions	√	As 1.5.4
1.5.4.2	Humic and fulvic acids	√	As 1.5.4
1.5.4.3	Microbes	√	As 1.5.4 (c.f. Minutes[1], page 11)
1.5.4.4	Organic complexes	√	As 1.5.4
1.5.4.5	Colloids	√	As 1.5.4

TABLE 1 (Cont.)

Item	Description	Inc.	Comments
1.6	Thermal effects	√	It was generally agreed that this main topic and all its subtopics require consideration (c.f. Minutes[1])
1.6.1	Differential elastic response	√	c.f. 1.4
1.6.2	Non-elastic response	√	c.f. 1.4
1.6.3	Fracture changes	√	c.f. 1.4
1.6.3.1	Aperture	√	c.f. 1.4
1.6.3.2	Length	√	c.f. 1.4
1.6.4	Hydrological changes	√	Secondary effect
1.6.4.1	Fluid pressure	√	
1.6.4.2	Density	√	Mainly a far-field concern
1.6.4.3	Viscosity	√	
1.6.5	Chemical changes	√	Thought to be the major item of 1.6 (c.f. Minutes[1])
1.6.5.1	Metal corrosion	√	Secondary effect
1.6.5.2	Concrete degradation	√	Secondary effect
1.6.5.3	Waste degradation	√	Secondary effect
1.6.5.4	Gas production	√	Secondary effect
1.6.5.5	Complex formation	√	Secondary effect
1.6.5.6	Colloid production	√	Secondary effect
1.6.5.7	Solubility	√	Primary effect (Minutes[1])
1.6.5.8	Sorption	√	Primary effect (Minutes[1])
1.6.5.9	Species equilibrium	√	Studied outside assessment to define sorption (Minutes[1])
1.6.6	Microbial effects	√	Secondary (Minutes[1])
1.6.6.1	Cellulose degradation	√	Secondary effect
1.6.6.2	Microbial activity	√	Secondary effect
1.6.6.3	Microbial product reactions	√	Secondary effect
1.7	Transport out of the repository	√	Major new entry (Minutes[1])
1.7.1	Solubility	√	Minutes[1]
1.7.2	Sorption	√	Minutes[1]
2.	Far-field	√	General area important
2.1	Extra-terrestrial	√	Secondary (Minutes[1])
2.1.1	Meteorite impact	√	Secondary (Minutes[1])
2.2	Geological	√	General area important
2.2.1	Regional tectonic	√	Marginal (compare EG(90)P4 and Minutes[1]). Not justified listing sub-items separately
2.2.2	Magmatic	x	EG(90)P4, Minutes[1]
2.2.3	Metamorphism	x	EG(90)P4, Minutes[1]
2.2.4	Diagenesis	x	EG(90)P4, Minutes[1]
2.2.5	Diapirism	x	EG(90)P4, Minutes[1]

TABLE 1 (Cont.)

Item	Description	Inc.	Comments
2.2.6	Seismicity	√	Secondary
2.2.6.1	Repository induced	√	As 2.2.6
2.2.6.2	Externally induced	√	As 2.2.6
2.2.6.3	Natural	√	As 2.2.6
2.2.7	Faulting/fracturing	√	Related to 2.2.6
2.2.7.1	Activation	√	Secondary
2.2.7.2	Generation	x	Debatable with current UK levels of seismicity
2.2.7.3	Change of properties	√	Secondary
2.2.8	Major incision	√	Secondary (Minutes[1])
2.2.9	Weathering	√	Secondary in far-field
2.3	Hydrological	√	General area important (Minutes[2])
2.3.1	Variation in groundwater recharge	√	Major control
2.3.2	Groundwater losses	√	Major control
2.3.3	Rock property changes	√	Secondary (c.f. 2.2.6, 2.2.7 and 2.2.9)
2.3.3.1	Porosity	√	As 2.3.3
2.3.3.2	Permeability	√	As 2.3.3
2.3.3.3	Microbial pore blocking	√	Theoretical possibility
2.3.3.4	Channel formation, closure	√	Related to 2.2.6, 2.2.7, 2.2.9
2.3.4	Groundwater flow	√	Major process
2.3.4.1	Darcy flow	√	Usual basis
2.3.4.2	Non-Darcy flow	√	Minutes[1], p.10
2.3.4.3	Intergranular (matrix)	√	Secondary
2.3.4.4	Fracture	√	Especially in Chalk (Minutes[1])
2.3.4.5	Effects of solution channels	√	Secondary
2.3.4.6	Unsaturated	√	Possibly not required for geosphere (Minutes[1], p.10)
2.3.5	Salinity	x	EG(90)P4
2.3.6	Variations in groundwater temperature	x	Excluding repository induced effects (see 2.4.13)
2.4	Transport and geochemical	√	General area important
2.4.1	Advection	√	Major process
2.4.2	Diffusion	√	Major process for near-stagnant groundwater
2.4.2.1	Bulk	√	As 2.4.2
2.4.2.2	Matrix	√	Effects on retardation, secondary
2.4.2.3	Surface	x	EG(90)P4, Minutes[1]
2.4.3	Hydrodynamic dispersion	√	Major process
2.4.4	Solubility constraints	x	EG(90)P4, Minutes[1] - This was a major, debated decision, see also Minutes[2]

TABLE 1 (Cont.)

Item	Description	Inc.	Comments
2.4.5	Sorption	√	Major process, all the sub-heads require consideration, though not all need necessarily be included in an assessment (Minutes[1])
2.4.5.1	Linear	√	
2.4.5.2	Non-linear	√	Might be omitted (Minutes[1])
2.4.5.3	Reversible	√	
2.4.5.4	Irreversible	√	Might be omitted (Minutes[1])
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	√	Probably of much less importance than complexation (Minutes[1])
2.4.5.11	Effects of colloids formed in the near-field	√	As 2.4.5.10
2.4.5.12	Effects of major ions migrating from the near-field	√	Explore in external models and fold into assessment (Minutes[1])
2.4.5.13	Effects of microbial activity	√	Research topic (Minutes[1])
2.4.6	Fracture surface changes	x	Primarily fracture demineralisation in clay when carbonate dissolves (Minutes[2])
2.4.7	Organic colloid transport	√	See 2.4.5.10, Marginal process
2.4.7.1	Porous media	√	See 2.4.7
2.4.7.2	Fractured media	√	See 2.4.7
2.4.7.3	Effects of pH and Eh	√	See 2.4.7
2.4.7.4	Effects of ionic Strength	√	See 2.4.7
2.4.8	Inorganic colloid transport	√	Comments as for 2.4.7
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	√	Possible for starved microbes (Minutes[1], Minutes[2])
2.4.10	Isotopic exchange	√	Contribution to sorption (Minutes[1])

TABLE 1 (Cont.)

Item	Description	Inc.	Comments
2.4.11	Gas transport	√	Potentially important transport pathway
2.4.11.1	Solution	√	Minutes[2]
2.4.11.2	Gas phase	√	Major process
2.4.12	Gas-induced groundwater transport	√	Potentially significant
2.4.13	Thermally induced groundwater transport	√	Potentially significant
2.4.13.1	Repository induced	√	Minutes[1]
2.4.13.2	Naturally induced	x	EG(90)P4, Minutes[1]
2.4.14	Biogeochemical changes	x	EG(90)P4, Minutes[1] (c.f. 2.4.5.7)
3.	Biosphere	√	General area important
3.1	Climatology	√	General area important
3.1.1	Transient greenhouse gas induced warming	√	Minutes[1]
3.1.1.1	Precipitation	√	Minutes[1]
3.1.1.2	Temperature	√	Minutes[1]
3.1.1.3	Sea level rise	x	Minutes[1]
3.1.1.4	Storm surges	x	Minutes[1]
3.1.1.5	Ecological effects	√	Minutes[1], EG(90)P6
3.1.1.6	Potential evaporation	√	Minutes[1]; derived quantity
3.1.2	Glacial/interglacial cycling	√	Minutes[1]
3.1.2.1	Precipitation	√	Minutes[1]
3.1.2.2	Temperature	√	Minutes[1]
3.1.2.3	Sea level fall	√	Rise excluded (Minutes[1]); fall not important locally (EG(90)P6)
3.1.2.4	Storm surges	x	EG(90)P4, Minutes[1]
3.1.2.5	Ecological effects	√	Minutes[1], EG(90)P6
3.1.2.6	Seasonally frozen ground	√	Minutes[1]
3.1.2.7	Permanently frozen ground	√	Minutes[1]
3.1.2.8	Glaciation	√	Minutes[1]
3.1.2.9	Deglaciation	√	Minutes[1]
3.1.2.10	Potential evaporation	√	Minutes[1]; derived quantity
3.1.3	Exit from glacial/interglacial cycling	√	Unlikely, but not excluded (EG(90)P6, Minutes[2])
3.1.3.1	Greenhouse-gas induced	√	Most likely cause
3.1.3.2	Other causes	√	Possible on 10^6 - 10^7 y timescale
3.2	Geomorphology	√	General area important
3.2.1	Generalised denudation	√	Minutes[1]
3.2.1.1	Fluvial	√	Minutes[1]
3.2.1.2	Aeolian	√	Marginal (Minutes[1])
3.2.1.3	Glacial	√	Minutes[1]
3.2.2	Localised denudation	√	Minutes[1]

TABLE 1 (Cont.)

Item	Description	Inc.	Comments
3.2.2.1	Fluvial (valley incision)	√	Minutes[1], EG(90)P6
3.2.2.2	Fluvial (weathering/mass movement)	√	Minutes[1]
3.2.2.3	Glacial	√	Minutes[1]
3.2.2.4	Coastal	x	EG(90)P4, Minutes[1], EG(90)P6 Minutes[1]
3.2.3	Sediment redistribution	√	Minutes[1]
3.2.3.1	Fluvial	√	Minutes[1]
3.2.3.2	Aeolian	√	Minutes[1]
3.2.3.3	Glacial	√	Minutes[1]
3.2.4	Effects of sea level change	√	Marginal; effects only considerable distances downstream from site (EG(90)P6, Minutes[2])
3.2.4.1	River incision/sedimentation	√	As 3.2.4
3.2.4.2	Coastal erosion	x	As 3.2.2.4
3.3	Hydrology	√	General area important, virtually all sub-areas have to be incorporated for a coherent approach
3.3.1	Soil moisture and evaporation	√	
3.3.2	Surface hydrology	√	Includes near-surface components (renamed) (Minutes[1])
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	√	New item; various overlaps in the interpretation of all the above items
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	√	Belongs more under geomorphology
3.3.4.4	Natural lake formation/sedimentation	√	Marginal (EG(90)P6, Minutes[2])
3.3.4.5	Effects of sea level change	√	Debated significance (EG(90)P4, Minutes[1], EG(90)P6, Minutes[2])

TABLE 1 (Cont.)

Item	Description	Inc.	Comments
3.3.5	Surface flow characteristics (estuarine)	√	Marginal; only if there are substantial reconcentrating processes in the estuarine environment (Minutes[1])
3.3.5.1	Tidal cycling	√	As 3.3.5
3.3.5.2	Sediment transport	√	As 3.3.5
3.3.5.3	Successional development	√	As 3.3.5 (NB. This is in relation to hydrological factors, see also item 3.4.2)
3.3.5.4	Effects of sea level change	√	As 3.3.5
3.3.6	Coastal waters	√	Marginal (Minutes[1])
3.3.6.1	Tidal mixing	√	As 3.3.6
3.3.6.2	Residual current mixing	√	As 3.3.6
3.3.6.3	Effects of sea level change	√	As 3.3.6
3.3.7	Ocean waters	x	EG(90)P4, Minutes[1]
3.4	Ecological development	√	General area important, included sub-items consistent with hydrology (Minutes[1])
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	√	Marginal, see 3.3.5
3.4.3	Coastal waters	√	Marginal, see 3.3.6
3.4.4	Oceans	x	
3.5	Radionuclide transport	√	General area important, sub-topics, follow assignment in previous headings
3.5.1	Erosive	√	
3.5.1.1	Fluvial	√	
3.5.1.2	Aeolian	√	
3.5.1.3	Glacial	√	
3.5.1.4	Coastal	√	Marginal (EG(90)P4, Minutes[1])
3.5.2	Groundwater discharge to soils	√	Potential major route of contamination,all components relevant
3.5.2.1	Advective	√	
3.5.2.2	Diffusive	√	
3.5.2.3	Biotic	√	
3.5.2.4	Volatilisation	√	Specific radionuclides

TABLE 1 (Cont.)

Item	Description	Inc.	Comments
3.5.3	Groundwater discharge to wells or springs	√	Potential major route of contamination
3.5.4	Groundwater discharge to freshwaters	√	As 3.5.3
3.5.5	Groundwater discharge to estuaries	√	Marginal (compare EG(90)P4 and Minutes[1])
3.5.6	Groundwater discharge to coastal waters	√	Marginal (compare EG(90)P4 and Minutes[1])
3.5.7	Surface water bodies	√	Defines initial redistribution, all sub-items potentially important
3.5.7.1	Water flow	√	
3.5.7.2	Suspended sediments	√	
3.5.7.3	Bottom sediments	√	
3.5.7.4	Biogeochemical cycling	√	Generalised description
3.5.7.5	Effects of fluvial system development	√	
3.5.8	Estuaries	√	Marginal (compare EG(90)P4 and Minutes[1])
3.5.8.1	Water flow	√	As 3.5.8
3.5.8.2	Suspended sediments	√	As 3.5.8
3.5.8.3	Bottom sediments	√	As 3.5.8
3.5.8.4	Effects of salinity and pH variation	√	As 3.5.8; extended description
3.5.8.5	Biogeochemical cycling	√	As 3.5.8; generalised description
3.5.8.6	Effects of estuarine development	√	As 3.5.8
3.5.8.7	Effects of sea level change	√	As 3.5.8
3.5.9	Coastal waters	√	Marginal (compare EG(90)P4 and Minutes[1])
3.5.9.1	Water transport	√	As 3.5.9
3.5.9.2	Suspended sediment transport	√	As 3.5.9
3.5.9.3	Bottom sediment transport	√	As 3.5.9
3.5.9.4	Effects of sea-level change	√	As 3.5.9
3.5.9.5	Effects of estuarine development	√	As 3.5.9
3.5.9.6	Effects of coastal erosion	√	As 3.5.9
3.5.9.7	Effects of sea level change	√	As 3.5.9
3.5.10	Plants	√	Important that all items are represented either explicitly or in aggregated parameters (Minutes[1])
3.5.10.1	Root uptake	√	
3.5.10.2	Deposition on surfaces	√	
3.5.10.3	Vapour uptake	√	Specific radionuclides

TABLE 1 (Cont.)

Item	Description	Inc.	Comments
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 process	√	
3.5.11	Animals	√	As 3.5.10
3.5.11.1	Uptake by ingestion	√	
3.5.11.2	Uptake by inhalation	√	Generally less important than ingestion
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	√	New area (Minutes[1])
3.6.1	Urbanisation	√	Minutes[1]
3.6.2	Management of water resources	√	Minutes[1]
3.6.2.1	Lake formation	√	Minutes[2]
3.6.3	Agricultural policy	√	Minutes[1]
3.6.4	Recreation policy	√	Minutes[1]
3.7	Human Exposure	√	Fundamental component, previously item 3.6, virtually all sub-items important and included in biosphere models (Minutes[1])
3.7.1	External	√	Minutes[1]
3.7.1.1	Land	√	Minutes[1]
3.7.1.2	Sediments	√	Minutes[1]
3.7.1.3	Water bodies	√	Minutes[1]
3.7.2	Ingestion	√	Minutes[1]
3.7.2.1	Drinking water	√	Minutes[1]
3.7.2.2	Agricultural crops	√	Minutes[1]
3.7.2.3	Domestic animal products	√	Minutes[1]
3.7.2.4	Wild plants	√	Marginal (Minutes[1])
3.7.2.5	Wild animals	√	Marginal (Minutes[1], Minutes[2])
3.7.2.6	Soils and sediments	√	Minutes[1]
3.7.3	Inhalation	√	Minutes[1]
3.7.3.1	Soils and sediments	√	Minutes[1]
3.7.3.2	Gases and vapours (indoors)	√	Minutes[1]
3.7.3.3	Gases and vapours (outdoors)	x	Minutes[1]
3.7.3.4	Biotic material	√	Marginal (Minutes[1])
3.7.3.5	Salt particles	x	EG(90)P4, Minutes[1]

TABLE 1 (Cont.)

Item	Description	Inc.	Comments
4.	Short-circuit pathways related to	√	General area important
4.1	human activities		
4.1.1	Related to repository construction	√	Minutes[1] (by inference)
4.1.1.1	Loss of integrity of borehole seal	√	Minutes[1] (by inference), Minutes[2]
4.1.1.2	Failure	√	Minutes[1] (by inference)
4.1.2	Degradation	√	Minutes[1] (by inference)
	Loss of integrity of shaft or	√	Minutes[1] (by inference), Minutes[2]
4.1.2.1	access tunnel seal		
4.1.2.2	Failure	√	Minutes[1] (by inference)
4.1.3	Degradation	√	Minutes[1] (by inference)
	Damage to the host medium	√	Minutes[2]
4.2	around shafts or access tunnels		
4.2.1	Post-closure	√	Minutes[1]
	Deliberate recovery of wastes or	x	EG(90)P4, Minutes[1]
4.2.2	associated materials		
4.2.3	Malicious intrusion	x	EG(90)P4, Minutes[1]
4.2.4	Exploratory drilling	√	Minutes[1]
4.2.5	Exploitation drilling	√	Minutes[1]
4.2.6	Geothermal energy production	x	EG(90)P4, Minutes[1]
4.2.7	Resource mining	√	Minutes[1]
4.2.8	Tunnelling	√	Minutes[1]
	Construction of underground	√	Minutes[1]
4.2.9	storage/disposal facilities		
	Construction of underground	√	Minutes[1]
4.2.10	dwellings/shelters		
4.2.11	Archaeological investigations	√	Minutes[1]
4.2.12	Injection of liquid wastes	√	Minutes[1]
4.2.13	Groundwater abstraction	√	Minutes[1]
	Underground weapons' testing	x	EG(90)P4, Minutes[1]

Notes: Minutes[1] = Minutes of the meeting of 26th June 1990
Minutes[2] = Minutes of the meeting of 25th September 1990

TABLE 1 (Cont.)

a) Neglect metal corrosion, but include physical and chemical degradation of concrete and degradation of wastes.

Item	Description	Status
1.1.1	Structural and container metal corrosion	x
1.1.2	Physical degradation of concrete	L/M
1.1.3	Chemical degradation of concrete	H
1.1.4	Degradation of wastes	H

b) Gas generation in the repository must be included, but only selected aspects of transport in the near-field need be included explicitly.

Item	Description	Status
1.2.1	Generation of hydrogen by metal corrosion	H
1.2.2	Generation of methane and carbon dioxide by microbial degradation	H
1.2.3	Gas generation from concrete	x
1.2.4	Generation of active gases	H
1.2.5	Generation of toxic gases	x
1.2.6	Transport in the near-field, especially in the vicinity of shafts and adits	M
1.2.7	Flammability	x

c) Radiation phenomena must be included, but not criticality.

Item	Description	Status
1.3.1	Radioactive decay and ingrowth	H
1.3.2	Nuclear criticality	x

d) Effects of fracturing in the near-field should be included. Mechanical effects of gas production on the stress field should be studied outside the assessment. All other mechanical effects can be neglected.

Item	Description	Status
1.4.1	Canister or container movement	x
1.4.2	Changes in in situ stress field	s
1.4.3	Embrittlement	x
1.4.4	Subsidence/collapse	x
1.4.5	Rock creep	x
1.4.6	Fracturing	L/M

TABLE 2
Characteristics of a Minimal Assessment

e) Only groundwater flows in saturated conditions in the near-field should be included.

Item	Description	Status
1.5.1	Changes in moisture content	x
1.5.2	Groundwater flow (unsaturated)	x
1.5.3	Groundwater flow (saturated)	H

f) Neglect transport of chemically active substances into the near-field.

Item	Description	Status
1.5.4	Transport of chemically active substances into the near-field	x

g) Repository induced thermal effects should be included. Thermo-mechanical effects should be the subject of a supplementary geotechnical study outside the assessment. Thermal modifications of microbial effects can be neglected.

Item	Description	Status
1.6.1	Differential elastic response	s
1.6.2	Non-elastic response	s
1.6.3	Fracture changes	s
1.6.4	Hydrological changes	L
1.6.5	Chemical changes	L
1.6.6	Microbial effects	x

h) Transport out of the repository should be included, taking account of solubility constraints and sorption in the near-field.

Item	Description	Status
1.7.1	Solubility controls on transport	H(*)
1.7.2	Sorption controls on transport	H(*)

i) Extra-terrestrial processes can be neglected.

Item	Description	Status
2.1.1	Meteorite impact	x

TABLE 2 (Cont.)

j) Regional tectonic effects, seismicity and the effects of faulting and fracturing should be included in supplementary studies outside the assessment. Weathering should be included, but as a component of geomorphology rather than under geology.

Item	Description	Status
2.2.1	Regional tectonics	s
2.2.2	Magmatic effects	x
2.2.3	Metamorphism	x
2.2.4	Diagenesis	x
2.2.5	Diapirism	x
2.2.6	Seismicity	s
2.2.7	Faulting/fracturing	s
2.2.8	Major incision	x
2.2.9	Weathering	moved
2.2.10	Effects of natural gases	x
2.2.11	Geothermal effects	x

k) Far-field hydrological characteristics generally need to be included.

Item	Description	Status
2.3.1	Variation in groundwater recharge	H
2.3.2	Groundwater losses	H
2.3.3	Rock property changes	M
2.3.4	Groundwater flow	H
2.3.5	Salinity effects on flow	x
2.3.6	Effects of variations in groundwater temperatures on flow	x

l) Transport should be assumed to be in aqueous form, taking speciation and complexation into account.

Item	Description	Status
2.4.1	Advective transport	H(*)
2.4.2	Diffusive transport	H(*)
2.4.3	Hydrodynamic dispersion	H(*)
2.4.4	Solubility constraints	x
2.4.5	Sorption	H
2.4.6	Fracture surface changes, notably demineralisation	M
2.4.7	Organic colloid transport	M
2.4.8	Inorganic colloid transport	H

Table 2 (Cont.)

Item	Description	Status
2.4.9	Transport of radionuclides bound to microbes	M
2.4.10	Isotopic exchange	x
2.4.11	Gas transport	H
2.4.12	Gas-induced groundwater transport	H
2.4.13	Thermally induced groundwater transport	x
2.4.14	Biogeochemical changes	x

m) Glacial/interglacial cycling should be assumed. Greenhouse gas warming giving rise to an end of such cycling is considered to be a low-probability event with huge non-radiological consequences.

Item	Description	Status
3.1.1	Transient greenhouse gas induced warming	M(*)
3.1.2	Glacial/interglacial cycling	H(*)
3.1.3	Exit from glacial/interglacial cycling	x(*)

n) Geomorphological change should generally be included.

Item	Description	Status
3.2.1	Generalised denudation	H
3.2.2	Localised denudation	L
3.2.3	Sediment redistribution	M/H
3.2.4	Effects of sea-level change	x
2.2.9	Weathering	H(*)

o) Surface hydrology should be included in a comprehensive and coherent way. Development and application of a detailed model outside the assessment would be appropriate. Estuarine and coastal water hydrology could be investigated in supplementary studies and not included directly in the assessment.

Item	Description	Status
3.3.1	Soil moisture and evaporation	H(*), d
3.3.2	Terrestrial near-surface hydrology	H(*), d
3.3.3	Groundwater recharge	H(*), d
3.3.4	Surface flow characteristics (freshwater)	H(*), d
3.3.5	Surface flow characteristics (estuarine)	s
3.3.6	Flow characteristics (coastal waters)	s
3.3.7	Flow characteristics (ocean waters)	x

Table 2 (Cont.)

p) Effects of ecological development on the terrestrial surface hydrological system should be included. Effects of estuarine and coastal water ecology can be investigated in a supplementary study and not included directly in the assessment. Effects of oceanic ecology need not be considered.

Item	Description	Status
3.4.1	Effects of terrestrial ecological development on hydrology	H,d(*)
3.4.2	Effects of estuarine ecological development on hydrology	s
3.4.3	Effects of coastal water ecological development on hydrology	s
3.4.4	Effects of oceanic ecological development on hydrology	x

q) Radionuclide transport processes in the environment should generally be included. However, groundwater discharges to estuaries and coastal waters can be ignored, while transport in estuaries and coastal waters can be treated in a supplementary study outside the assessment.

Item	Description	Status
3.5.1	Erosive transport (N.B. glacial and coastal erosion to be treated outside the assessment)	H(*)
3.5.2	Groundwater discharge to soils	H(*)
3.5.3/ 3.5.4 3.5.7	Groundwater discharge to wells, springs, streams, rivers and surface water bodies	H(*)
3.5.5	Groundwater discharge to estuaries	x
3.5.6	Groundwater discharge to coastal waters	x
3.5.7	(see above)	
3.5.8	Radionuclide transport in estuaries	s
3.5.9	Radionuclide transport in coastal waters	s
3.5.10	Radionuclide uptake, retention and cycling in plants	H(*)
3.5.11	Radionuclide uptake, retention and cycling in animals	H(*)

r) Planning considerations, including land and water management policies, should be taken into account in determining the range of potential human influences on the disposal system.

Item	Description	Status
3.6.1	Urbanisation	M(*)
3.6.2	Management of water resources	H(*)
3.6.3	Agricultural policy	H(*)
3.6.4	Recreation policy	L(*)

s) The assessment should include a comprehensive treatment of human exposure pathways.

Item	Description	Status
3.7.1	External exposure	H(*)
3.7.2	Ingestion	H(*)
3.7.3	Inhalation	H(*)

t) Short-circuit pathways related to repository construction, including those associated with damage to the host media in the vicinity of boreholes, should be included.

Item	Description	Status
4.1.1	Loss of integrity of borehole seals	M
4.1.2	Loss of integrity of shaft or access tunnel seals	M
4.1.3	Damage to the host medium around shaft or access tunnels	M/H

u) A limited number of post-closure short-circuit pathways should be included, others could, if necessary, be covered by scoping or scaling calculations.

Item	Description	Status
4.2.1	Deliberate recovery of wastes or associated materials	x
4.2.2	Malicious intrusion	x
4.2.3	Exploratory drilling	H
4.2.4	Exploitation drilling	x, sc(*)
4.2.5	Geothermal energy production	x
4.2.6	Resource mining	x, sc(*)
4.2.7	Tunnelling	x, sc(*)
4.2.8	Construction of underground storage/disposal facilities	x, sc(*)
4.2.9	Construction of underground dwellings/shelters	x, sc(*)
4.2.10	Archaeological investigations	x
4.2.11	Injection of liquid wastes	x
4.2.12	Groundwater abstraction	H
4.2.13	Underground weapons' testing	x

TABLE 2 (Cont.)

Notes:

- x - excluded
- L - low priority
- M - medium priority
- H - high priority
- s - subject of a supplementary study outside the assessment
- d - component of a detailed model of the surface hydrological system to be applied outside the assessment
- sc - appropriate topic for scoping or scaling calculations
- * - includes significant subjective judgement by the secretariat; requires careful scrutiny

Origins	Targets	Comment
1.1.4	1.2.1/1.2.2/1.2.4	Degradation of wastes is the source of gas production
1.1.4	1.7	Degradation of wastes is the source of radionuclides for transport out of the near-field
1.2.1/1.2.4/1.2.6	1.5.3	Gas production in the near-field can induce or impede groundwater flow
1.2.1/1.2.4/1.2.6	1.4.6	Gas production can lead to over-pressurisation and fracturing
1.2.1/1.2.2/1.2.4/1.2.6	1.7	Gas can migrate out of the near-field
1.3.1	1.1/2.4/3.5	Radioactive decay and ingrowth occurs primarily during residence in the near-field, transport through the far-field and transport in the biosphere
1.4.6	1.5.3	Fracturing influences groundwater flow characteristics of the near-field
1.4.6	1.2.6	Fracturing influences gas transport properties of the near-field
1.5.3	1.7	Groundwater flow in the near-field is a primary determinant of radionuclide transport out of the near-field
1.6.4	1.5.3	Thermal effects modify near-field hydrological transport
1.6.5	1.1.2/1.1.3/1.1.4	Thermal effects modify near-field chemical degradation
1.7	2.4	Transport out of the near-field is the source term for far-field transport

TABLE 3

Structural Relationships Incorporated in the Minimal Assessment

Origins	Targets	Comment
1.7	4.1	Transport out of the near-field is the source term for transport via preferential pathways associated with repository construction
2.3	1.5.3	Far-field hydrology controls groundwater flow through the repository
2.3	2.4	Far-field hydrology controls far-field transport
2.3	4.1	Far-field hydrology controls transport via preferential pathways associated with repository construction
2.3	3.3.2/3.3.4	Groundwater discharge as a determinant of surface hydrology (e.g. springs, baseflow)
2.4	3.5	Far-field transport as a source of radionuclides to the biosphere
3.1	3.2.1/3.2.2/3.2.3/2.2.9	Climate as a primary determinant of denudation and weathering
3.1	3.3	Climate as a primary determinant of surface hydrology
3.1	3.4.1	Climate as a control on terrestrial ecological development
3.1	3.6.2/3.6.3	Climate as a determinant of the management of water resources and of agricultural policy
3.2	2.3	Land form change modifies the boundary conditions of the far-field hydrological system, weathering alters the hydraulic properties of far-field materials
2.2.9	2.4.5/2.4.6	Weathering alters the transport properties of far-field materials

TABLE 3 (Cont.)

Origins	Targets	Comment
3.2	3.3	Land form change modifies the characteristics of the surface hydrological system
3.2	3.4	Land form change influences ecological development
3.2.1/3.2.2/3.2.3	3.5.1	Denudation and sediment redistribution control the erosive transport of radionuclides
3.3	2.3	Surface hydrology defines the boundary conditions for far-field hydrology
3.3.1/3.3.2/3.3.4	3.4.1	Surface hydrology constrains the types of ecosystems that can develop
3.3.2/3.3.4	3.2	Surface hydrology is a major determinant of denudation, sediment redistribution and weathering
3.3	3.5.2/3.5.3/3.5.4/3.5.7	Surface hydrology is a major determinant of radionuclide transport in the environment, both in solution and bound to sediments
3.4.1	3.2.1/3.2.2/3.2.3	Vegetation cover as a control on denudation and sediment transport
3.4.1	3.3.1/3.3.2/3.3.3	Vegetation cover as a control on surface hydrology
3.4.1	3.5.10/3.5.11	Ecological development partly defines the foodchain pathways
3.5	3.7	Biosphere transport is the primary determinant of human exposure pathways
3.6.2	2.3.4	Management of water resources modifies groundwater flow
3.6.1/3.6.3/3.6.4	3.2.1/3.2.2/3.2.3	Land management controls denudation and sediment redistribution

TABLE 3 (Cont.)

Origins	Targets	Comment
3.6	3.3	All aspects of land management can influence the surface hydrological system
3.6	3.4.1	Land management and management of water resources are primary determinants of ecological development
3.6	3.5	Land management determines the type of biosphere pathways likely to occur, while management of water resources can influence the utilisation and distribution of contaminated water
3.6	3.7	Management practices partly determine behavioural characteristics and hence exposure pathways
4.1	3.5	Short-circuit pathways related to repository construction primarily provide source terms for biosphere transport
4.2	3.5	Post-closure short-circuit pathways provide source terms for biosphere transport
4.2.3	3.7	Exploratory drilling results directly in exposures of those involved in the operation or examination of the extracted material.

Notes: This table has been developed by the secretariat and requires careful review;

Where secondary headings only are listed, all the tertiary headings included in Figure 1 are implied.

TABLE 3 (Cont.)

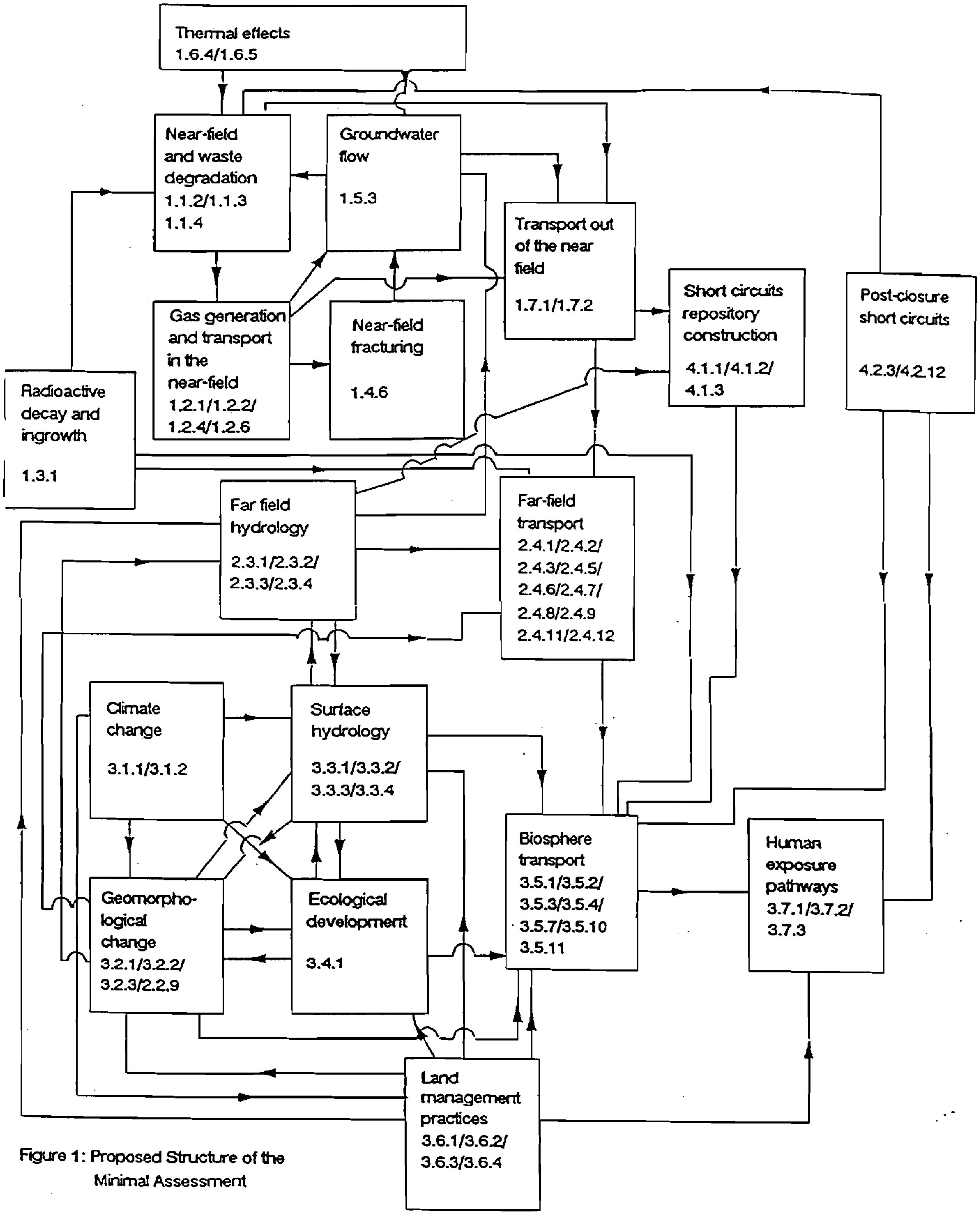


Figure 1: Proposed Structure of the Minimal Assessment

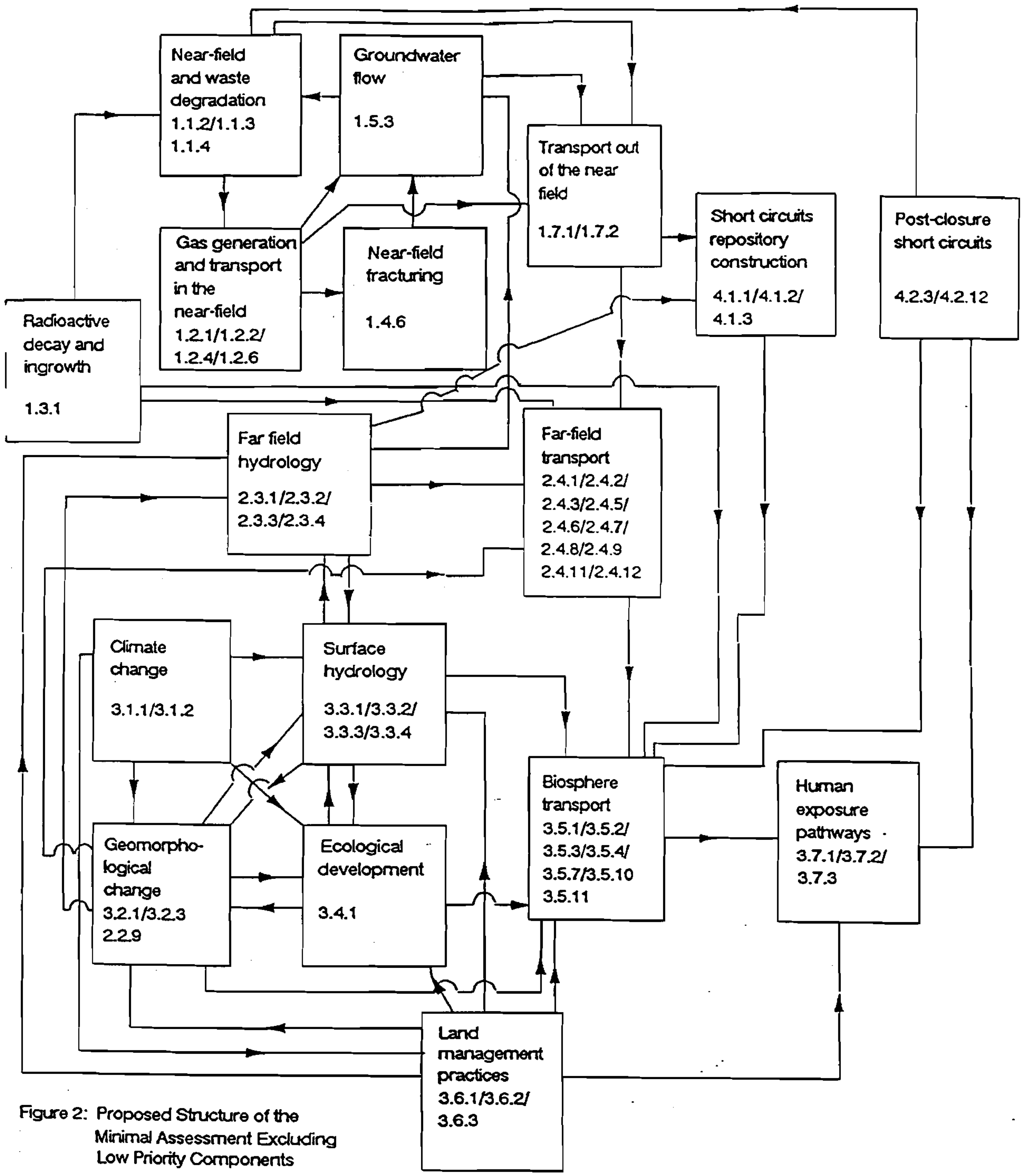


Figure 2: Proposed Structure of the Minimal Assessment Excluding Low Priority Components

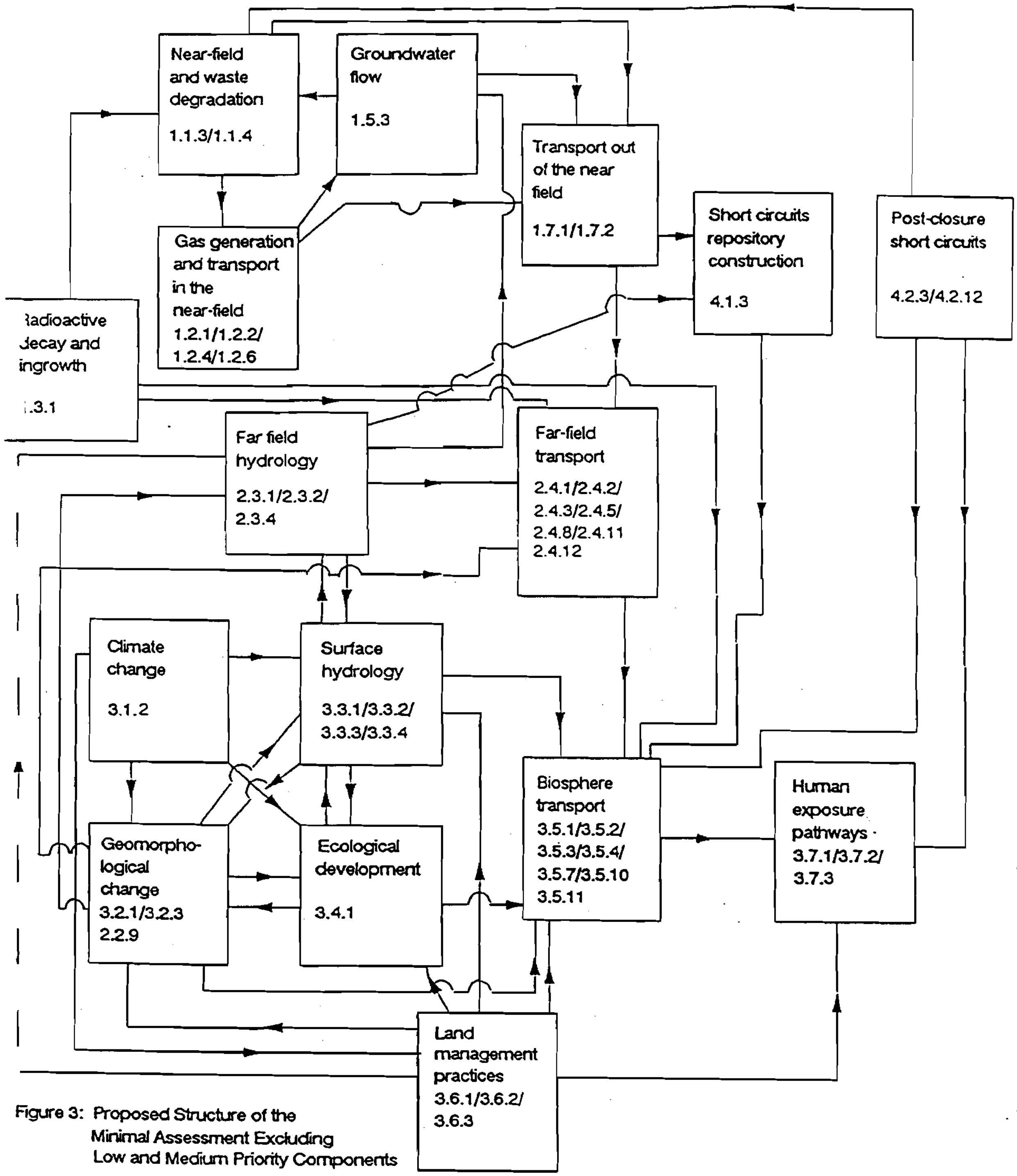


Figure 3: Proposed Structure of the Minimal Assessment Excluding Low and Medium Priority Components

APPENDIX A

Extracts from DoE Report No. DOE/RW/89/030: Assessment of the Radiological Risks of Underground Disposal of Solid Radioactive Wastes

Department of the Environment

Commissioned research on radioactive waste management 1988/89

Report Title: Assessment of the Radiological Risks of Underground Disposal of Solid Radioactive Wastes

DOE Report No: DOE/RW/89/030

Contract Title: Support work for the programme of vault model development for post-closure assessment

DOE Reference: PECD 7/9/192   Sector No: 3.4

Contractor's Reference: EWE 2618.032

Author/Affiliations etc: M C Thorne, Electrowatt Engineering Services (UK) Ltd, Grandford House, 16 Carfax, Horsham, W. Sussex, RH12 1UP

Date of submission to DOE: December 1988

Period covered by report: August 1988 – December 1988

Abstract (100-200 words as desired):

One of the general principles for assessing proposals for operating a land-based facility for solid radioactive waste dieposal is that the site should be chosen and the facility should be designed so that the risk or probability of fatal cancer, to any member of the public, from any movement of radioactivity from the facility, is not greater than 1 in a million in any one year. This report provides advice to the Department of the Environment as to how this risk may be defined and gives a prescription for how it can be calculated.

Keywords (maximum of five to be taken from DOE standard keyword list provided)

140   146   148   149   151

Executive Summary

One of the general principles for assessing proposals for operating a land-based facility for solid radioactive waste disposal is that the site should be chosen and the facility should be designed so that the risk or probability of fatal cancer, to any member of the public, from any movement of radioactivity from the facility, is not greater than one in a million in any one year. This report provides advice as to how risk may be defined and gives a prescription for how it can be calculated.

A brief summary of the risks from radiation exposure is provided and implications of recent recommendations and guidance from ICRP and NRPB are discussed. This summary provides a basis for discussing recommendations on assessing risks from uncertain exposures and on appropriate application of the critical group concept in post-closure radiological safety assessments.

Because it is not possible to predict the precise future evolution of a repository and its environment, it is necessary to take into account both the probability of different future evolutions and the individual risks associated with them. A detailed prescription for combining risks from different potential futures constitutes the central feature of the report. This prescription implies the use of a variety of conceptual and mathematical models. Application of such models can give rise to uncertainties and biases in risk estimates. The need to consider such matters is addressed, as is the related question of the period post-closure for which an assessment should be undertaken.

The report is supplemented by appendices on the risks of non-stochastic effects and on the advantages and drawbacks of alternative measures of risk.

CONTENTS

INTRODUCTION

Disposal of solid radioactive wastes requires an authorisation from the appropriate Department or Departments under Section 6 of the Radioactive Substances Act 1960. Such an authorisation will not be given unless the authorising Departments are satisfied, after careful scrutiny, that the proposed site has been properly chosen, that the facilities can be fully developed, that the wastes proposed for disposal are appropriate to the engineering structure and geological and hydrogeological environment, that their disposal forms part of the national strategy for waste management, and that the proposals will secure the protection of man and his environment on a continuing basis. The stage of formal authorisation will not be reached until a facility has been constructed and is ready for operation. However, prior to planning permission being given to construct a facility, the authorising Departments will give their provisional view on whether the proposed facility would be suitable for authorisation (Ref. 1).

To give guidance to developers, the authorising Departments, in consultation with the Nuclear Installations Inspectorate (NII) of the Health and Safety Executive (HSE) and the National Radiological Protection Board (NRPB) issued a document setting out the principles which the authorising Departments will apply when assessing proposals by a developer in order to decide whether a general authorisation to operate a land disposal facility should be given, and, if so, what conditions should attach to it (Ref. 1).

One of the general principles is that the site should be chosen and the facility should be designed so that the risk or probability of fatal cancer, to any member of the public, from any movement of radioactivity from the facility, is not greater than 1 in a million in any one year. It was recognised that the general principles might have to be augmented as research and development proceeded, and in the light of advice and recommendations from other bodies. This report provides advice to the Department of the Environment (DOE) as to how risk may be defined and gives a prescription for how it can be calculated.

Only risks to members of the public in the post-closure period are addressed herein. Doses and risks to workers and members of the public during repository operation are not discussed. It is expected that an operating repository will be a licensed installation, as defined in the Nuclear Installations Act 1965, and that the relevant provisions of that Act will apply.

This report is supplemented by appendices on non-stochastic radiation effects and on alternative measures of risk.

2. THE RISKS FROM RADIATION EXPOSURE

The International Commission on Radiological Protection (ICRP) recognises two broad categories of effect resulting from exposure to ionising radiations (Ref. 2). Stochastic effects are those for which the probability of an effect occurring, rather than its severity, is regarded as a function of radiation dose, without threshold. Non-stochastic effects are those for which the severity of the effect varies with the dose, and for which a threshold may therefore exist. At low doses and dose rates, only stochastic effects arise. These include cancer induction in the exposed individual and the induction of serious hereditary disease in his descendants.

In the case of underground repositories for solid radioactive wastes, annual doses to members of the public will, in general, be sufficiently low that non-stochastic effects will not occur. However, it is recommended that, if annual organ or tissue doses at any time exceed 0.1 Sv, the risk of induction of non-stochastic effects be assessed explicitly. Guidance on the types of non-stochastic effects which may occur and the associated threshold doses and dose rates are given in Appendix A.

For assessment of stochastic risks at low doses and dose rates, the ICRP recommends use of a linear dose response relationship, without threshold. In order to take account of differences in the effectiveness with which radiations of various types induce these effects, radiation doses are multiplied by a non-dimensional quality factor to give dose equivalents. To take account of spatial inhomogeneities of radiation exposure from external sources or internally-incorporated radionuclides, an effective dose equivalent, H_E, is calculated by summing weighted organ and tissue doses:

$$H_E = \sum_T W_T H_T \qquad (1)$$

where W_T is the weighting factor for organ or tissue T; and
H_T is dose equivalent to organ or tissue T.

In the case of intakes of radionuclides by inhalation or ingestion, the ICRP extends the concept of dose equivalent to that of committed dose equivalent. In particular, in setting Annual Limits on Intake for workers (Ref. 3) the committed dose equivalent is defined as the dose equivalent received in the 50 years following intake of a radionuclide.

The weighting factors specified by the ICRP are based on, and recommended for use in conjunction with, an overall risk from whole-body radiation exposure of 0.0165 Sv^{-1}. The risk is both of fatal cancer and of serious hereditary disease in the first two generations of offspring of the irradiated individual.

In November 1987, the NRPB produced interim guidance on implications of recent revisions of the risk estimates, taking into account new dosimetric and epidemiological information derived from studies of the survivors of the atomic bomb explosions at Hiroshima and Nagasaki (Ref. 4). If no consideration is given to various relevant modifying factors, these studies indicate a risk estimate which could be 5-10 times the ICRP estimate. However, consideration of these modifying factors results in a risk estimate for this population of survivors which is about a factor of two larger than the ICRP estimate. The NRPB considers that, when all the available human data have been taken into account, an increase of a factor of two or three in the risk estimates used for radiological protection purposes should be anticipated (Ref. 4).

It is recognised that this new information on risks may well require a change in the definition of effective dose equivalent, as well as a change to the whole-body risk factor. However, until the United Nations Scientific Committee on Atomic Radiations (UNSCEAR) has published its forthcoming review of the human data on radiation carcinogenesis and the ICRP has made new recommendations taking this review into account, it is proposed that the risks of stochastic effects should be assessed using the effective dose equivalent, as currently defined, in conjunction with a whole-body dose to risk conversion factor of 0.0165 Sv^{-1}. It is emphasised that this is a modification of the general principles (Ref. 1), since use of the effective dose equivalent implies consideration not only of fatal cancer but also of serious hereditary disease in the first two generations of offspring of the irradiated individual.

It is recognised that the proposed formalism is not only likely to be subject to revision, but that it also gives only an indication of individual risks from radiation exposure. It neglects differences in radiation sensitivity at different ages and between the sexes. It also neglects variations in individual sensitivity and differences in the relative effectiveness of various radiation types in inducing biological effects in different organs and tissues.

At annual effective dose equivalents in excess of 0.1 Sv, the use of linear dose response relationships becomes less justifiable and non-linear relationships may be more appropriate. In general, doses of this magnitude will occur only as a result of intrusion into a repository or subsequent to gross disturbance due to natural events. For these cases, individual risks have to be assessed using appropriate dose-response relationships and the results taken into account using the formalism set out in Sections 3 and 5, and in Appendix B.

3. RISKS FROM UNCERTAIN RADIATION EXPOSURES

The ICRP recommends that, for the purpose of including events and processes which are not certain to occur (probabilistic events), risk should be defined as the probability that a serious detrimental health effect will occur in a potentially-exposed individual or his descendants. The risk, R, to an individual from an event giving rise to a dose in the range from D to D+dD is given by:

$$R = P(D).p(eff/D) \tag{2}$$

where P(D) is the probability of an initiating event, and other environmental changes, giving rise to a dose between D and D+dD to the individual; and p(eff/D) is the probability of a serious detrimental health effect in that individual or his descendants from the resultant dose, D (Ref. 5; para. 52).

For doses in the stochastic region, in which effective dose equivalent, H_E, can be used, the above expression simplifies to:

$$R = P(H_E)\ \gamma\ H_E \tag{3}$$

where γ is the probability of a serious detrimental health effect per unit effective dose equivalent (Ref. 5; para. 52), i.e. the whole-body dose to risk conversion factor discussed in Section 1.

The above definition of risk is the one which is proposed for use in assessing post-closure individual risks from the disposal of solid radioactive wastes (see also Section 5).

4. APPLICATION OF THE CRITICAL GROUP CONCEPT

For future exposures and risks, the specific individuals who receive the exposures and risks cannot be identified. This is not a position which is unique to radioactive waste disposal, it arises whenever a radiological assessment is undertaken prior to the operation of a new facility. In these circumstances, it is appropriate to define a hypothetical critical group of most exposed individuals. A major difference in radioactive waste disposal is that the doses and risks may be incurred in the far distant future. To take account of this, the authorising Departments have adopted the philosophy that a future population should be guaranteed the same degree of protection as would be expected today. It is proposed that this be done by defining hypothetical critical group behaviour on the basis of current behaviour patterns and by showing that the annual risk to a representative member of that critical group is less than the specified risk target at any time in the future (but see also Section 7).

It is emphasised that this approach avoids the need to forecast future lifestyles, attitudes to risk, and developments in the diagnosis and treatment of disease.

Notwithstanding the above remarks, it is proposed that the behaviour patterns selected should take account of long-term changes in site characteristics. Thus, for example, if radionuclide migration from a repository is estimated over a sequence of glacial/interglacial cycles, releases during a periglacial epoch should be assessed on the basis of current lifestyles in tundra-type environments and not on the basis of current lifestyles in temperate latitudes. The aim is to avoid significant under or over-estimation of risks because of the use of incompatible assumptions.

In defining the lifestyle of the hypothetical critical group, as in other applications, account should be taken of reasonable variations in behaviour, but the adopted lifestyle should not reflect the extreme, perverse or pathological characteristics which may be exhibited by particular individuals.

Post-closure radiological risks from a repository are to be assessed on an annual basis (Ref. 1). Thus, in principle, the critical group should be defined by age, since intakes, metabolism and dosimetry of radionuclides are all strongly conditioned by this factor (Ref. 6). In practice, because of the magnitude of other uncertainties in post-closure radiological assessments and the limited amounts of metabolic and dosimetric data available for juveniles, it will seldom be appropriate to make such distinctions. Where it is appropriate, it is recommended that the assessment be undertaken for one or more of the following:

- infants (up to 1 year);
- children (1-10 years);
- adults (20-30 years).

The results obtained for these three age groups are expected to span the range appropriate to all age groups.

Where meaningful distinctions cannot be made, it is proposed that the critical group be taken to comprise adults, as defined above.

COMBINATION OF RISKS FROM VARIOUS FUTURES

It is not possible to predict the precise future evolution of the repository and its environment. Therefore, it is necessary to take into account both the probability of different future evolutions and the individual risks associated with them.

In general, specific futures are characterised by a vector of parameter values $\underline{x}$ which defines the properties of the repository and its environment at any time for which the assessment of risk is to be undertaken. Individual components of $\underline{x}$ may be either continuous or discrete. Specific examples of continuous variables are the hydraulic conductivity of the host rock, the time at which a glacier reaches the site, the time of human intrusion and the volume of material excavated as a consequence of intrusion. Discrete variables, which are often a computational convenience rather than a necessity, are typically on/off switches, e.g. does a new fault develop in the geology close to the repository.

The future defined by vector $\underline{x}$ is associated with two functions. These are:

$P(\underline{x})$ - the probability density of futures with characteristics $\underline{x}$,

$R(\underline{x},t)$ - the annual risk to a representative member of the critical group in future $\underline{x}$ at time t.

At annual doses of less than 0.1 Sv, $R(\underline{x}, t) = \gamma H_E(\underline{x},t)$, where $H_E(\underline{x},t)$ is the effective dose equivalent to the representative member of the critical group.

Because $P(\underline{x})$ can contain both continuous and discrete variables, the concept of probability density has to be applied carefully. Without loss of generality, it is possible to write:

$$P(\underline{x}) = P(\underline{x}' , \underline{x}'') \quad (4)$$

where $\underline{x}'$ is the vector of continuous variables; and
$\underline{x}''$ is the vector of discrete variables.

By integration:

$$P(\underset{\sim}{x}'') = \int_{\Omega_{\underset{\sim}{x}''}} P(\underset{\sim}{x}' , \underset{\sim}{x}'')\, d\underset{\sim}{x}' \qquad (5)$$

where $P(\underset{\sim}{x}'')$ is the total probability of the discrete variables being set to the combination $\underset{\sim}{x}''$; and

$\Omega_{\underset{\sim}{x}''}$ is the region of $\underset{\sim}{x}'$ space over which $P(\underset{\sim}{x}',\underset{\sim}{x}'')$ is non-zero for the particular combination $\underset{\sim}{x}''$.

Since some future must necessarily occur:

$$\sum_{\underset{\sim}{x}''} P(\underset{\sim}{x}'') = 1 \qquad (6)$$

An appropriate measure of individual risk at time t is obtained by weighting the individual risk estimate for each future, R (x', x", t), by its probability of occurrence. Thus, it is proposed that the individual risk at time t be calculated using:

$$\bar{R}(t) = \sum_{\underset{\sim}{x}''} \int_{\Omega_{\underset{\sim}{x}''}} P(\underset{\sim}{x}', \underset{\sim}{x}'').R(\underset{\sim}{x}',\underset{\sim}{x}'',t).d\underset{\sim}{x}' \qquad (7)$$

It is noted that other measures of risk could be adopted. Some of these alternative measures, and the reasons why they are not used, are discussed in Appendix B.

The uncertainties in parameter values $\underset{\sim}{x}$ derive from several sources. These include:

- measurement errors;
- applications of point data in deriving spatial averages;
- limitations in the capacity of the conceptual and mathematical models used in assessment studies to represent the present and future characteristics of the repository and its environment;
- difficulties in assessing the likelihood of future human actions.

Thus, for example, measurements of hydraulic conductivity have an uncertainty associated with the measurement process and are also only representative of a limited spatial domain. Application of these data in calculations of groundwater flow and radionuclide transport requires that they should be interpreted and used to characterise spatially extensive regions.

The predictive capabilities of mathematical models are often limited by imperfect understanding of the underlying processes, e.g. the factors governing climatic change or the mechanisms of sorption of radioactive species on solid surfaces.

Future human actions which are uncertain include the times at which inadvertent intrusions into the repository, or into contaminated groundwaters close to it, may occur. Similarly, the type of agricultural practice which will be adopted in the vicinity of a repository under particular climatic conditions is subject to considerable uncertainty.

Although these uncertainties derive from different sources, they all imply a lack of knowledge concerning the future behaviour of the repository and its environment. They differ in that some can be reduced by the acquisition of generic or site-specific data, whereas others can only be reduced by the development of improved mathematical models of the relevant processes. Finally, there are some, such as those relating to human actions in the far-distant future, which are intrinsically uncertain.

It is proposed, for the purposes of assessment, that all types of uncertainty be considered in the same way. This is implicit in the calculation of $\bar{R}(t)$ set out above.

6. CONFIDENCE IN RISK ESTIMATES

Calculations of risk, as defined in Section 5, typically require the use of a variety of conceptual and mathematical models. In every case, the process of modelling involves idealisation and simplification, with the attendant possibility of introducing systematic bias into the assessment process. Furthermore, utilisation of quantitative models implies collection and interpretation of substantial amounts of data, so as to derive appropriate input data values or probability distributions. This process is also associated with the possibility of bias.

In view of these considerations, it is proposed that post-closure radiological assessments should include a comprehensive description of the derivation of the models used. In particular, the assumptions made and the limits of applicability of these models should be stated. Wherever possible, a quantitative estimate should be presented of the uncertainties in the results associated with the modelling procedures adopted. In addition, relevant work relating to the quality assurance, verification and validation of the models should either be described or appropriately referenced.

With respect to the derivation of data, in determining values of $\bar{R}(t)$, it is necessary to define probability densities for parameters or combinations of parameters and probabilities for events or combinations of events. Some of these probability densities and probabilities will be based on relatively large amounts of data, whereas others will be almost entirely matters of subjective judgement. However, it is unlikely that the definition of any distribution or the specification or any probability will be entirely objective, since interpretation of the available data is always important.

It is emphasised that the incorporation of subjective judgement into an assessment is not an admission of failure. Indeed, the quantitative procedure for estimation of risk set out herein is designed to provide a formalism by which expert judgement on factors relevant to the assessment may readily be taken into account.

It is proposed that documentation on post-closure radiological assessments should set out in full the data which have been taken into account, the methods used to elicit subjective judgements and the techniques employed to refine these subjective judgements in the light of additional data.

Calculations of $\bar{R}(t)$, as defined in Section 5, will typically require either numerical integrations over a multi-dimensional space or, more often, sampling of a large number of potential futures from which an estimate of $\bar{R}(t)$ can be derived. In either case, the calculated value of $\bar{R}(t)$ will be an estimate of the true value, because of the approximations introduced by interpolation or as a consequence of the finite number of samples used.

Because of the various approximations involved in the assessment procedure, there is not considered to be a requirement to calculate a very accurate estimate of the true value of $\bar{R}(t)$. Nevertheless, the estimate which is produced must have well-characterised uncertainties associated with it. Thus, values of $\bar{R}(t)$ presented in assessment documents should always be associated with quantitative statements as to statistical and computational uncertainties, e.g. well-justified confidence limits, and at least qualitative statements respecting potential systematic errors and biases.

In addition, it is considered to be important that assessment documents include information on the processes and factors which have a major influence on the estimated values of $\bar{R}(t)$ and that they also describe the contributions to $\bar{R}(t)$ from various pathways of exposure.

7. PERIOD OF ASSESSMENT

A characteristic of geological disposal is the very long periods before contaminated groundwaters are predicted to reach the biosphere and give rise to significant radiation doses to man. Even for shallow disposal, timescales in excess of one thousand years are typical and periods in excess of ten thousand years are possible. For deep disposal, periods in excess of 100,000 years are typically considered and calculations for periods in excess of a million years may be relevant.

It is debatable whether predictions beyond a million years have any credibility. Environmental changes may be so marked as to make all available methods of assessment totally unreliable.

However, although the conceptual and practical difficulties of undertaking such calculations are well recognised, it is difficult to specify a period for assessment, since the appropriate cut-off date will depend upon the particular repository concept under consideration.

Taking these considerations into account, it is suggested that the period for assessment should be such that there is a reasonable assurance that the peak value of $\bar{R}(t)$ has been determined. However, it is recognised that estimates of $\bar{R}(t)$ for more than a million years in the future will be very speculative and it is suggested that explicit calculations of $\bar{R}(t)$ beyond ten million years into the future should not be attempted. However, supporting evidence that the disposal system and its environment is not likely to be grossly degraded over longer timescales should also be presented.

In some cases, environmental events and processes may result in major disruption of the disposal system and its environment at some time in the future. Such predicted destruction may be used as a justification to terminate assessments at the predicted time of occurrence, if it can be demonstrated that the immediate radiological consequences of the disruptive event are acceptable and that the consequences continue to decrease with time after the

the event. Values of individual annual effective dose equivalent occuring after the event can be combined with the annual probability of occurrence to calculate risk, as described in Section 5.

8. CONCLUSIONS

In this report, it is demonstrated that a coherent approach to the definition of risk can be formulated for use in post-closure radiological safety assessments of the disposal of solid radioactive wastes. It is recognised that various alternative approaches are possible and that the methodology adopted is determined by judgemental decisions on matters such as the application of the critical group concept and the combination of risks from various futures.

Taking these factors into account, an unambiguous definition of risk has been provided, based on explicitly stated judgements. In addition, a prescription for calculating this risk has been presented. This definition and prescription is broadly in agreement with current practices and provides a coherent basis, which may be used both by authorising Departments and the nuclear industry, for assessing the post-closure radiological safety of repositories.

REFERENCES

1. Disposal Facilities on Land for Low and Intermediate-Level Radioactive Wastes: Principles for the Protection of the Human Environment. HMSO, London, December 1984.

2. ICRP Publication 26. Recommendations of the International Commission on Radiological Protection. Annals of the ICRP, 1(3), 1977.

3. ICRP Publication 30. Limits for Intakes of Radionuclides by Workers. Part 1. Annals of the ICRP, 2(3/4), 1979.

4. NRPB. Interim Guidance on the Implications of Recent Revisions of Risk Estimates and the ICRP 1987 Como Statement. NRPB-GS9, HMSO, November 1987.

5. ICRP Publication 46. Radiation Protection Principles for the Disposal of Solid Radioactive Waste. Annals of the ICRP, 15 (4), 1985.

6. Statement from the 1983 Washington Meeting of the ICRP. Annals of the ICRP, 14(1), 1984.

DISTRIBUTION

K M Clayton
T D Davies
F P Glasser
J Higgo
A D Horrill
J Knill
C C Naish
M L Parry
J H Rees
E Tufton
J West
H S Wheater

M C Thorne
B G J Thompson
T J Sumerling
J Taylor

EG(90)P8

HMIP Expert Group on Post-Closure Radiological Assessment: Briefing Note 8

M C Thorne

Electrowatt Engineering Services (UK) Ltd
Grandford House
16 Carfax
Horsham
West Sussex
RH12 1UP

December 1990

1. INTRODUCTION

This briefing note contains a compilation and analysis of the replies received to briefing note 7 [EG(90)P7]. On the basis of this material, some general conclusions are drawn relating to the exercise as a whole. This material is made available to members of the Expert Group for comment prior to finalisation of the study.

2. COMPILATION OF REPLIES

Briefing note EG(90)P7 included a questionnaire. For convenience, the questions are reproduced below, together with the replies received. Other comments are grouped together at the end of this section.

2.1 RESPONSE TO THE QUESTIONNAIRE

1. **Are there any factors or phenomena excluded from the minimal assessment which could render estimates of peak individual risk substantially in error?**

2. **What are these factors and/or phenomena?**

H S Wheater

Thermal effects on groundwater transport (2.4.13) were described as potentially significant in Table 1 but have been excluded. The consequences would be significant if the geosphere pathway were shortened.

J J W Higgo

No such factors or phenomena have been excluded.

K M Clayton

Only glaciation (see also Section 2.2).

E Tufton

I doubt if they could affect things "substantially", but I have two items which I believe have been omitted inequitably. They are subsidence/collapse (1.4.4) (for ungrouted LLW only) and thermally induced groundwater transport (2.4.13).

J H Rees

There is the possibility of exposure to active gases without transport in the biosphere. Given the admittedly limited assessments that have been carried out for Nirex on their impact to man, I would not expect this omission to have a substantial effect on the peak annual dose to an individual (see also Section 2.2).

A D Horrill

No additions to factors or phenomena.

J West

In relation to the near and far fields I cannot see any factors that have been excluded which would seriously alter estimates of peak individual risk.

C C Naish

My response to whether there are significant factors which have been excluded from the minimal assessment is "not to my knowledge", hence questions 2 to 5 become inapplicable.

F P Glasser

No additions to factors or phenomena.

3. **What are your estimates of their probability of occurrence on the following timescales.**

   0 - 10^2 years post-closure
   10^2 - 10^3 years post-closure
   10^3 - 10^4 years post-closure
   10^4 - 10^5 years post-closure
   10^5 - 10^6 years post-closure

   Note that these timescales increase as a geometric progression.

4. **What are your estimates of their likely separate effects on the values of peak individual risk calculated from the minimal assessment?**

   Limited (less than a factor of two)
   Moderate (less than a factor of ten)
   Severe (greater than a factor of ten)
   Unquantifiable without modelling studies
   Unquantifiable even with modelling studies

5. **If several factors and/or phenomena are listed under item (2), are there any interactions between their various probabilities of occurrence and/or their likely effects on the results of the assessment?**

H S Wheater

Temperature effects are probable on the 0 - 100 years timescale. My guess would be that such effects will be limited or moderate, but it would be relatively easy to model likely effects.

K M Clayton

The timescale for glaciation would be possibly 10^4 - 10^5 y post-closure and certainly 10^5 - 10^6 y post-closure. Glaciation could well have a severe effect (i.e. greater than a factor of ten). Question 5 is not applicable.

E Tufton

The probability of occurrence is suggested to be roughly:

		Time (y)				
		0 - 10^2	10^2 - 10^3	10^3 - 10^4	10^4 - 10^5	10^5 - 10^6
Subsistence/collapse (1.4.4)	Occurrence Effects	0.5 0.5	1.0 1.0	0.5 1.0	- 1.0	- 0.5
Thermal (2.4.13)		<.1	1.0	1.0	0.2	<.1

This is actually modified by some feeling of significance, as the thermally-driven groundwater flow will start as soon as any groundwater sees a temperature rise, but the flow itself will for a while be trivial.

These effects I consider to be "Unquantifiable without study", but intuitively to be "Limited" at most.

There is no obvious interaction between 1.4.4 and 2.4.13.

6. **As described in Section 2.2 [of EG(90)P7], the following components were excluded from the minimal assessment to produce the reduced assessment shown in Figure 2 [of EG(90)P7]:**

Item	**Description**
1.6.4	**Thermally induced hydrological changes in the near-field**
1.6.5	**Thermally induced chemical changes in the near-field**
3.2.2	**Localised denudation**
3.6.4	**Recreation policy developments**

All of these are likely to occur. What is your estimate of the effects on calculated values of peak individual risk of their combined exclusion from the assessment?

Limited (less than a factor of two)
Moderate (less than a factor of ten)
Severe (greater than a factor of ten)
Unquantifiable without modelling studies

7. **What were the main considerations you took into account in responding to item 6?**

H S Wheater

3.6.4 I find it difficult to see recreation developments which will substantially modify peak individual risk.

3.2.2 My estimate is "limited".

1.6.5 Cannot sensibly comment.

1.6.4 These could significantly influence short-term unsaturated and long-term saturated near-field flows, and hence modify near-field flow paths. If bypassing of near-field chemical containment occurs, I would guess that effects could be "moderate" but are more likely to be "limited".

Combined effects are likely to be "limited", possibly "moderate", but scoping calculations could significantly reduce the uncertainty in defining potential importance.

J J W Higgo

Not qualified to assess.

K M Clayton

In answer to question 6, I regard the effect as unquantifiable, but with the exception of glaciation under the localised denudation head, I believe the exclusion of 3.6.4 poses no problem at all, and nor does 3.2.2. I cannot answer for the near-field topics.

In answer to question 7, unlike agriculture which conceivably could grow foodstuffs which transferred radioactive material to consumers on sufficient scale to cause concern, I regard recreational uses as too episodic to offer a route of any significance. Apart from the threat of glaciation I do not believe that localised denudation here could reach any appreciable depth, even over 10^6 year. I regard the highest value feasible through denudation by fluvial erosion (rain and rivers in the sense of the nineteenth century title of Colonel Greenwood) as about 125 m after 10^6 year. This is very much a maximum and I would anticipate about half that value in practice. The figure assumes that the River Thames continues to incise for the whole period at a rate of 5 cm/1000 yr, and that it migrates laterally to the site of Harwell which at present lies 70 - 75 m above the local level of the Thames.

E Tufton

For the four items omitted, I consider effects to be "Unquantifiable without study", but intuitively to be "Limited" at most. This would be unchanged if 2.4.7, 8, and 12 were also excluded at this point.

The quotable response (i.e. "unquantifiable") is simply a reaction to the situation that I have no ready reckoner of cause-and-effect. On an intuitive basis, I worry more about localised denudation (3.2.2) than about the others. I see this as glacial incision producing a valley, perhaps cut into the formation that the radionuclide plume had reached, so increasing the dose to a critical group of people who later live in the valley.

If recreation policy (3.6.4) is excluded, it forces a conservative view to be taken of land use and human activity which would increase my confidence, however slightly, in the result.

J H Rees

I am not sufficiently experienced in areas 3.2.2 and 3.6.4 to express a view on their impact. I would expect the combined effects of 1.6.4 and 1.6.5 on the peak individual risk to be limited (< a factor of 2) because thermal effects in the near field caused by radioactive decay and backfill curing are short-term consequences compared with the timescale on which the peak dose will probably be delivered.

A D Horrill

My estimate of the combined effect of the four categories is 'Limited'.

Considering the depth of the Repository and the degree to which it is likely to be marked, it is highly improbable that 3.2.2 or 3.6.4 will affect the assessment. As a non-expert in the field, I would think that 1.6.5 - Thermally induced chemical changes in the near field, might be relevant in the early life of the Repository when decay is most active.

J West

I think the result of excluding the items given from the minimal assessment are unquantifiable without modelling studies, when taken as a whole. For items 1.6.4 and 1.6.5 only, I consider the effects to be limited.

I do not feel I have competence to comment on items 3.2.2 and 3.6.4 hence my reluctance to quantify the effects. For items 1.6.4 and 1.6.5 the thermal effects will be present for a limited period of time hence my feeling that their effect on peak individual risk is limited.

C C Naish

I would estimate that the combined effects of the listed items excluded from the minimal assessment could lead to an error in risk of moderate level, less than a factor of 10.

Within the buffered alkaline chemical environment of the repository the second component should not be significant if the temperature is kept below 100°C. Likewise the first component is probably of limited significance if the temperature range is kept to a minimum.

My response to this question is biased towards the components 1.6.4 and 1.6.5 because I have only a superficial understanding of the other two and do not feel qualified to comment on their occurrence or magnitude.

F P Glasser

Items 1.6.4 and 1.6.5 depend upon the magnitude of the thermally-induced changes, the extent of the thermal halo and repository depth. I would conclude "unquantifiable without modelling studies". For items 3.2.2 and 3.6.4, their effect is limited.

8. As described in Section 2.2 [of EG(90)P7], the following components were excluded from the minimal assessment to produce the reduced assessment shown in Figure 3 [of EG(90)P7]:

Item	**Description**
1.1.2	**Physical degradation of concrete**
1.4.6	**Fracturing in the near field**
1.6.4	**Thermally induced hydrological changes in the near-field**
1.6.5	**Thermally induced chemical changes in the near-field**
2.3.3	**Modification to far-field hydrology due to rock property changes**
2.4.6	**Fracture surface changes in the far-field, notably demineralisation**
2.4.7	**Organic colloid transport**
2.4.9	**Transport of radionuclides bound to microbes**
3.1.1	**Transient greenhouse gas induced warming**
3.2.2	**Localised denudation**
3.6.4	**Recreation policy developments**
4.1.1	**Short-circuit pathways relating to loss of integrity of borehole seals**
4.1.2	**Short-circuit pathways relating to loss of integrity of shaft or access tunnel seals**

8a. What are your estimates of their probabilities of occurrence on the following timescales.

0 - 10^2 years post-closure
10^2 - 10^3 years post-closure
10^3 - 10^4 years post-closure
10^4 - 10^5 years post-closure
10^5 - 10^6 years post-closure

Note that these timescales increase as a geometric progression.

8b. What are your estimates of the effects on calculated values of peak individual risk of their combined exclusion from the assessment?

Limited (less than a factor of two)
Moderate (less than a factor of ten)
Severe (greater than a factor of ten)
Unquantifiable without modelling studies

9. What were the main considerations you took into account in responding to item 8.

H S Wheater

Question 8a.

1.1.2 No comment.
1.4.6 Probable 0 - 100 years.
1.6.4 Probable 0 - 100 years.
1.6.5 No comment.
2.3.3 Could be locally significant on 0 - 100 years timescale if repository disturbs flow field, otherwise > 1000 years.
2.4.6 As 2.3.3.
2.4.7 No comment.
2.4.9 Probable 0 - 100 years within near-field.
3.1.1 Highly likely to perturb Biosphere on 0 - 100 years timescale, with possible irreversible effects.
3.2.2 Small-scale effects immediate, significant effects > 1000 years.
3.6.4 Probable 0 - 100 years, but may not be significant.
4.1.1 0 - 100 years if construction defects.
4.1.2 As 4.1.1.

Question 8b.

4.1.1/4.1.2 could have "severe" consequences.
3.1.1 by alternating groundwater recharge, could significantly modify groundwater flows and have "severe" effects.
2.4.7/2.4.9 could influence transport processes such as to give "severe" effects.

My guess for the combined effect of the other terms is "moderate", but scoping calculations are needed.

Question 9.

See notes above.

J J W Higgo

Question 8a.

	Time (y)				
	0 - 10^2	10^2 - 10^3	10^3 - 10^4	10^4 - 10^5	10^5 - 10^6
1.1.2	low	low	low	low	low
1.4.6	high	medium	low	low	low
1.6.4	medium	low	low	low	low
1.6.5	medium	low	low	low	low
2.3.3	low	low	low	low	low
2.4.6	low	low	low	low	low
2.4.7	medium	medium	medium	medium	medium
2.4.8	medium	medium	medium	medium	medium
3.1.1	Probably will occur but how will this affect the assessment?				
3.2.2	May occur but how will this affect the assessment?				
3.6.4	May occur but how will this affect the assessment?				
4.1.1	medium	low	low	low	low
4.1.2	medium	low	low	low	low

Question 8b.

Unquantifiable without modelling studies.

Question 9.

Fracturing in the near field (or dilation of existing fractures), e.g. as a result of pressure build up, could result in severe increases in risk relative to the calculated assessment.

Short circuit pathways could be catastrophic. I am in no position to assess the possibility of such events.

K M Clayton

Question 8a.

I answer this as a table of values:

1.1.2	0 - 10^4 yr post-closure
1.4.6	0 - 10^4 yr post-closure
1.6.4	0 - 10^3 yr post-closure
1.6.5	0 - 10^3 yr post-closure
2.3.3	10^4 - 10^6 yr post-closure
2.4.6	10^4 - 10^6 yr post-closure
2.4.7	10^2 - 10^6 yr post-closure
2.4.9	10^2 - 10^6 yr post-closure

3.1.1 0 - 10^4 yr post-closure
3.2.2 10^4 - 10^6 yr post-closure
3.6.4 0 - 10^4 yr post-closure
4.1.1 10^2 - 10^4 yr post-closure
4.1.2 10^2 - 10^4 yr post-closure

Question 8b.

Unquantifiable without modelling studies (surely!)

Question 9.

1.1.2 I assumed that physical degradation did not need to proceed very far for it to allow some release of activity. Full physical change would of course take longer than this. In this situation, of course, it is very difficult to separate physical change from chemical changes, which themselves generate volume changes and thus physical alteration.

1.4.6 This could presumably occur at any time, but it might not contribute significantly after 10^3 yr because by then other changes would be coming into play.

1.6.4 and 1.6.5 I know too little about these for the durations to be more than a guess.

2.3.3 This seemed to me to be on a long timescale, if indeed it is actually very important, which I doubt. Perhaps the one exception is solution of the Chalk below the watertable.

2.4.6 Recognised as important but certainly long term, perhaps even after 10^5 yr.

2.4.7 I do not know much about this.

2.4.9 Nor this.

3.1.1 One must assume that some amount of greenhouse gas warming will occur and that it will persist for some time. It is conservative to suggest that it will only terminate with global cooling, and that could be 10^4 yr ahead. Some time before then I presume it should be labelled equilibrium, rather than transient.

3.2.2. This will only accumulate to a large value either over a long time ($>10^4$ yr) or with the occurrence of glaciation beyond this site, unlikely to be before 6 x 10^3 year. The latter is outside your model.

3.6.4 I remain dubious about the relevance of this component, but it can only be significant whilst other more serious developments have yet to occur, hence the limited timescale. It is not that I anticipate recreation to go out of fashion at 10^4 yr.

4.1.1 and 4.1.2 I here assume reasonable competence in design in the first place, but since the methods chosen will not have been tested over any appreciable time, it seems unwise not to allow for failure at any time after 10^2 yr. By 10^4 yr it seems likely that other routes (e.g. groundwater movement) will be well established and thus that this route will not then be of such potential significance.

E Tufton

Question 8a.

	Estimated Probabilities of Occurrence				
	Timescale: Years post-closure				
Item	$0 - 10^2$	$10^2 - 10^3$	$10^3 - 10^4$	$10^4 - 10^5$	$10^5 - 10^6$
1.1.2	1.0	1.0	1.0	0.1	-
1.4.6	0.1	1.0	1.0	0.1	0.1
1.6.4	0.5	1.0	1.0	0.5	0.1
1.6.5	0.75	0.75	0.5	0.1	<0.1
2.3.3	-	-	0.1	0.25	0.5
2.4.6	-	-	0.1	0.25	0.25
2.4.7			no opinion		
2.4.9			no opinion		
3.1.1	-	0.75	0.75	no opinion	no opinion
3.2.2	-	-	-	0.1	0.25
3.6.4	0.5	1.0	1.0	1.0	1.0
4.1.1	0.25	0.75	0.75	0.1	0.1
4.1.2	0.25	0.75	0.75	1.0	0.1

Question 8b.

As with question 6, the result as far as I am concerned is "Unquantifiable without study". There are now too many parameters involved that I am unfamiliar with for a sensible guess at the overall effect.

Question 9.

The estimates of probability are intuitive. The avoidance of an estimate of the effect is philosophical. I believe such an estimate can only be made in one of two ways: either qualitatively by reference to previous similar work (even if this is done intuitively) or quantitatively by some kind of algorithm with input, process (however crude), and result.

J H Rees

I am not able to comment on items 2.3.3, 2.4.6, 2.4.9, 3.1.1, 3.2.2 and 3.6.4 in this part of the questionnaire.

For the remaining items I have listed estimates of the probability of their occurrence during the first 10^6 years of the repository's existence in the following table.

Because the peak individual risk may occur on a timescale of 10^5 years or greater, the only one of these factors that is potentially hazardous is 2.4.7 - organic colloid transport (this argument assumes that none of the modelling of the near field takes credit for radionuclide hold up due to any remaining structural features at times of 10^5 years or more). The impact of this will probably be limited (< a factor or two), given Jenny Higgo's comments as noted in the minutes of the meeting of 25th September 1990.

	Estimated probability of event occurring, post-closure, during				
Item	$0 - 10^2$	$10^2 - 10^3$	$10^3 - 10^4$	$10^4 - 10^5$	$10^5 - 10^6$
1.1.2	0.1	1.0	(0)	-	-
1.4.6	0.1	1.0	(0)	-	-
1.6.4	1.0	0.1	(0)	-	-
1.6.5	1.0	0.1	(0)	-	-
2.4.7	-	-	10^{-2}	High[a]	High
4.1.1	0.1	0.1	Low[b]	Low	Low
4.1.2	0.1	0.1	Low[b]	Low	Low

a Probability > 0.1 during the timescale under consideration
b Probability < 10^{-3} during the timescale under consideration

<u>A D Horrill</u>

	Timescale	Probability of Occurrence
1.1.2	100 - 1000 yrs	Medium
1.4.6	100 - 1000 yrs	Medium
1.6.4	100 - 1000 yrs	Medium
1.6.5	0 - 100 yrs	Low
2.3.3	$10^5 - 10^6$ yrs	Medium
2.4.6	$10^5 - 10^6$ yrs	Medium
2.4.7	$10^4 - 10^5$ yrs	Medium
2.4.9	$10^4 - 10^5$ yrs	Low
3.1.1	0 - 100 yrs	High
3.2.2	1000 onwards	Low
3.6.4	1000 onwards	Low
4.1.1	1000 onwards	Low
4.1.2	> 10^4	Low

The combined effects of the risk are likely in my estimation to be low, the most probable happening in the first 100 years is Transient greenhouse warming which would only affect the repository if near or at sea level.

<u>J West</u>

Question 8a

I will only comment on subsets where I feel I can usefully contribute information.

1.1.2 Severe up to 10^3 years then moderate to 10^4 years, low after this time.

2.4.9 Limited up to 10^2 years, moderate after this time to 10^6 years.

Question 8b

Once again I think the effects are unquantifiable without modelling studies. Maybe I'm just a coward but there appear to be so many unknowns. If really pressed I would become extremely cautious and say that the effects would be severe on peak individual risk if all these factors were excluded from the minimal assessment.

Question 9

My ignorance and gut reaction that I feel we are going too fast with too little information on some of the factors we are throwing out.

C C Naish

Question 8a

1.1.2 The concrete degradation will be split into phases; there will be juvenile cracking over the first few years possibly followed by local cracking caused by gas generation over the 100 - 1000 year period. Beyond this time it will be difficult to predict the exact course of further physical degradation which will be linked to the concrete's chemical degradation as alkalinity is leached from the system. Moderate probability of occurrence.

1.4.6 Fracturing of the near field, if caused by gas generation will occur over the 0 to 1000 year timescale, within this time period gas generation should go through a maximum. Moderate probability of occurrence.

1.6.4 Thermal effects are most likely to be significant at early periods when the rate of change is greatest. This will probably fall in the 0 to 100 years post-closure period with a decreasing effect in the 100 to 1000 year period. High probability of occurrence but limited significance (depending on temperature gradients).

1.6.5 Likewise thermally induced chemical effects will be most significant in the 0 to 100 year period, will definitely occur but probably be of limited significance.

2.3.3 and beyond: No qualified opinion.

Question 8b

In view of the diversity of factors I do not feel qualified to assess the combined effects although superficial knowledge/study would lead me to the conclusion that their combined effects are unlikely to be greater than moderate by your definition.

Question 9

My response to 8b is heavily biased by my understanding/assessment of the first few factors which I have knowledge of. My overall conclusion is based on the premise that the other experts have assigned the same approximate degree of risk to the other named factors in the group as I have to the first few.

F P Glasser

Question 8

Item	Probable Time of Occurrence	Effects on Peak Risk
1.1.2	10^3 - 10^4	Limited
1.4.6	10^4 - 10^5	Moderate
1.6.4	10^5 - 10^6	Moderate
1.6.5	10^5 - 10^6	Moderate
2.3.3	10^5 - 10^6	Limited
2.4.6	10^5 - 10^6	Limited
2.4.7	10^4 - 10^5	Limited to moderate
2.4.9	10^4 - 10^5	Limited
3.1.1	0 - 10^2 or 10^3	Limited
3.2.2	10^3 - 10^4	Limited
3.6.4	10^2 - 10^3	Limited
4.1.1	10^2 - 10^3	Moderate
4.1.2	10^2 - 10^3	Moderate

Question 9

The main considerations were:

i) that the repository will be at 500 - 1000 m deep in crystalline, low permeability rock.
ii) groundwater regime is semi-static.
iii) many of the factors listed have only weak interactions.
iv) the repository is in an area of low tectonic activity and seismicity.
v) the repository is sealed according to some planned system after it is filled - we are not dealing with a retrievable system.
vi) "recreation" continues along present ways; amateur deep mining or drilling does not become a commonplace pastime.

2.2 OTHER MATERIAL RECEIVED

This can be distinguished into the following general areas:

i) Comments on Tables 1 - 3 and Figure 1 - 3 of EG(90)P7;
ii) General comments on EG(90)P7 and the exercise as a whole;
iii) Matters arising from the meeting of 25th September 1990.

2.2.1 Comments on Tables and Figures in EG(90)P7

H S Wheater

Table 1

Content agreed.

Item 2.3.2 appears somewhat cryptic. I assume that it includes boundary fluxes such as discharges to surface waters, leakage to adjacent groundwater systems and capillary rise, and losses within the groundwater system due to abstractions. There is no easy alternative, so "losses" should stay, but an explanatory comment would be helpful.

Section 4.2 has Item numbers displaced.

Table 2

Content agreed, with two exceptions:

a) The priority given to 1.4.6 (Fracturing), which I see as M/H rather than L/M, since it could be significant in influencing groundwater flow at the near-field/far-field interface (1.5.3).

b) The appearance of far-field weathering (2.2.9) in the Biosphere needs further clarification. For weathering to appear as a Biosphere term, a new classification number is desirable (i.e. 3...). The placement in the Geomorphology section suggests that physical weathering is being considered, whereas the Far-field origin was presumably primarily chemical. In fact both physical and chemical weathering will be important for Biosphere transport, and it would be helpful to differentiate between them. Physical weathering will be important for erosion processes and hence 3.5.1. Chemical weathering of subsurface minerals is important in controlling the chemistry of base-flows in streams, and will affect 3.5.7.4, for example, but in soils in addition there are complex biogeochemical processes which would be referred to under weathering and which determine soil chemistry and soil structural development and hence affect ecology, hydrology and biosphere transport in a fundamental way.

With respect to the several points which are based on judgements by the secretariat, I formally support the following:

1.7.1, 1.7.2, 2.4.1, 2.4.2, 2.4.3, 3.3.1, 3.3.2, 3.3.3, 3.3.4, 3.4.1, 3.5.2, 3.5.3, 3.5.4, 3.5.7, 3.5.10, 3.6.1, 3.6.2, 3.6.3, 3.6.4, 4.2.4, 4.2.6, 4.2.7, 4.2.8, 4.2.9.

Table 3 and Figures 1 - 3

In general, the secretariat has done an excellent job in producing the summary figures. A minor comment is that in Table 3, the gas production origins which are targeted at 1.5.3 and 1.4.6 should presumably include 1.2.2. My comments on Table 2 have direct implications for Table 3 and Figures 1, 2 and 3.

J J W Higgo

i) Adequacy of Table 1.

I am happy that Table 1 covers sorption and migration in the far field adequately (that is assuming that speciation is taken into account when estimating retardation of radionuclides). The rest looks satisfactory to me, but I am not an expert.

ii) Adequacy of Table 2.

As for Table 1.

iii) Figures 1 to 3 and associated Table.

I must congratulate the secretariat. The figures are comprehensive and a useful summary of the various flow paths and interactions.

K M Clayton

I confirm that I have crawled over Table 1 and could not do as good a job as the secretariat has done on it, it seems comprehensive and well organised.

Further, I am similarly happy with Table 2 with the following comments: in (3.2.2) Localised denudation, L is OK except for the exclusion of ice already discussed ad nauseam. For those other items which have asterisks and where I have some competence, I confirm the designations for m (3.1.1, 3.1.2 and 3.1.3). Also n (2.2.9). I wonder whether p (3.4.1) should not be M (the effect on hydrology is appreciable, but the present vegetation allows most recharge and deeper-rooted vegetation would reduce it and thus the effect on radionuclide transport would not be very great? I wonder how far q (3.5.2 and 3.5.3/4) can be separated in any model? Following much the same argument as for the effects of terrestrial ecological development on hydrology, I would query r (3.6.3) agricultural policy as H and think M quite sufficient. For t (4.1.3) I prefer H to M. Finally, under u, the chance of 4.2.3 is surely extremely low, though were it to occur H is appropriate - does the H allow for the low risk (cf. meteorite impact)? As for 4.2.12, I wondered how far it could logically be treated separately from 3.6.2?

I have no further comments on Figures 1 - 3 or Table 3.

E Tufton

Substantive comments are in fact quite few in number, which probably reflects the limits relevance of "ordinary" civil engineers' stock knowledge to long-term safety assessment. I have therefore added some less specific points which I hope are of use.

Table 1 Factors and Phenomena

General Note: this table and, particularly, the comments have been abbreviated to the point where some very useful remarks are rather obscure. You have probably already noticed that the item numbers is Section 4 are misaligned.

1.2.6.4 and 5: I believe that both these items belong rather in the far-field section, being cases of (damage to) zones within the far field, distant from the waste vaults. If 1.2.6.5 is different from 2.4.11, it is unclear how they are distinguished.

1.4.1, 3 and 5: It was agreed on 26th June 1990 to exclude these items.

2.2 and 2.3: Arising from the consideration of damage to the barrier function of the clay by construction work, I suggested that collapse of the LLW Vaults (1.4.4.1) could modify the ILW far field. If we assume the LLW to be vertically above the ILW, the effect would more likely be on gas transport and diffusion than on a groundwater flow which I have taken to be initially horizontal.

2.4.6: The implication of the latest Minutes is that this item is retained - as it is in Table 2.

2.2.10 and 11: These items should, for completeness, be listed in Table 1, as they appear in Table 2.

3.6: This Section has not been amended with respect to the latest Minutes.

4.2.10 and 11: These items should be marked as excluded by reference to the Minutes of 26th June 1990.

Table 2 Characteristics of a Minimal Assessment

I have tried to compare the "evaluation comments" in Table 1 with the H/M/L ratings given in Table 2. While effects considered to be of "major" or "fundamental" importance have consistently been rated "H", comments such as "secondary" or "marginal" transcribe less consistently. It is therefore somewhat unclear what "secondary" as a comment really means.

Item 1.1.1 has, I assume, been absorbed into 1.2.

Section 1.4: My recommendation remains that subsidence/collapse (1.4.4) be considered with changes in the stress field (1.4.2), initially in a separate study, with the option to bring them into the assessment if the study shows them to be significant. Table 1 implies that all of 1.4.1 to 1.4.6 would be included in separate studies. Collapse is a certainty for ungrouted LLW and I suggest should be rated M/H for that case.

Item 1.5.4: It is unclear why this item should be excluded, unless it has been absorbed into 1.7 or 2.4.5.

Item 1.6.6: Exclusion of this item is not consistent with the comment against 1.6 in Table 1 or its being called "secondary" like 1.6.4.

Item 2.1.1: Exclusion is not justified by comments to date. A separate scoping calculation should cover it.

Items 2.4.7 and 8: Both these items are termed "marginal" in Table 1, which elsewhere earns an "s" or an "x". It is unclear why they are given different ratings here and why their ratings are so high. I suggest 2.4.7 and 2.4.8 could fairly both be rated "L".

Item 2.4.10: Exclusion is not justified by comments to date. Has this been transferred to 2.4.5?

Item 2.4.13 has up to now been given the same importance as 2.4.12 and in my view should be considered more likely to be significant. I suggest it could be rated "M" while 2.4.12 could be rated "L".

Table 3 Structural Relationships

1.1.3 affects 1.7.1 and 2 and 2.4.5; there is a link in Figure 1 from 1.1 to 1.7 but not one (1.1. to 2.4) to take account of chemical changes to far field conditions due to migration of non-radioactive ions.

1.2.2 can affect 1.5.3 and 1.4.6 if the other factors in 1.2 can.

1.6.5 thermally induced chemical changes can affect 1.7 transport characteristics or limits.

1.7 and/or 2.4 can affect 4.2.12 as the abstracted water is from the far field.

<u>J H Rees</u>

Table 1

I am happy with this, apart from the following minor comments:

a) Item 1.2.2.5 should be brought in line with the comment describing 1.6.5.4 as a secondary effect.

b) Item 2.4.5.4 - I agree with the tick, but not the comment. After all, irreversible sorption could remove an element (and its radionuclides) completely, thereby simplifying the safety assessment.

c) The numbering of the items in Section 4 appears to contain errors.

Table 2

I have reviewed items (a) - (i) and (l). My comments are as follows:

i) I have reservations concerning the position of item 1.1.2 in Table 1. The Group decided, however, to retain it in that Table. I feel, though, that it should be removed from (a) in Table 2.

ii) Transport processes involving shafts and adits (item 1.2.6) appear not to be well characterised, and for this reason I would prefer to see their status marginally upgraded to M/H in (b).

iii) Item 1.4.6 in (d) I would prefer to see omitted, consistent with 1.1.2.

iv) Items 2.4.7 and 2.4.8 are described as marginal processes in Table 1, and yet they have been assigned M and H priorities respectively in (l). Specialist advice on this might usefully be sought.

v) Because the significance of gas-induced groundwater transport is as yet unclear, I would prefer to see the status amended to M/H.

Table 3/Figures 1 - 3

First Page of Table 3

Second entry, comment column: waste degradation leads to the formation of organic complexing agents and sorption sites.

Third entry: delete 1.2.4 (active gases formed only in trace amounts, and do not influence groundwater flow) add 1.2.2 (CH_4 + CO_2 generation). Comments column could read: Gas production can impede or induce groundwater flow in the near field.

Fourth entry: again, delete 1.2.4, add 1.2.2. Item 1.1.2 could be added to the targets column.

Fifth entry: Item 1.7 does not seem to include gas migration. 2.4.11 and 2.4.12 seem to be relevant here.

Sixth entry: Radioactive decay, etc. could occur in short circuit pathways and be significant in modifying radiological impacts of certain radionuclides. Add 4.1 and 4.2 to targets column.

Second Page of Table 3

First entry: Is 1.7 an origin for 4.2 as well as for 4.1? If not, how is the source term for 4.2 defined?

Fourth entry: Transport via preferential pathways (4.1) is controlled to an appreciable extent by the relatively high permeabilities that could be found in these pathways. Far-field hydrology is not the only control.

Third Page of Table 3

Eleventh entry: Is the comment true for active gases? Geosphere transport (2.4.11) could be at least as important as biosphere processes - e.g. radon in houses.

Fourth Page of Table 3

Fifth and Sixth entries: Again biosphere transport (as defined in 3.5) of gases may not be significant for some of the short-circuit pathways (4.1 and 4.2). Direct exposure could occur.

A D Horrill

As far as I can judge from my experience the factors and phenomena in the minimal assessment and covered in Table 1 are adequate.

The contents of Table 2 seem satisfactory.

Table 3 gives the structural relationships for the minimal assessment. Whilst I acknowledge that the preparation of flow diagrams such as in Figures 1 - 3 is a very difficult task, I am not sure the present diagrams are very successful. All paths at the present are given equal weighting and there is no obvious start and end points. I think these should be the boxes 'Near-field and waste degradation' and Human exposure pathways' respectively. Maybe some highlighting of more important 'boxes' and pathways would help the less expert reader.

F P Glasser

I confirm that Tables 1 and 2 are adequate, as are Table 3 and Figures 1 - 3.

2.2.2 General Comments

J J W Higgo

I have scrutinised the tables carefully as well as the associated documentation. I found it difficult to answer the questionnaire as my field of expertise is confined to sorption and migration in the far field. Furthermore, I do not have a feel for effect that a particular factor will have on the final peak individual risk. I feel that the only way to estimate this is by sensitivity studies. However, I do think that our coverage of the factors that need to be taken into account has been comprehensive, although quantitative modelling will be very difficult in some cases.

K M Clayton

I found two particular problems which I should draw to your attention:

a) that glacial erosion is to be "treated outside the assessment" - the lack of attention within the assessment is clearly a problem for me (particularly given the physiographic location of the Harwell site) and I am not entirely clear what "outside the assessment" will mean.

b) that, where your lists (e.g. under 6) include a mix of near-field and far-field changes, I feel reasonable competent to assess the effect of far-field exclusions, but not the near-field - yet they are mixed in with them! I suspect that the expertise of the group may often divide in this way, and it may be that you should separate the two groups of components.

J West

1. Adequacy of Table 1

I have checked through the table and in my opinion it represents my own and the group's views.

2. Adequacy of Table 2

In general I think the table is adequate. I am happy with the priorities given to microbial effects in this minimal assessment. I am not entirely sure about 'u' and the allocation of * to some of the items (e.g. 4.2.4, 4.2.6 etc.) where scoping calculations are suggested. It seems a little 'over the top' and I would be tempted to drop this suggestion.

3. Comments on Figures 1 to 3 and associated Table 3

I have studied the Figures and Tables and am mostly happy with the minimal assessment. I just have a nagging worry that it is "too" minimal (especially Figure 3) although logically it appears correct.

C C Naish

1. Adequacy of Table 1

Removing consideration of corrosion, apart from its effect on gas production, also removes any possible benefit from containment of radioactivity by the canister/box, which may be significant up to 1000 years. However, unless a short circuit pathway to the geosphere is identifiable over time periods of this order there should be no problem with this.

There is a broader question of how far one needs to go in making and supporting the multi-barrier concept, which I still believe the canister forms an important part of; if not in terms of the overall modelling of source term/scientific case, then in its relevance and value as a public relations aspect, being something which is conceptually easy to support as a definite barrier.

As you will remember at the meeting the "near-fielders" believe (to a varied degree admittedly) in the usefulness of a separate model of the repository/near-field over the 0 to 1000 or 10000 year period. I still think this would be a useful exercise with both a scientific and PR benefit. This model would encompass concrete degradation etc., be a useful adjunct to the present modelling exercise and include factors which are, probably quite rightly, being disregarded for present purposes.

1.2 Adequacy of Table 2

The same comments are relevant from Table 1.

1.3 Comments of Figure 1 to 3 and Table 3

Within the requirements for the minimal assessment table 3 looks satisfactory. The top left section of figures 1 to 3 would form the basis for a model of the repository over the 0 to 10^3 - 10^4 years period.

2.2.3 Matters Arising from the Meeting of 25th September 1990

E Tufton

Gas Migration

I note the item calling for a contribution on 1.2.6.4: Near Field/Gas Transport/Close to Shafts and Adits. The following is a somewhat off-the-cuff opinion, which comes from a discussion between a colleague in Arup Geotechnics and myself.

The materials of interest - Gault Clay at 100 m and Oxford Clay t 300 m are described in the Background Information page 98. Both are "Mudstone", i.e. heavily overconsolidated clay, with notes referring to non-clay materials or characteristics such as cemented layers.

In an overconsolidated clay, stress relief at the excavated surface of a shaft or tunnel will give rise to bulk volume change through slippage and opening of existing fissures; some new fissures or fractures may be created. The intact "blocks" of clay between fissures may not change in volume in the short term as the fine-grained structure of the clay does not allow the intake of water necessary for the clay to swell. With time, however, the presence of water could be expected to allow:

- swelling of the clay "blocks" between fissures hence
- closure of the fissures, and
- development of compressive stresses on the tunnel and shaft linings.

Ultimately, in this scenario, a stress pattern close to the original one is restored and the fissuring is returned virtually to its pre-excavation state.

However, in reality, the lithological description indicates the presence of materials not susceptible to swelling, such as silts and cemented zones. Silts would be more permeable than clay anyway, and cemented zones would not swell although they might conceivably re-cement.

The prudent assumption is therefore that shaft and tunnel excavation will cause a local rise in permeability. This, I think, is the implication of the reference to Mol although we are interested in longer durations than experiments will have run for.

Permeability

The next question is whether this is significant to the flow rate of the gas to the surface. Estimates given of permeability to vertical flow of water can only be a guide to the permeability to gas. In our discussions, we were working up a crude theory that - for gas to be held at depth - the different between the pressure of the gas and the hydrostatic pressure would have to be resisted by surface tension of the water in the fissures.

This suggests that locally stiff features in the clay, producing a few large fissures, would have a disproportionately large effect on the permeability. It also suggests that, if gas evolution cannot be stopped by pressurisation, the gas will eventually force its way out.

I am sure there are sophisticated models in the natural gas exploitation industry, which we could research if you wanted them. I recall also that, when we visited Forsmark, SKB were researching gas migration and reckoning they could not keep it in with bentonite-based backfill materials.

Groundwater Flow

Whether the gases themselves are of major importance I would not give an opinion on. You also asked whether the gas flow could drive a groundwater flow.

It seems unlikely. I believe a gas bubble migrates upwards because the water above it is not stable; therefore as the gas goes up, water goes down. There will be perturbations in the waste as bubbles grow, migrate upwards, and expand (as hydrostatic pressure reduces), but I see no first order reason for gas migration to drive a flow of water. If gas were supplied through a pipe with an appreciable momentum at the point of discharge, that would be a different matter.

Model of Vault Contents

Could I comment also on page 6 item 2.3(a): soup vs concrete. These are at least two separate issues.

Firstly, the fact that a particular barrier component - e.g. flow restriction by intact concrete - is not included in the model does not mean that we should not provide it if we can. What is more important is that, in going for better concrete we could actually detract from a property that is modelled: clearly that should not be allowed.

Secondly, it all depends on what you mean by good concrete. A certain strength will be desirable for the safe performance of the tunnel lining - but that will be segmented and therefore not by itself watertight. Grout outside the lining and backfill around the packages would be cement-based mixes selected for fluidity, low bleed and low shrinkage.

Clearly, an adequate long-term strength is desirable for stability, but given the stress required and the strength of the surrounding clay, the backfill strength does not have to be very great.

Encapsulation matrices are a separate subject; the mixes adopted by BNFL et al. are not exactly the same as we are heading for at Nirex, but not far off.

At the end of the day, you would have four mixes in a tunnel repository:

- tunnel linings: decent structural concrete specified for strength;

- tunnel internal features: low grade structural concrete specified for economy;
- encapsulation matrices: special mixes formulated for fluidity and control in the mixing process;
- backfill: a special mix formulated for good void filling and acceptable chemistry.

I see no merit in using a physical model for ILW at 300 metres depth to represent the niceties of degradation of a monolith of grouts/concrete/wastes. It might be interesting to have a sort of "super-element" within the soup that released to it a range of gas/liquid/solute/particulate radionuclides at rates determined from a separate model.

I am less certain about the LLW as it is, I recall, not encapsulated. The difference is not to call for a physical model but to recognise the effect of "early" structural failure and migration of voids into the neighbouring mass of clay - 2.3.3 refers?

J H Rees

In the Minutes of this meeting, I am actioned to (a) outline the justification for omitting unsaturated near-field water flow (1.5.2) as a parameter of the Minimal Assessment; and (b) justify the inclusion of 1.2.2 - microbial gas evolution - in a modified form of the Minimal Assessment and select the most vital elements of the assessment.

I have no further comments to make on the inclusion of 4.2.3 and 4.2.12 in this modified version.

Unsaturated Water Flow

Studies of resaturation periods for repositories have been undertaken on the Nirex programme for a range of disposal depths in hard and soft host rocks and a range of permeability values (Ref. 1). Host rock permeability was found to be the main factor influencing resaturation times. When taken with the large difference in hydrostatic pressure between the unsaturated vault and the host rock, relatively short saturation periods can result. It was concluded that (1): "resaturation times are relatively short in comparison with the expected gas generation period of 10^2 - 10^4 years, and considerably shorter than the timescales anticipated for radionuclide transport through the geosphere (10^4 - 10^6 years). The only exception to this is with a hard host rock is of very low permeability (10^{-18} - 10^{-19} m^2), when times of up to 17000 years are calculated. A short resaturation period is significant because predictable conditions are rapidly established within the repository and disturbances to groundwater flows are of relatively short duration".

Beyond the resaturation period, gas evolution could expel water from the repository. Because of gas buoyancy effects, there will be a tendency for 2 layers to form. The amount of gas migrating through the lower water layer at any one time will be small because of the low rate of formation. Flow in the water layer can therefore be considered as taking place under saturated conditions.

I therefore suggest that 1.5.2 not be included in the Minimal Assessment, although it could be considered for the enhanced version.

Microbial Gas Evolution

Although the total volume of hydrogen generated from metals in a repository will greatly exceed the volumes of microbial gas, it is possible that their rates of production will be comparable over some hundreds of years following repository closure (Ref. 2). Further clarification is necessary on the basic rate of the processes, the exposed surface areas of metals, and initial microbe populations before this point can be clarified. It is therefore recommended that 1.2.2 be retained in the Minimal Assessment. The following key factors are recommended for this modified version:

1.2.2.1 Cellulosics
1.2.2.4 Anaerobic degradation
1.2.2.9 Effects of hydrogen from metal corrosion
1.2.2.12 Energy and nutrient control of metabolism

Most of the exclusions have been clarified in Expert Group discussions (see Table 1 of EG(90)P6 and Minutes of Meeting on 25/9/90). I will comment only on 1.2.2.5, Effects of temperature. Most of the microbial gas will be generated from LLW whose temperature will be influenced mainly by host rock rather than heating by radioactive decay.

References

1. Cox, I.C.S. and Rodwell, W.R. Post-Closure Resaturation of a Deep Radioactive Waste Repository. NSS/41 (1989).

2. Rees, J.H. and Rodwell, W.R. Gas Evolution and Migration in Repositories - Current Status. NSS/G104 (1988).

3. ANALYSIS OF THE REPLIES

3.1 RESPONSE TO THE QUESTIONNAIRE

3.1.1 Structure of the Minimal Assessment

There was a general agreement that Figure 1 of EG(90)P7 is a suitable representation of the minimal assessment. The following were noted as potential topics of concern:

- Thermal effects on groundwater transport;
- Glaciation;
- Subsidence/collapse, for ungrouted LLW only;
- Exposure to active gases without transport in the biosphere.

The question of thermal effects on groundwater was discussed. It is included in the near-field (EG(90)P7, Table 2, item g), but not in the far-field. The general view appeared to be that, in a host formation of limited hydraulic conductivity, it would be of limited significance.

With respect to glaciation, the conclusion reached at the meeting of 25th September 1990 was that, if glaciation reaches Harwell, it will be a catastrophic event. It was agreed that its implications should be the subject of a separate study. Some work on this has been performed as part of Dry Run 3. The judgements made as to the adequacy of the minimal assessment are taken to be conditioned on major glaciation not reaching the site.

The point on subsidence/collapse is noted. It was not clear, in the factual material provided to the group, whether LLW will be grouted. This remains an open question.

The point on active gases is accepted. An extra arrow on Figures 1 to 3 of EG(90)P7 is required. This arrow links Far-Field Transport and Human Exposure Pathways.

The estimated effects of these factors are summarised below.

Factor	Effect	Timescale (y)
Thermal	Limited/Moderate (H S Wheater)	$0 - 10^2$
	Limited/Unquantifiable without study (E Tufton)	$10^2 - 10^4$
Glaciation	Severe (K M Clayton)	$10^4 - 10^6$
Subsidence/Collapse	Limited/Unquantifiable without study (E Tufton)	$0 - 10^4$
Direct Exposure to Active Gases	Not substantial (J H Rees)	-

3.1.2 THE FIRST REDUCED ASSESSMENT

This excluded:

<u>Item</u> <u>Description</u>

1.6.4 Thermally induced hydrological changes in the near-field
1.6.5 Thermally induced chemical changes in the near-field
3.2.2 Localised denudation
3.6.4 Recreation policy developments

A brief summary of responses is given below, regarding only positive views.

Item	Effect	Source
1.6.4	Probably Limited, but could be Moderate	H S Wheater
	Unquantifiable without study/Limited	E Tufton
	Limited	J H Rees
	Limited	A D Horrill
	Limited	J West
	Limited/Moderate	C C Naish
	Unquantifiable without study	F P Glasser
1.6.5	Unquantifiable without study/Limited	E Tufton
	Limited	J H Rees
	Limited	A D Horrill
	Limited	J West
	Limited/Moderate	C C Naish
	Unquantifiable without study	F P Glasser

Item	Effect	Source
3.2.2	Limited Limited (excluding glaciation) Unquantifiable without study/Limited Limited Limited	H S Wheater K M Clayton E Tufton A D Horrill F P Glasser
3.6.4	Limited Limited Unquantifiable without study/Limited Limited Limited	H S Wheater K M Clayton E Tufton A D Horrill F P Glasser
1.6.4/1.6.5	Limited Limited Limited/Moderate Unquantifiable without study	J H Rees A D Horrill C C Naish F P Glasser
1.6.4/1.6.5/3.2.2/ 3.6.4	Limited/Moderate Limited Unquantifiable without study Moderate	H S Wheater A D Horrill J West C C Naish

With some caveats as to the need for modelling, there seems to be broad agreement on the following judgements.

Item	Effect
1.6.4	Limited/Moderate
1.6.5	Limited/Moderate
1.6.4/1.6.5	Limited/Moderate
3.2.2	Limited
3.6.4	Limited
1.6.4/1.6.5/3.2.2/3.6.4	Limited/Moderate

These judgements form a coherent set and indicate a general view of the group that this reduced assessment would yield results within an order of magnitude of those obtained from the minimal assessment.

3.1.3 The Second Reduced Assessment

In this assessment, the following items were excluded relative to the minimal assessment.

Item	Description
1.1.2	Physical degradation of concrete
1.4.6	Fracturing in the near field
1.6.4	Thermally induced hydrological changes in the near field
1.6.5	Thermally induced chemical changes in the near field
2.3.3	Modification to far-field hydrology due to rock property changes
2.4.6	Fracture surface changes in the far-field, notably demineralisation
2.4.7	Organic colloid transport
2.4.9	Transport of radionuclides bound to microbes
3.1.1	Transient greenhouse gas induced warming
3.2.2	Localised denudation
3.6.4	Recreation policy developments
4.1.1	Short-circuit pathways relating to loss of integrity of borehole seals
4.1.2	Short-circuit pathways relating to loss of integrity of shaft or access tunnel seals

Responses were requested on time of occurrence and effects. These responses are most conveniently considered separately.

Time of Occurrence

Item	Timescale (y)	Probability	Source
1.1.2	$0 - 10^6$	Low	J J W Higgo
	$0 - 10^4$	-	K M Clayton
	$0 - 10^4$	1.0	E Tufton
	$10^4 - 10^6$	0.1	
	$0 - 10^2$	0.1	J H Rees
	$10^2 - 10^3$	1.0	
	$10^2 - 10^3$	Medium	A D Horrill
	$0 - 10^3$	-	J West
	$0 - 10^3$ (cracking)	Moderate	C C Naish
	$> 10^3$ (leaching)		
	$10^3 - 10^4$	-	F P Glasser
1.4.6	$0 - 10^2$	Probable	H S Wheater
	$0 - 10^2$	High	J J W Higgo
	$10^2 - 10^3$	Medium	
	$10^3 - 10^6$	Low	
	$0 - 10^4$	-	K M Clayton
	$0 - 10^2$	0.1	E Tufton
	$10^2 - 10^4$	1.0	
	$10^4 - 10^6$	0.1	
	$0 - 10^2$	0.1	J H Rees
	$10^2 - 10^3$	1.0	

Item	Timescale (y)	Probability	Source
	10^2 - 10^3	Medium	A D Horrill
	0 - 10^3	Moderate	C C Naish
	10^4 - 10^5	-	F P Glasser
1.6.4	0 - 10^2	Probable	H S Wheater
	0 - 10^2	Medium	J J W Higgo
	10^2 - 10^6	Low	
	0 - 10^3	-	K M Clayton
	0 - 10^2	0.5	E Tufton
	10^2 - 10^4	1.0	
	10^4 - 10^5	0.5	
	10^5 - 10^6	0.1	
	0 - 10^2	1.0	J H Rees
	10^2 - 10^3	0.1	
	10^2 - 10^3	Medium	A D Horrill
	0 - 10^2 (10^3)	High	C C Naish
	10^5 - 10^6	-	F P Glasser
1.6.5	0 - 10^2	Medium	J J W Higgo
	10^2 - 10^6	Low	
	0 - 10^3	-	K M Clayton
	0 - 10^3	0.75	E Tufton
	10^3 - 10^4	0.5	
	10^4 - 10^5	0.1	
	10^5 - 10^6	<0.1	
	0 - 10^2	1.0	J H Rees
	10^2 - 10^3	0.1	
	0 - 10^3	Low	A D Horrill
	0 - 10^2	1.0	C C Naish
	10^5 - 10^6	-	F P Glasser
2.3.3	0 - 10^2 (locally)	-	H S Wheater
	$>10^3$ (otherwise)	-	
	0 - 10^6	Low	J J W Higgo
	10^4 - 10^6	-	K M Clayton
	10^3 - 10^4	0.1	E Tufton
	10^4 - 10^5	0.25	
	10^5 - 10^6	0.5	
	10^5 - 10^6	Medium	A D Horrill
	10^5 - 10^6	-	F P Glasser
2.4.6	0 - 10^2 (locally)	-	H S Wheater
	$>10^3$ (otherwise)	-	
	0 - 10^6	Low	J J W Higgo
	10^4 - 10^6	-	K M Clayton
	10^3 - 10^4	0.1	E Tufton
	10^4 - 10^5	0.25	

Item	Timescale (y)	Probability	Source
	10^5 - 10^6	0.25	
	10^5 - 10^6	Medium	A D Horrill
	10^5 - 10^6	-	F P Glasser
2.4.7	0 - 10^6	Medium	J J W Higgo
	10^2 - 10^6	-	K M Clayton
	10^3 - 10^4	0.01	J H Rees
	10^4 - 10^5	>0.1	
	10^5 - 10^6	>0.1	
	10^4 - 10^5	Medium	A D Horrill
	10^4 - 10^5	-	F P Glasser
2.4.9	0 - 10^2	High (in near-field)	H S Wheater
	0 - 10^6	Medium	J J W Higgo
	10^2 - 10^6	-	K M Clayton
	10^4 - 10^5	Low	A D Horrill
	0 - 10^2	Limited	J West
	10^2 - 10^6	Moderate	
	10^4 - 10^5	-	F P Glasser
3.1.1	0 - 10^2 (+)	High	H S Wheater
	-	High	J J W Higgo
	0 - 10^4	-	K M Clayton
	10^2 - 10^4	0.75	E Tufton
	0 - 10^2	High	A D Horrill
	0 - 10^2 or 10^3	-	F P Glasser
3.2.2	>10^3 (sig. effects)	-	H S Wheater
	-	May occur	J J W Higgo
	10^4 - 10^6	-	K M Clayton
	10^4 - 10^5	0.1	E Tufton
	10^5 - 10^6	0.25	
	>10^3	Low	A D Horrill
	10^3 - 10^4	-	F P Glasser
3.6.4	0 - 10^2	Probable	H S Wheater
	-	May occur	J J W Higgo
	0 - 10^4 (+)	-	K M Clayton
	0 - 10^2	0.5	E Tufton
	10^2 - 10^6	1.0	
	>10^3	Low	A D Horrill
	10^2 - 10^3	Limited	F P Glasser
4.1.1	0 - 10^2	Depends on competence of construction	H S Wheater
	0 - 10^2	Medium	J J W Higgo

Item	Timescale (y)	Probability	Source
	$10^2 - 10^6$	Low	
	$10^2 - 10^4$	-	K M Clayton
	$0 - 10^2$	0.25	E Tufton
	$10^2 - 10^4$	0.75	
	$10^4 - 10^6$	0.1	
	$0 - 10^3$	0.1	J H Rees
	$10^3 - 10^6$	<0.001	
	$>10^3$	Low	A D Horrill
	$10^2 - 10^3$	-	F P Glasser
4.1.2	$0 - 10^2$	Depends on competence of construction	H S Wheater
	$0 - 10^2$	Medium	J J W Higgo
	$10^2 - 10^6$	Low	
	$10^2 - 10^4$	-	K M Clayton
	$0 - 10^2$	0.25	E Tufton
	$10^2 - 10^4$	0.75	
	$10^4 - 10^5$	1.0	
	$10^5 - 10^6$	0.1	
	$0 - 10^3$	0.1	J H Rees
	$10^3 - 10^6$	<0.001	
	$>10^4$	Low	A D Horrill
	$10^2 - 10^3$	-	F P Glasser

There is, to some degree, a confounding of probability of occurrence with timescale of significant effects in the above responses. However, some useful conclusions may be drawn.

a) Physical degradation of concrete (1.1.2) is expected to occur over a timescale of $<10^4$ years. The early phase ($<10^3$ years) is expected to be cracking, with leach-associated degradation occurring on the longer timescale.

b) Fracturing in the near-field (1.4.6) is seen as likely to occur on a timescale of $<10^2$ years and almost certain on a timescale of $<10^4$ years.

c) Thermally induced hydrological changes in the near field (1.6.4) are expected on a timescale of $<10^2$ years and may persist for up to $10^5 - 10^6$ years.

d) Thermally induced chemical changes in the near field (1.6.5) are expected on a timescale of $10^2 - 10^3$ years and may persist for up to $10^5 - 10^6$ years.

e) Modification to far-field hydrology due to rock property changes (2.3.3) is expected on a timescale of $10^4 - 10^6$ years, though some effects on the flow field local to the repository could occur on a timescale of $<10^2$ years.

f) Fracture surface changes in the far field, notably demineralisation (2.4.6) are moderately likely to occur on a timescale of 10^4 - 10^6 years.

g) Organic colloid transport (2.4.7) is moderately likely to occur and may well persist for 10^5 - 10^6 years post closure.

h) Transport of radionuclides bound to microbes (2.4.9) is moderately likely to occur and may well persist for 10^5 - 10^6 years post closure.

i) Transient greenhouse gas warming (3.1.1) is expected to occur, with its environmental effects persisting for $\sim 10^4$ years.

j) Localised denudation (3.2.2) may begin to be of significance on a timescale of 10^3 years and will become of increasing importance over the interval 10^3 - 10^6 years.

k) Recreation policy developments (3.6.4) are anticipated on the timescale 0 - 10^3 years.

l) Members of the group with near-field or engineering expertise anticipate a moderate to high probability of short-circuit pathways relating to loss of integrity of borehole, shaft or access tunnel seals (4.1.1/4.1.2) on a timescale of $<10^3$ years.

It is notable that all the above are at least moderately likely to occur (probability ≥ 0.1) within the assessment period and that most have effects persisting for periods of 10^4 - 10^6 years. These considerations are an indication of why these various factors and phenomena were included in the minimal assessment.

Given that these various factors and phenomena are likely to occur, attention can be concentrated on their potential implications.

Responses on this topic are summarised below. In general, members of the group were not comfortable about assessing the combined impact of so many exclusions. Thus, the most general response was "Unquantifiable without modelling studies" (J J W Higgo, K M Clayton, E Tufton, J West). This position is supported by H S Wheater, who considers that 2.4.7, 2.4.9, 3.1.1, 4.1.1 and 4.1.2, separately or in combination, could have severe (> factor 10) effects on individual risk estimates, with the combined effect of all other factors being moderate (factor 2 - 10). The position of J H Rees is more equivocal. His comments may be interpreted as indicating that the combined effect of 1.1.2, 1.4.6, 1.6.4, 1.6.5, 2.4.7, 4.1.1 and 4.1.2 is limited (< factor 2). However, he was not able to comment on the effects of 2.3.3, 2.4.6, 2.4.9, 3.1.1, 3.2.2 and 3.6.4. In contrast, A D Horrill took the view that the combined effect of all the excluded factors would be low. C C Naish ventured a view that the combined effect of all the factors is unlikely to be greater than moderate, but caveated this by the statement that he did not feel competent to assess the combined effects. Finally, F P Glasser provided a table of effects on peak risk by factor. However, this was conditioned on the assumption that the repository is 500 - 1000 m deep in crystalline, low permeability rock, an assumption that differs substantially from that adopted by the other participants and by the secretariat.

3.1.4 Discussion

The response to the questionnaire essentially confirmed previous views relating to the minimal assessment. There was general agreement as to its structure (Section 3.1.1), small deletions could be tolerated with only a Limited/Moderate effect on peak individual risks (Section 3.1.2), but more extensive deletions results in a general feeling that too much of substance had been deleted and that the degree of bias would be unquantifiable without modelling studies (Section 3.1.3), which effectively corresponds to reintroducing the factors/phenomena into the assessment.

3.2 COMMENTS ON TABLES AND FIGURES IN EG(90)P7

The following is a brief response to the comments presented in Section 2.2.1. To keep this material to a minimum, only points of dissent from the secretariat's interpretation are discussed.

3.2.1 Table 1

Item 2.3.2 (Groundwater losses) does include boundary fluxes and abstractions.

The displacement of numbers in Section 4.2 is noted.

Speciation is implicitly included in far-field sorption, e.g. in evaluating items 2.4.5.5 and 2.4.5.6.

The comments are necessarily brief. The main aim is to ensure traceability to previous, more extensive discussions.

Item 1.2.6.4 could be included in either the near- or far-field section. It is agreed that 1.2.6.5 is identical to 2.4.11. As 2.4.11 provides more detail, 1.2.6.5 can be deleted.

It was only agreed on 26th June 1990 to exclude 1.4.1, 1.4.3 and 1.4.5 from the minimal assessment.

The point concerning damage to the barrier function of the clay by construction work is noted. This does not modify Table 1.

Item 2.4.6 should be reinstated. The text of the comment is already appropriate.

Item 2.2.10 (Effects of natural gases) and item 2.2.11 (Geothermal effects) were omitted in error from Table 1. They will be reinstated.

Section 3.6 could be modified to:

3.6 Land Use
3.6.1 Urbanisation
3.6.2 Agricultural Policy

3.6.3 Recreation Policy
3.6.4 Management of Water Resources

However, this is primarily a cosmetic change and would be unhelpful at this stage, as it could cause confusion in interpreting replies from expert group members. It is noted for future reference.

It was only agreed on 26th June 1990 to exclude 4.2.10 and 4.2.11 from the minimal assessment.

For item 1.2.2.5, the comment should read "Secondary effect modifying metabolic activity and the chemical degradation of cellulose".

The comment on 2.4.5.4 should be deleted. It related only to the definition of a minimal assessment.

3.2.2 Table 2

The status of item 1.4.6 is debatable. It was assigned L/M, but M/H is suggested by H S Wheater, whereas J H Rees would like to see it omitted. It is probably best to leave it as it stands, noting the comments as a basis for future discussion.

The comments on 2.2.9 by H S Wheater are appropriate and should be taken into account in any future study of this type.

K M Clayton suggests the following status assignments for items where tentative proposals were made by the secretariat.

Item	Secretariat Status	K M Clayton
3.1.1	M	M
3.1.2	H	H
3.1.3	x	x
2.2.9	H	H
3.4.1	H,d	M
3.6.3	H	M
4.1.3	M/H	H

The changes are marginal and do not affect the development of the three assessment structures to which the questionnaire related.

The intimate connection between 3.5.2, 3.5.3 and 3.5.4 is noted. The frequency and consequences of 4.2.3 have been explored in scoping calculations. It is very difficult to evaluate the potential radiological impact of intrusions without such calculations. This item is scored H because of its potential importance.

Item 4.2.12 is related to far-field transport. This requires an extra line on Figures 1 to 3.

Item 1.1.1, in relation to gas production, is included in 1.2.

E Tufton suggests the status on 1.4.4 should be changed from x to s. This is accepted.

Item 1.5.4 was excluded on the basis of EG(90)P6. There was extensive discussion of this topic at the meeting of 25th June 1990, but fuller justification for its exclusion would be useful. It is thought to arise from a general view that repository materials will be the primary control on near-field behaviour.

Item 1.6.6 is excluded only from the minimal assessment, not from all consideration.

Scoping calculations for 2.1.1 have been performed and are being reported as part of Dry Run 3.

It is agreed that 2.4.7 and 2.4.8 are highly rated relative to Table 1. This appears primarily to be a result of reconsideration of these items in the context of an overconsolidated and fractured host medium.

Item 2.4.10 is included under 2.4.5, as noted in Table 1.

Item 2.4.13 is discussed in Section 3.1.1. This is identified as a topic requiring further review.

It is difficult to exclude item 1.1.2 from Table 2 because of the potential significance of cracking in changing near-field hydrology and the potential sorption sites accessible to radionuclides in transport.

Item 1.2.6 could reasonably be regraded M/H. This would not change the structure of Figures 1 to 3.

Item 2.4.12 could reasonably be regraded M/H. This would not change the structure of Figures 1 to 3.

3.2.3 Table 3 and Figures 1 to 3

It is agreed that 1.1.3 affects 1.7.1 and 1.7.2. The connection is shown on the figures, but is not listed in Table 3. Effects of 1.1.3 on 2.4.5 are via transport of radioactive and non-radioactive materials out of the near field (1.7.1/1.7.2). No new connection is required.

There is an error in Table 3. The following corrections are required.

Origins	Targets	Comments
1.2.1/1.2.2/1.2.6	1.5.3	Gas production can induce or impede groundwater flow in the near field.
1.2.1/1.2.2/1.2.6	1.4.6	Gas production can lead to overpressurisation and fracturing.

It is agreed that 1.6.5 can influence 1.7, but this influence is primarily via effects on degradation phenomena (1.1.2/1.1.3/1.1.4). No new connections are required.

It is agreed that 4.2.12 should be linked to 2.4.

Gas transport out of the near field is implied in 1.7, which feeds into 2.4.11 and 2.4.12.

Radioactive decay occurs primarily in the transport pathway. The short-circuit components reflect their existence and influence, not the transport within them. No new connections are required.

The following new or modified entries in Table 3 are required.

Origins	Targets	Comments
1.1.4	1.7	Waste degradation is the source of radionuclides for transport out of the near field, as well as leading to the formation of organic complexing agents and sorption sites.
1.2.1/1.2.2/1.2.6	1.1.2	Overpressurisation may lead to cracking of concrete. CO_2 production and sorption may also be significant.

Item 1.7 is not considered to be the source for 4.2. This is either the contents of the repository or the far-field plume. No new connection is required.

Given the characteristics of the preferential pathways (internal to item 4.1), far-field hydrology is the primary control. No change required.

The following new and modified entries to Table 3 are required.

Origins	Targets	Comments
3.5	3.7	Biosphere transport is the primary determinant of human exposure pathways, except possible for active gases.
2.4.11	3.7.1/3.7.2	Direct exposure to active gases.

Where new entries to Table 3 are given, new connections on Figures 1 - 3 are implied.

4. RESPONSE REQUIRED

This note, as it stands, will be used to finalise the first draft of Dry Run 3: Volume 7: Uncertainty and Bias Audit. This draft will be the subject of external peer review. Comments by members of the Expert Group relating to this note will be taken into account together with those of the peer reviewer relating to the documentation as a whole. Any such comments should be sent to the secretariat no later than 15th February 1991.

DISTRIBUTION

K M Clayton
T D Davies
F P Glasser
J Higgo
A D Horrill
J Knill
C C Naish
M L Parry
J H Rees
E Tufton
J West
H S Wheater

M C Thorne
B G J Thompson
T J Sumerling
J Taylor

APPENDIX B
Details of Modelling Studies

Dry Run 3: Uncertainty and Bias Audit

APPENDIX B

DETAILS OF MODELLING STUDIES

B1 INTRODUCTION

This appendix is arranged as a series of calculation notes. These are listed below.

Note	Topic
1	Meteorite impact
2	Gross erosion and incision
3	Release of radioactive gases
4	Human intrusion

Calculation Note: 1

Topic: Meteorite Impact

Date Prepared: 18 May 1990

Author: M C Thorne

Background

Large-scale meteorite impacts have the potential for disrupting a deep repository and releasing radionuclides directly to the accessible environment. However, such large-scale impacts are of low frequency. Thus, McCall (1979) lists a total of 151 craters and structures worldwide that may have resulted from the impact of extra-terrestrial bodies. Of these, 27 were classified as certainly or probably due to impacts. In Europe, there was only one certain or probable impact and a further 15 possible impacts (Dames & Moore, 1984). Typical crater sizes vary from 1 km to 45 km diameter. Such craters have a total depth of around one third of their diameter. This includes the thickness of shattered rock fragments which are originally dispersed into the air by the impact and then fall back into the crater. Below this layer is a zone of intense fracturing of the in situ materials (Dames & Moore, 1984). Because even large craters are destroyed by erosive processes, rates of meteorite impact can only be calculated if the ages of the observed features are known.

Age-determinations for five of the European craters range from 8000 to 1.5×10^7 y. A further three craters are considered to be of Precambrian age ($>6 \times 10^8$ y) and a feature in Shetland may be of late Mesozoic age ($\sim 10^8$ y). A total impact rate of 0.5 per 10^6 y has been proposed for Europe as a whole and 0.006 per 10^6 y for Britain (Dames & Moore, 1984). This suggests that the probability of meteorite damage to a deep repository is $\sim 10^{-9}$ per year or less, taking into account the possibility that rock fracturing may occur up to 150 km from the point of impact for a large meteorite (Dames & Moore, 1984).

Alternatively, the methodology developed by Hartmann (1979) may be used to estimate that the fractional area of land, F, covered per year by craters of a diameter greater than or equal to D is given by:

$$F = 1.29 \times 10^{-12} [2.8 - D^{0.2}]$$

where D is measured in km.

Recalling that the depth of the damaged zone is about D/3, values of D of interest in deep disposal are in the range 0.15 to 3.0 km. Values of F for selected values of D are listed below.

D (km)	F (y^{-1})
0.15	2.7×10^{-12}
0.60	2.4×10^{-12}
3.00	2.0×10^{-12}

For comparison, Bonne (1986) estimated that for a hypothetical HLW repository located 200 m beneath Mol, Belgium, the frequency of disruptive meteorite impact would be 3.4×10^{-12} per year.

Using the methodology proposed by Hartmann, the following table of values of D, F and ΔF values for each increment ΔD has been constructed.

D (km)	F	Δ	D	F	ΔF
0.15	$2.73\ 10^{-12}$		20.0	$1.26\ 10^{-12}$	
		$0.13\ 10^{-12}$			$0.19\ 10^{-12}$
0.3	$2.60\ 10^{-12}$		30.0	$1.07\ 10^{-12}$	
		$0.15\ 10^{-12}$			$0.39\ 10^{-12}$
0.6	$2.45\ 10^{-12}$		60.0	$0.68\ 10^{-12}$	
		$0.13\ 10^{-12}$			$0.31\ 10^{-12}$
1.0	$2.32\ 10^{-12}$		100.0	$0.37\ 10^{-12}$	
		$0.19\ 10^{-12}$			$0.27\ 10^{-12}$
2.0	$2.13\ 10^{-12}$		150.0	$0.10\ 10^{-12}$	
		$0.12\ 10^{-12}$			$0.10\ 10^{-12}$
3.0	$2.01\ 10^{-12}$		175.0	0.0	
		$0.24\ 10^{-12}$			
6.0	$1.77\ 10^{-12}$				
		$0.20\ 10^{-12}$			
10.0	$1.57\ 10^{-12}$				
		$0.31\ 10^{-12}$			
20.0	$1.26\ 10^{-12}$				

Since the area of each crater is $\pi D^2/4$, mean numbers of craters per unit area per year, N, can be calculated as:

$$N = 4\Delta F/\pi D^2$$

Values are given below:

D (km)	ΔF	N (y^{-1} km^{-2})
0.15 - 0.3	0.13 10^{-12}	3.3 10^{-12}
0.3 - 0.6	0.15 10^{-12}	9.4 10^{-13}
0.6 - 1.0	0.13 10^{-12}	2.6 10^{-13}
1.0 - 2.0	0.19 10^{-12}	1.1 10^{-13}
2.0 - 3.0	0.12 10^{-12}	2.4 10^{-14}
3.0 - 6.0	0.24 10^{-12}	1.5 10^{-14}
6.0 - 10.0	0.20 10^{-12}	4.0 10^{-15}
10.0 - 20.0	0.31 10^{-12}	1.8 10^{-15}
20.0 - 30.0	0.19 10^{-12}	3.9 10^{-16}
30.0 - 60.0	0.39 10^{-12}	2.5 10^{-16}
60.0 - 100.0	0.31 10^{-12}	6.2 10^{-17}
100.0 - 150.0	0.27 10^{-12}	2.2 10^{-17}
150.0 - 175.0	0.10 10^{-12}	4.8 10^{-18}

Two possible effects of meteorite impact should be considered:

- direct disturbance of the repository leading to surface contamination;
- rock fracturing, leading to changes in groundwater pathways.

In Dry Run 3, the waste repositories are at depths of more than 107.5 m (LLW) and 290 m (ILW). For direct disturbance to a repository at a depth of 107.5 m, the crater diameter would be >320 m. Taking the target area to be max $\{4, \pi D^2/4\}$ km^2, to allow for the finite extent of the repository (taken as ~4 km^2), the frequency of direct disturbance is estimated as 7.4 10^{-12} y^{-1}. Over a 10^6 y period, the cumulative probability is 7.4 10^{-6}. Similarly, for direct disturbance to a repository at a depth of >290 m, the crater diameter would be >870 m and the frequency of direct disturbance is estimated as 3.1 10^{-12} y^{-1}. Over a 10^6 y period, the cumulative probability is 3.1 10^{-6}.

For rock fracturing, the conservative assumption is made that meteorites impacting within 10 km of the repository would be of importance. This yields a frequency ~10^{-9} y^{-1} and a cumulative probability over 10^6 y of ~10^{-3}.

The likely effect of rock fracturing would be to enhance hydraulic conductivities of the rocks in the vicinity of the repository. Nevertheless, the overall pattern of groundwater flows would probably not be altered substantially, though groundwater velocities might. Thus, meteorite impact is most reasonably aggregated with a variety of other potential causes of changes in hydraulic conductivity (e.g. isostatic flexuring) and its potential effects on individual risk may be treated in groundwater flow and transport sensitivity studies.

Given that cumulative probabilities of gross disturbance are only 7.4 10^{-6} for the LLW repository and 3.1 10^{-6} for the LLW and ILW repositories (taking the ILW repository to immediately underlie the LLW repository), evaluating the risks of such disturbance is of only marginal relevance. Nevertheless, a scoping calculation has been performed and is reported below.

Consider a crater just sufficiently deep to grossly disturb the ILW repository, i.e. depth ~300 m, diameter ~900 m. The total volume of material disturbed is ~10^8 m^3 and the total mass ~1.5 10^{11} kg. For the radionuclides considered (c.f. main text Tables 2 and 3), the total inventory does not change very rapidly. For this calculation, values at 10^4 years post-closure are adopted to ensure significant in-growth of daughter products. This activity is assumed to be uniformly distributed throughout the disturbed material, leading to the concentrations listed below.

Radionuclide	Concentration (Bq/kg)	Radionuclide	Concentration (Bq/kg)
C-14	1.02 10^3	Th-230	1.87 10^1
Cl-36	3.92 10^0	Pa-231	5.37 10^0
Se-79	1.33 10^1	U-233	1.63 10^1
Tc-99	1.20 10^3	U-234	1.78 10^2
Sn-126	2.27 10^1	U-235	1.21 10^1
I-129	2.85 10^0	U-238	1.29 10^2
Cs-135	3.71 10^1	Np-237	2.91 10^2
Pb-210	1.53 10^1	Pu-239	3.02 10^4
Ra-226	1.54 10^1	Pu-242	2.23 10^2
Th-229	8.21 10^0	Am-243	8.29 10^1

These values can be set in context by comparing the highest value, which is 3.02 10^4 Bq/kg for Pu-239 with the Generalised Derived Limit (GDL) for well-mixed soil of 1 10^3 Bq/kg recommended by the NRPB (1987). Because the GDL is derived from a principle dose limit of 1.0 mSv/y using pessimistic assumptions, it is estimated that the dose rate from the disturbed material is likely to be no more than 30 mSv/y, corresponding to a conditional risk ~6 10^{-4} y^{-1}. It should be noted that the other radionuclides with concentrations in excess of 10^3 Bq/kg (C-14 and Tc-99) are of low radiotoxicity. Finally, the values of 1.70 10^2 and 1.29 10^2 Bq/kg for U-234 and U-238, respectively can be compared with the naturally occurring concentration of uranium in soil of 1 ppm (Brooks, 1972). This corresponds to 12.5 Bq/kg of U-234 and 12.4 Bq/kg of U-238.

Conclusions

Over 10^6 y, the cumulative probability of gross repository disturbance is estimated to be 7.4 10^{-6} (LLW) and 3.1 10^{-6} (ILW). If gross disturbance of the LLW and ILW repositories occurs the conditional risk to exposed individuals is estimated as no more than 6 10^{-4} y^{-1}. Thus, the peak absolute risk over the period is $\leq$2 10^{-9}. For rock fracturing, the cumulative probability over 10^6 y is estimated to be $\sim 10^{-3}$. The likely effect would be to enhance hydraulic conductivities of the rocks in the vicinity of the repository. The overall pattern of groundwater flows would probably not be altered substantially, though groundwater velocities might. Thus, meteorite impact is most reasonably aggregated with other potential causes of changes in hydraulic conductivity, which can be treated in groundwater flow and transport sensitivity studies.

References

Bonne, A. (1986). Safety analysis of a HLW repository in a clay formation. In: Burkholder, H.C. (Ed.). High Level Nuclear Waste Disposal, NEA/OECD, Paris.

Brooks, P.R. (1972). Geobotany and biogeochemistry in mineral exploration. Harper and Row, New York, 290 pp.

Dames & Moore (1984). Influence of Time Dependent Effects on the Disposal Environments of Low and Intermediate Level Radioactive Wastes. DoE Report No. DOE/RW/85.036-037. 2 Volumes.

Hartmann, W.K. (1979). Long-term meteorite hazards to buried nuclear waste. Pacific Northwest Laboratory Report, PNL-2851.

National Radiological Protection Board (1987). Revised Generalised Derived Limits for Radioisotopes of Strontium, Iodine, Caesium, Plutonium, Americium and Curium. NRPB-GS8.

McCall, G.J.H. (1979). (Ed.). Astroblemes-cryptoexplosion structures. Benchmark Papers in Geology, Vol. 50, Dowden Hutchinson & Ross Inc.

Calculation Note: 2

Topic: Gross Erosion and Incision

Date Prepared: 18 May 1990

Author: M C Thorne

Background

As described in Dry Run 3, Volume 3, Chapter 7, glaciers are expected to reach and, in some cases, cover the hypothetical site. While these glaciers might cause only superficial erosion (as assumed in the calculations reported in Volume 6), it is also possible that gross generalised erosion or incision could occur. Examination of Figure 3.5, Volume 1, suggests that gross erosion would lead primarily to removal of the chalk scarp; but would not necessarily result in the exposure of the repository. However, Wingfield (1990a) has drawn attention to the potential significance of major incisions. These are incised, enclosed depressions of elongate form up to 400 m deep, 5 km wide and 30 km long. Some 400 such incisions were cut below lowland plains or into the seabed of the present continental shelf around Britain in the last 25,000 years. Current research suggests that each major incision was cut in less than 3 hours by the catastrophic release of large (c. 50 to 200 km^3) volumes of melt water at the margin of an ice sheet. Another 200 to 500 major incisions are to be expected around Britain during the next major glacial episode (Wingfield, 1989; 1990; 1990a).

Given the data outlined above, it is reasonable to estimate that ~3000 major incisions might occur over lowland Britain and associated offshore areas over the next 10^6 years. Taking each deep to be 2 km wide and 10 km long, the area covered would be 60,000 km^2, or ~10% of the total area available. This indicates that the possibility of a major incision in the vicinity of the repository has to be considered as moderately likely.

Taking the depth of such an incision to be sufficient to reveal the ILW repository (~300 m), the total volume of material incised in estimated as $6\ 10^{10}\ m^3$. As a scoping calculation, and taking into account the energetic nature of the erosive process, it is reasonable to assume that the activity content of the LLW and ILW repositories is uniformly mixed into this volume as it is redistributed. As the volume is a factor of 600 larger than that adopted for meteorite impact (Calculation Note 1), the estimated dose is a factor of 600 lower, i.e. no more than ~0.025 mSv/y, corresponding to a conditional risk $\leq 5\ 10^{-7}\ y^{-1}$.

Conclusions

Over 10^6 years, the cumulative probability of gross repository disturbance is estimated as $\sim 10^{-1}$. If such disturbance occurs, the conditional risk to exposed individuals is estimated as $\leq 5\ 10^{-7}\ y^{-1}$. Thus, the peak absolute risk over the period is estimated as $\leq 5\ 10^{-8}\ y^{-1}$.

References

Wingfield, R.T.R. (1989). Glacial incisions indicating Middle and Upper Pleistocene ice limits off Britain. Terra nova, Vol. 1, pp. 538-548.

Wingfield, R.T.R. (1990). The origin of major incisions within the Pleistocene deposits of the North Sea. Marine Geology, Vol. 91, pp. 31-52.

Wingfield, R.T.R. (1990a). Pers. comm. to M.C. Thorne, Electrowatt, 18 February 1990.

Calculation Note: 3

Topic: Release of Radioactive Gases

Date Prepared: 21 May 1990

Author: M C Thorne

Background

As described in Dry Run 3, Volume 3, Section 6, microbial degradation of organic matter and corrosion of metals can give rise to the production of large volumes of gases. In addition, radionuclides such as C-14 may be released from the wastes in gaseous form and transported along with these bulk gases.

In the most recent review of the gas evolution studies funded by Nirex, Rees (1989) presents the following best estimates of volumes of bulk gases generated from LLW and ILW.

Waste	Gases	Volume (m^3 STP)	Period of Evolution (y)
Steels - LLW	H_2	$6\ 10^8$	200 - 10,000
Steels - ILW	H_2	$1.6\ 10^8$	200 - 10,000
Magnox - ILW	H_2	$1\ 10^7$	10,000
Zircaloy - ILW	H_2	$1\ 10^7$	10,000
Cellulosics - LLW	CH_4, CO_2	$4\ 10^6$	500

The volumes of gas evolved and the rates of production are similar to those estimated in an earlier review (Rees and Rodwell, 1988). In that review, it was argued that dissolution of gases would not be adequate as a removal mechanism and, therefore, transport in the gas phase would be required.

Furthermore, Rees (1989) comments, in respect of low permeability clays, that the inclusion of a sparse network of capillaries could substantially ease gas escape, while having a negligible effect on overall porosity and a barely significant effect on permeability, as determined on the field scale.

On the basis of the above, and taking into account the discussions in Volume 3, Section 6, the following scoping calculations are identified.

a) 50% of the LLW inventory of ^{14}C is released from the repository as $^{14}CH_4$ leaks upward to the surface and is released without modification to its chemical form.

b) 50% of the LLW inventory of ^{14}C is released as $^{14}CH_4$ and 50% as $^{14}CO_2$. Pathway as for (a).

c) As for (b), but taking the total LLW inventory of ^{129}I, ^{79}Se and ^{126}Sn also to be released to the environment in methylated forms.

d) As for (a), but for the LLW and ILW inventory of ^{14}C.

e) As for (b), but for the LLW and ILW Inventory of ^{14}C.

f) As for (c), but for LLW and ILW.

Of the above, (a) is considered the most likely. Options (b) and (c) are less likely because CO_2 will react strongly with any cementitious materials it encounters and because methylated forms of iodine, selenium and tin are of limited stability. Option (d) is a reasonable bounding calculation, because ~50% of the ^{14}C in ILW is associated with the organic component (c.f. Volume 1, Section 1, Table 1.4). Options (e) and (f) are less likely, for the reasons given above.

At the surface, the area of release is taken as 4 km², i.e. approximately equal to the plan area of the LLW repository (Volume 1, Section 6, Table 6.3). It could be argued that selective migration up particular fracture paths could lead to a more localised release, but given that the organic waste is well-distributed throughout the repository, a substantially reduced area is not anticipated.

The total release period is taken to be 500 years in each case. Values as low as ~100 years are plausible and values as high as a few thousand years are possible.

On release from the surface, the gas is assumed to enter houses with a ventilation rate of 1 h^{-1}. Values in the range 0.3 h^{-1} to 3 h^{-1} are reasonable for sensitivity studies.

The formalism adopted for each component of the release is:

$$H = (Q/T.A_r).(A_h/V_h).(1/\lambda_v).S.O_f$$

where H (Sv y^{-1}) is the dose rate received;
Q (Bq) is the total release;
T(h) is the period of release;
A_r (m^2) is the area of release;
A_h (m^2) is the floor area of the house;
V_h (m^3) is the volume of ground floor rooms;
λ_v (h^{-1}) is the ventilation rate;
S (Sv/y per Bq/m^3) is the exposure to dose conversion factor; and
O_f (-) is the occupancy factor.

Taking $T = 500 \times 8766 = 4.38\ 10^6$ h;

$A_r = 4\ 10^6\ m^2$;
$V_b/A_b = 2.5$ m;
$\lambda_v = 1\ h^{-1}$;
$O_f = 1.0$.

This reduces to:

$$H = 2.3\ 10^{-14}\ Q.S$$

Values of S are required for $^{14}CO_2$, $^{14}CH_4$, $CH_3{}^{129}I$, $(CH_3)_2Se$ and methylated forms of ^{126}Sn (mono-, di-, tri- and tetra-methyl forms). Derivation of such values is described below.

For $^{14}CO_2$, the ICRP (1979-1982) gives a dose per unit intake value of 6.4 10^{-12} Sv/Bq. The breathing rate of Reference Man (ICRP, 1975) is 23 m^3/day or 8400 m^3/y. Thus, the requisite factor is 8400 x 6.4 10^{-12} = 5.4 10^{-8} Sv/y per Bq/m^3.

A new metabolic model for $^{14}CH_4$ has recently been developed (Phipps et al., 1990). Results from this model are summarised below.

		Effective Dose Equivalent (Sv/s per Bq/m^3)			
Group	Age (y)				
		Absorbed Gas	Gas in lung	Metabolised Gas	External
Adults	20	2.1 10^{-18}	2.9 10^{-18}	1.7 10^{-17}	2.8 10^{-18}
Children	10	2.1 10^{-18}	5.5 10^{-18}	1.9 10^{-17}	7.0 10^{-18}
Infants	1	2.1 10^{-18}	7.9 10^{-18}	1.0 10^{-17}	7.0 10^{-18}

Adopting the value for children, gives a total of 1.1 10^{-9} Sv/y per Bq/m^3.

With methyl iodide, it is observed that, if an individual is exposed to the vapour, ~75% of that inhaled will typically enter the circulation and be metabolised. Metabolism involves the release of the iodide ion, which can then be expected to follow the same metabolic pathways as for intravenously injected iodide (Thorne et al., 1986).

On the basis of these observations, it is assumed that 75% of inhaled ^{129}I, ^{79}Se and ^{126}Sn enters the systemic circulation and is metabolised according to the models developed by the ICRP (1979, 1982). Dosimetric data in the following calculations are taken from the publication.

I-129

Oral intake of 1 Bq of ^{129}I results in a rapid systemic uptake of 1 Bq and a committed dose equivalent of 7.4 10^{-8} Sv. Thus, an air concentration of C Bq m^{-3} of $CH_3\ ^{129}I$ will result in an intake rate of 8400C Bq/y. The uptake to the systemic circulation will be 6300C Bq/y. Hence, the rate of accumulation of effective dose equivalent is estimated as 4.7 10^{-4} Sv/y per Bq/m^3.

Se-79

Oral intake of 1 Bq of ^{79}Se results in a rapid systemic uptake of 0.8 Bq and a committed dose equivalent of 2.3 10^{-9} Sv, i.e 2.9 10^{-9} Sv for an uptake of 1 Bq to the systemic circulation. By the same arguments as for ^{129}I, the rate of accumulation of effective dose equivalent is estimated as 1.8 10^{-5} Sv/y per Bq/m^3.

Sn-126

Oral intake of 1 Bq of ^{126}Sn gives rise to a rapid systemic uptake of 0.02 Bq and to a committed effective dose equivalent of 9.3 10^{-10} Sv. (It should be noted that doses to the lower parts of the gastrointestinal tract are excluded from this computation, since the result is to be applied to inhalation of a ^{126}Sn-labelled gas). Thus, the committed effective dose equivalent for uptake of 1 Bq to the systemic circulation is 4.7 10^{-8} Sv. By the same arguments are for ^{129}I, the rate of accumulation of effective dose equivalent is estimated as 3.0 10^{-4} Sv/y per Bq/m^3.

Scoping Calculations

a) $Q = 0.5 \times 2.8\ 10^{13}$ for $^{14}CH_4$
$S = 1.1\ 10^{-9}$ for $^{14}CH_4$
$H = 3.5\ 10^{-10}$

b) As for (a), but add:

$Q = 0.5 \times 2.8\ 10^{13}$ for $^{14}CO_2$
$S = 5.4\ 10^{-8}$ for $^{14}CO_2$
$H(^{14}CO_2) = 1.7\ 10^{-8}$ Sv/y

So, $H = 1.7\ 10^{-8} + 3.5\ 10^{-10} = 1.8\ 10^{-8}$

c) As for (b), but add:

$Q = 5.409\ 10^{9}$ for ^{79}Se
$Q = 5.400\ 10^{9}$ for ^{129}I
$Q = 5.420\ 10^{9}$ for ^{126}Sn
$S = 1.8\ 10^{-5}$ for ^{79}Se
$S = 4.7\ 10^{-4}$ for ^{129}I
$S = 3.0\ 10^{-4}$ for ^{126}Sn
$H(^{79}Se) = 2.2\ 10^{-9}$

$H(^{129}I) = 5.8\ 10^{-8}$
$H(^{126}Sn) = 3.7\ 10^{-8}$

So, $H = 1.8\ 10^{-8} + 2.2\ 10^{-9} + 5.8\ 10^{-8} + 3.7\ 10^{-8} = 1.2\ 10^{-7}$

d) $Q = 0.5\ (2.8\ 10^{13} + 4.8\ 10^{14})$
$S = 1.1\ 10^{-9}$ for $^{14}CH_4$
$H = 6.4\ 10^{-9}$

e) As for (d), but add:

$Q = 0.5\ (2.8\ 10^{13} + 4.8\ 10^{14})$
$S = 5.4\ 10^{-8}$ for $^{14}CO_2$
$H(CO_2) = 3.2\ 10^{-7}$

So, $H = 3.2\ 10^{-7} + 6.4\ 10^{-9} = 3.3\ 10^{-7}$

f) As for (e), but add:

$Q = 2.22\ 10^{12}$ for ^{79}Se
$Q = 4.27\ 10^{11}$ for ^{129}I
$Q = 3.65\ 10^{12}$ for ^{126}Sn
$S = 1.8\ 10^{-5}$ for ^{79}Se
$S = 4.7\ 10^{-4}$ for ^{129}I
$S = 3.0\ 10^{-4}$ for ^{126}Sn
$H(^{79}Se) = 9.2\ 10^{-7}$
$H(^{129}I) = 4.6\ 10^{-6}$
$H(^{126}Sn) = 2.5\ 10^{-5}$

So, $H = 3.3\ 10^{-7} + 9.2\ 10^{-7} + 4.6\ 10^{-6} + 2.5\ 10^{-5} = 3.1\ 10^{-5}$

Conclusions

A certain amount of bulk plus radioactive gas release is likely to occur. Six scoping calculations give the following results.

Calculation	Gases/Nuclides	Wastes	Dose Rate (Sv/y)	Annual Risk*
a	$^{14}CH_4$	LLW	3.5 10^{-10}	7.0 10^{-12}
b	$^{14}CH_4/^{14}CO_2$	LLW	1.8 10^{-8}	3.6 10^{-10}
c	$^{14}CH_4/^{14}CO_2/^{79}Se/^{129}I/^{126}Sn$	LLW	1.2 10^{-7}	2.4 10^{-9}
d	$^{14}CH_4$	LLW/ILW	6.4 10^{-9}	1.3 10^{-10}
e	$^{14}CH_4/^{14}CO_2$	LLW/ILW	3.3 10^{-7}	6.6 10^{-9}
f	$^{14}CH_4/^{14}CO_2/^{79}Se/^{129}I/^{126}Sn$	LLW/ILW	3.1 10^{-5}	6.2 10^{-7}

Based on a risk coefficient of 0.02 Sv^{-1}.

For a minimum release period of 100 y and a minimum ventilation rate of 0.3 h^{-1}, the above values could be increased by up to a factor of 17.

<u>References</u>

International Commission on Radiological Protection (1975). Report of the Task Group on Reference Man. ICRP Publication 23. Pergamon Press, Oxford.

International Commission on Radiological Protection (1979-1982). Limits for Intakes of Radionuclides by Workers. Annals of the ICRP, Vol. 2(3/4), 3(1-4), 4(3/4), 5(1-6), 6(2/3), 7(1-3), 8(1-3).

Phipps, A.W., Kendall, G.M., Fell, T.P. and Harrison, J.D. (1990). Doses from radioactive methane. Submitted to Radiat. Prot. Dosim. (pers. comm. to M.C. Throne, 1990).

Rees, J.H. (1989). Gas Evolution and Migration in Repositories: Current Status, May 1989. Nirex Safety Series NSS/G112. Available from UK Nirex Ltd.

Rees, J.H. and Rodwell, W.R. Gas Evolution and Migration in Repositories - Current Status. Nirex Safety Series NSS/G104. Available from UK Nirex Ltd.

Thorne, M.C., Jackson, D. and Smith, A.D. (1986). Pharmacodynamic Models of Selected Toxic Chemicals in Man. Vol. 1., MTP Press, Lancaster.

Calculation Note: 4

Topic: Human Intrusion

Date Prepared: 22 May 1990

Author: M C Thorne

1. BACKGROUND

In Volume 3, Chapter 8, the following intrusive procedures are identified as being of potential relevance at the Dry Run 3 site.

a) Intrusion into the repository

- Exploration boreholes for coal
- Exploration boreholes for oil shale

b) Intrusion into the plume

- Exploration boreholes for coal
- Exploration boreholes for oil shale
- Mine access shaft

As no estimates of probabilities or radiological consequences of these various modes of intrusion was included as part of the main Dry Run 3 exercise, it was considered important to include some scoping calculations in support of the uncertainty and bias audit. However, because no information was available on likely radionuclide concentration profiles in the developing plume, attention is concentrated herein on direct intrusion into the repository. Also, to limit the number of calculations, no distinction is made between exploration boreholes for coal and those for oil shale.

In estimating the annual frequency of exploratory drilling into the repository, use has been made of NCB data on the frequency with which deep (>200 m) boreholes are drilled for coal exploration. In 1978, the year of maximum drilling rate, the total number of boreholes drilled was 153 over a prospective area of 3.6 10^4 km^2, corresponding to a drilling frequency of 4.25 10^{-3} holes/km^2/y (Jowett, J., SRD, pers. comm., 1990). Taking the repository area to be 4 km^2, this gives an upper bound to the frequency of intrusive drilling of 0.017 y^{-1}. This value is rounded down to 0.01 y^{-1} as a realistic estimate and indicates that it is virtually certain that exploratory drilling through the repository would occur within a few hundred years of site restrictions being lifted and planning controls having failed. (Of course, long-term national and international records of repository location might ensure effective planning controls for somewhat longer, but it is in conflict with the general principles of geological disposal of radioactive wastes to rely for safety on the positive actions of future generations.)

In mitigation, it should be noted that downhole logging of such boreholes might well include gamma detection. If this were the case, the anomalous nature of the repository would be flagged and actions might be taken to prevent human exposure. Again this depends on a positive response of future generations in identifying and reacting to the hazard.

Given that an exploratory intrusion appears likely to occur, it is relevant to estimate the likely consequences. A simplified approach is adopted and this is outlined below. Thus, two general types of actions are considered, designated types A and B, respectively. Type A relates primarily to the examination of small amounts of excavated material, whereas type B relates to actions which occur after excavated material has been spread over the surface of the land or removed from the site. In the following subsections, the various routes of exposure for each of these types of action is described.

1.1 TYPE A ACTIONS

1.1.1 External irradiation

Exposure is taken to occur from cylinders of extracted material. The relationship used is:

$$H_{ext} = 10^{-6}.S.V.n.T_{ext}.\sum y_j.H_j\ /d^2$$

where H_{ext} (Sv) is the effective dose equivalent from external irradiation;
S (Bq/m^3) is the radionuclide concentration in the extracted material;
V (m^3) is the volume of each sphere or cylinder of extracted material;
n (-) is the number of such objects;
T_{ext} (h) is the time of exposure;
d (m) is the average distance of the exposed individual from the objects;
y_j (-) is the yield of photon emissions in energy group j per transformation of the radionuclide;
H_j (mSv/h per kilotransformation/m^3) is the dose rate at 1 m from one of the objects, taking self-shielding into account.

In this calculation, the following shielding energy groups are adopted.

Group	Energy Interval (MeV)
1	0.00 - 0.14
2	0.14 - 0.40
3	0.40 - 0.62
4	0.62 - 0.90
5	0.90 - 1.10
6	1.10 - 2.00
7	2.00 - 2.40
8	2.40 - 2.60
9	>2.60

Values of H_j are available for cylinders of length 2 m and radius 0.05, 0.1, 0.2 and 0.5 m.

1.1.2 Ingestion

Exposure is taken to occur through inadvertent intake of material present on the hands as a result of handling contaminated material. The relationship used is:

$$H_{ing} = I_{ing}.m.S/\rho_e$$

where H_{ing} (Sv) is the effective dose equivalent from ingestion;
I_{ing} (Sv/Bq) is the dose per unit intake for ingestion by adults;
m (kg) is the mass of material ingested;
S (Bq/m^3) is the radionuclide concentration in the extracted material; and
ρ_e (kg/m^3) is the density of the extracted material.

1.1.3 Dust Inhalation

The relationship used for inhalation of dust is:

$$H_{inh} = I_{inh}.B.u.T_{inh}.S/\rho_e$$

where H_{inh} (Sv) is the effective dose equivalent from inhalation;
I_{inh} (Sv/Bq) is the dose per unit intake of the radionuclide for adults;
B (m^3/h) is the rate of intake of air by inspiration (60 x the minute volume);
u (kg/m^3) is the mass load of respirable dust in air;
T_{inh} (h) is the period of exposure;
S (Bq/m^3) is the radionuclide concentration in the extracted material; and
ρ_e (kg/m^3) is the density of the extracted material.

Values of I_{inh} for a range of Activity Median Aerodynamic Diameters (AMADs) have been taken from the RAPID database supplied by NRPB (Greenhalgh et al., 1986).

1.1.4 Radon Inhalation

Decay of Ra-226 in the extracted material would lead to release of Rn-222, which would accumulate together with its short-lived daughters in any enclosed space, e.g. a geotechnical laboratory for core examination. The relationship used is:

$$H_{Rn} = \lambda_{Rn}.S_{Ra\text{-}226}.V_T.f_{ex}^{Rn}.T_{Rn}.f_{inh\text{-}Rn}/(8760.K.V_I)$$

where H_{Rn} (Sv) is the effective dose equivalent from inhalation of Rn-222 (radon) and its daughters;
λ_{Rn} (s^{-1}) is the radioactive decay constant for Rn-222;
$S_{Ra\text{-}226}$ (Bq/m^3) is the concentration of Ra-226 in the extracted material;
V_T (m^3) is the total volume of extracted material, typically n.V as defined for external exposure;

f_{ex}^{Rn} is the fraction of produced Rn-222 that escapes from the extracted material (the exhaled fraction);
T_{Rn} (h) is the period of exposure;
$f_{inh\text{-}Rn}$ (Sv/y per Bq/m^3) relates Rn-222 plus daughter concentrations in air to rates of accumulation of effective dose equivalent;
K (s^{-1}) is the ventilation rate of the enclosed space;
V_I (m^3) is the volume of the enclosed space; and
8760 is the number of hours in a year.

The total dose is the sum of H_{ext}, H_{ing} and H_{inh}; plus H_{Rn} for Ra-226.

1.2 TYPE B ACTIONS

Type B actions are those which result in contamination of the site, its environs, or some other locality as a consequence of removal of contaminated material. In contrast to type A actions, the dose is not generally received only in the first year after intrusion and a more complex formalism is required.

The effective dose equivalent rate at time T from an event occurring at an earlier time τ, $H(\tau,T)$, can be decomposed as:

$$H(\tau,T) = F.\sigma(\tau,T)$$

where F (Sv/y per Bq/m^3) relates radionuclide concentration in soil to annual effective dose equivalent (taken as the sum of annual effective dose equivalent from external exposure and the committed effective dose equivalent from annual intakes of the radionuclide by ingestion and inhalation); and σ (Bq/m^3) is the concentration of the radionuclide in soil.

In general terms, $\sigma(\tau,\tau)$, the soil concentration immediately after intrusion through the full depth of waste is given by:

$$\sigma(\tau,\tau) = A_{ex}.Q(\tau)/(A_V.A_s.d_s)$$

where A_{ex} (m^2) is the excavated area;
A_v (m^2) is the total plan area of the repository;
$Q(\tau)$ (Bq) is the total inventory of the radionuclide in the repository;

A_s (m²) is the area of the surface over which the excavated material is spread;
d_s (m) is the depth of the soil zone in which the active material is distributed.

F values are calculated as the sum of contributions from external irradiation; inhalation of dust; and ingestion of soil, water, crops and animal products. The approaches adopted are set out below.

1.2.1 External Irradiation

The relevant equation is:

$$F_{ext} = O_f \sum_j y_j . H_j$$

where F_{ext} (Sv/y per Bq/m³) is the normalised dose rate from external exposure;
y_j (-) is the yield per transformation in photon energy group j; and
H_j (Sv/y per photon emitted per s per m³) is the dose rate from a slab source for photons in energy group j.

In order to overestimate rather than underestimate external doses, the slab source is taken to be infinite in areal extent and effectively infinite in thickness. A wet bulk density of 1500 kg/m³ is assumed. The relevant data are summarised below.

Group (j)	Energy Interval (MeV)	Hj
1	0.01 - 0.14	$3.02\ 10^{-11}$
2	0.14 - 0.40	$3.78\ 10^{-10}$
3	0.40 - 0.62	$8.42\ 10^{-10}$
4	0.62 - 0.90	$1.31\ 10^{-9}$
5	0.90 - 1.10	$1.73\ 10^{-9}$
6	1.10 - 2.00	$2.68\ 10^{-9}$
7	2.00 - 2.40	$3.76\ 10^{-9}$
8	2.40 - 2.60	$4.25\ 10^{-9}$
9	>2.60	$4.89\ 10^{-9}$

1.2.2 Dust Inhalation

The relevant equation is:

$$F_{inh} = I_{inh}.C_d.B_d.O_f/\rho_s$$

where F_{inh} (Sv/y per Bq/m³) is the normalised dose rate from inhalation exposure;
I_{inh} (Sv/Bq) is the dose per unit intake for the radionuclide by inhalation;
C_d (kg/m³) is the dust load in air above the contaminated area;
B_d (m³/y) is the rate of inspiration of air (minute volume x $5.26\ 10^5$);
O_f (-) is the fractional occupancy; and
ρ_s (kg/m³) is the dry bulk density of soil.

1.2.3 Radon Daughter Inhalation

The relevant equation is:

$$F_{inh}^{Rn} = \chi_{Rn}.f_{inh\text{-}Rn}.O_f/\rho_s$$

where F_{inh}^{Rn} (Sv/y per Bq/m^3) is the normalised dose rate from inhalation of radon daughters;
χ_{Rn} (Bq/m^3 per Bq/kg) is the equilibrium equivalent radon concentration in air corresponding to unit concentration of Ra-226 in soil;
$f_{inh\text{-}Rn}$ (Sv/y per Bq/m^3) relates Rn-222 plus daughter concentrations in air to rates of accumulation of effective dose equivalent;
O_f (-) is the fractional occupancy; and
ρ_s (kg/m^3) is the dry bulk density of soil.

This relationship is used only for Ra-226.

1.2.4 Ingestion of Drinking Water

It is not clear that drinking water would be derived from a contaminated area. Nevertheless, for completeness, a drinking water pathway is included, based on the assumption that the source of drinking water is in exchange equilibrium with the contaminated soil (as might be the case for a shallow well).

Thus, the relevant relationship is:

$$F_{ing}^{w} = I_{ing}.W/(\phi.v + \rho_s.K_d)$$

where F_{ing}^{w} (Sv/y per Bq/m^3) is the normalised dose rate from consumption of contaminated water;
I_{ing} (Sv/Bq) is the dose per unit intake for the radionuclide by ingestion;
W (m^3/y) is the annual consumption of water from the contaminated source (typically much less than the total rate of water consumption);
ϕ (-) is the fractional porosity of the soil zone;
v (-) is the fraction of that porosity which is water filled;
ρ_s (kg/m^3) is the dry bulk density of the soil; and
K_d (m^3/kg d.w.) is the distribution coefficient for the radionuclide in soil.

The derivation of the above equation is clarified by noting that:

$$C_s = K_d.C_w$$

where C_s (Bq/kg) is the radionuclide concentration associated with the solid phase of soil; and
C_w (Bq/m^3) is the radionuclide concentration associated with soil water.

Also:

$$C_T = \phi.v.C_w + \rho_s.C_s$$

where C_T (Bq/m^3) is the total concentration of the radionuclide in soil.

Hence:

$$C_w = C_T/(\phi.v + \rho_s.K_d)$$

1.2.5 Ingestion of Soil

The adventitious or deliberate ingestion of soil/dust is included in the model using the relationship:

$$F^s_{ing} = I_{ing}.M_s/\rho_s$$

where F^s_{ing} (Sv/y per Bq/m^3) is the normalised dose rate from consumption of soil/dust;
I_{ing} (Sv/Bq) is the dose per unit intake for the radionuclide by ingestion;
M_s (kg d.w./y) is the annual consumption of soil/dust; and
ρ_s (kg/m^3) is the dry bulk density of the soil.

where F_{ing}^{milk} (Sv/y per Bq/m^3) is the normalised dose rate from consumption of cow's milk;
TF_{milk} (d/l) is the equilibrium transfer factor from diet to milk;
M_{milk} (l/y) is the annual human consumption of milk; and
all other quantities are as defined previously.

Both M_{milk} and I_{ing} are age dependent.

2. SCOPING CALCULATIONS

Throughout, the characteristics of the ILW inventory at 100 years after closure are used for type A actions, whereas the sum of the LLW and ILW inventories is used for type B actions. As the radiological consequences of type A actions are determined by radionuclide concentrations in the wastes, whereas the radiological consequences of type B actions are determined by the total activity extracted, these assumptions maximise the estimated radiological impacts of intrusion.

2.1 TYPE A ACTIONS

The exposed individual is taken to be a worker in a geotechnical laboratory examining cores taken through the full waste thickness. Cores are assumed to remain in the laboratory for a working week (40 h) and 5 such cores are assumed to be present at any one time. Cores are take to be 0.1 m in diameter and 2 m long.

2.1.1 External Irradiation

$$V = \pi(0.05)^2\, 2 = 0.0157 \text{ m}^3$$

$$n = 5 \quad T_{ext} = 40 \quad d = 1$$

Thus,

$$H_{ext} = 3.14\ 10^{-6}.S.\sum y_j H_j$$

Values of S are derived by taking the inventory given in Table 3 of the main text and dividing by the internal volume of the repository for ILW (96000 x π x 2 x 2 = 1.206 10^6 m^3, c.f. Volume 1, Table 6.3). Values of $y_j.H_j$ were calculated using data from ICRP Publication 38 (ICRP, 1983), using standard techniques. Results are summarised below.

Radionuclide	S	y_jH_j	$H_{ext}(Sv)$
C-14	$3.97\ 10^{8}$	-	-
Cl-36	$4.83\ 10^{5}$	$1.45\ 10^{-11}$	$2.20\ 10^{-11}$
Se-79	$1.83\ 10^{6}$	-	-
Tc-99	$1.54\ 10^{8}$	-	-
Sn-126	$3.02\ 10^{6}$	$1.48\ 10^{-7}$	$1.40\ 10^{-6}$
I-129	$3.50\ 10^{5}$	$1.64\ 10^{-9}$	$1.80\ 10^{-9}$
Cs-135	$4.63\ 10^{6}$	-	-
Pb-210	$8.57\ 10^{5}$	$3.21\ 10^{-10}$	$8.64\ 10^{-10}$
Ra-226	$8.74\ 10^{5}$	$1.62\ 10^{-7}$	$4.45\ 10^{-7}$
Th-229	$3.56\ 10^{3}$	$5.95\ 10^{-8}$	$6.65\ 10^{-10}$
Th-230	$1.98\ 10^{4}$	$1.07\ 10^{-10}$	$6.65\ 10^{-12}$
Pa-231	$3.15\ 10^{4}$	$3.48\ 10^{-9}$	$3.44\ 10^{-10}$
U-233	$8.37\ 10^{4}$	$9.16\ 10^{-11}$	$2.41\ 10^{-11}$
U-234	$2.02\ 10^{7}$	$1.11\ 10^{-10}$	$7.04\ 10^{-9}$
U-235	$1.45\ 10^{6}$	$1.61\ 10^{-8}$	$7.33\ 10^{-8}$
U-238	$1.59\ 10^{7}$	$2.93\ 10^{-7}$	$1.46\ 10^{-5}$
Np-237	$2.82\ 10^{7}$	$7.91\ 10^{-8}$	$7.00\ 10^{-6}$
Pu-239	$4.99\ 10^{9}$	$5.39\ 10^{-11}$	$8.45\ 10^{-7}$
Pu-242	$2.83\ 10^{7}$	$9.60\ 10^{-11}$	$8.53\ 10^{-9}$
Am-243	$2.61\ 10^{7}$	$1.78\ 10^{-8}$	$1.46\ 10^{-6}$

Thus, the total external dose is estimated to be $2.58\ 10^{-5}$ Sv.

2.1.2 Ingestion

The mass of material ingested is taken to be 0.05 kg, based on 1 g/d for 5 days. The density of extracted material is taken to be that of concrete (2350 kg/m^3). Thus:

$$H_{ing} = 2.13\ 10^{-6}.S.I_{ing}$$

Values of I_{ing} for adults were taken from the RAPID database (Greenhalgh et al., 1986). Results are summarised below.

Radionuclide	S	I_{ing}	H_{ing} (Sv)
C-14	$3.97\ 10^{8}$	$5.60\ 10^{-10}$	$4.74\ 10^{-7}$
Cl-36	$4.83\ 10^{5}$	$8.20\ 10^{-10}$	$8.44\ 10^{-10}$
Se-79	$1.83\ 10^{6}$	$2.30\ 10^{-9}$	$8.97\ 10^{-9}$
Tc-99	$1.54\ 10^{8}$	$3.50\ 10^{-10}$	$1.15\ 10^{-7}$
Sn-126	$3.02\ 10^{6}$	$5.10\ 10^{-9}$	$3.28\ 10^{-8}$
I-129	$3.50\ 10^{5}$	$6.60\ 10^{-8}$	$4.92\ 10^{-8}$
Cs-135	$4.63\ 10^{6}$	$1.70\ 10^{-9}$	$1.68\ 10^{-8}$
Pb-210	$8.57\ 10^{5}$	$1.40\ 10^{-6}$	$2.56\ 10^{-6}$
Ra-226	$8.74\ 10^{5}$	$3.00\ 10^{-7}$	$5.58\ 10^{-7}$
Th-229	$3.56\ 10^{3}$	$1.10\ 10^{-6}$	$8.34\ 10^{-9}$
Th-230	$1.98\ 10^{4}$	$1.40\ 10^{-7}$	$5.90\ 10^{-9}$
Pa-231	$3.15\ 10^{4}$	$2.90\ 10^{-6}$	$1.95\ 10^{-7}$
U-233	$8.37\ 10^{4}$	$7.10\ 10^{-8}$	$1.27\ 10^{-8}$
U-234	$2.02\ 10^{7}$	$7.00\ 10^{-8}$	$3.01\ 10^{-6}$
U-235	$1.45\ 10^{6}$	$6.80\ 10^{-8}$	$2.10\ 10^{-7}$
U-238	$1.59\ 10^{7}$	$6.70\ 10^{-8}$	$2.27\ 10^{-6}$
Np-237	$2.82\ 10^{7}$	$1.10\ 10^{-6}$	$6.61\ 10^{-5}$
Pu-239	$4.99\ 10^{9}$	$9.50\ 10^{-7}$	$1.00\ 10^{-2}$
Pu-242	$2.83\ 10^{7}$	$9.00\ 10^{-7}$	$5.43\ 10^{-5}$
Am-243	$2.61\ 10^{7}$	$9.80\ 10^{-7}$	$5.45\ 10^{-5}$

Thus, the total ingestion dose is estimated to be $1.02\ 10^{-2}$ Sv, almost entirely due to ^{239}Pu.

2.1.3 Dust Inhalation

Taking B = 1.2 m^3/h (ICRP, 1975), u = $1\ 10^{-6}$ (20% of the Threshold Limit Value for respirable nuisance particulates, since geotechnical laboratories are known to be dusty environments), T_{inh} = 40 h and ρ_e = 2350 kg/m^3.

$$H_{inh} = 2.04\ 10^{-8}.S.I_{inh}$$

Values of I_{inh} for adults for an Activity Median Aerodynamic Diameter of 1 μm were taken from the RAPID database (Greenhalgh et al., 1986). Results are summarised below.

Radionuclide	S	I_{inh}	H_{inh} (Sv)
C-14	3.97 10^{8}	5.60 10^{-10}	4.54 10^{-9}
Cl-36	4.83 10^{5}	5.50 10^{-9}	5.42 10^{-11}
Se-79	1.83 10^{6}	1.70 10^{-9}	6.35 10^{-11}
Tc-99	1.54 10^{8}	2.00 10^{-9}	6.28 10^{-9}
Sn-126	3.02 10^{6}	2.30 10^{-8}	1.42 10^{-9}
I-129	3.50 10^{5}	4.20 10^{-8}	3.00 10^{-10}
Cs-135	4.63 10^{6}	1.10 10^{-9}	1.04 10^{-10}
Pb-210	8.57 10^{5}	3.50 10^{-6}	6.12 10^{-8}
Ra-226	8.74 10^{5}	2.10 10^{-6}	3.74 10^{-8}
Th-229	3.56 10^{3}	5.70 10^{-4}	4.14 10^{-8}
Th-230	1.98 10^{4}	8.60 10^{-5}	3.47 10^{-8}
Pa-231	3.15 10^{4}	3.50 10^{-4}	2.25 10^{-7}
U-233	8.37 10^{4}	3.60 10^{-5}	6.15 10^{-8}
U-234	2.02 10^{7}	3.50 10^{-5}	1.44 10^{-5}
U-235	1.45 10^{6}	3.30 10^{-5}	9.76 10^{-7}
U-238	1.59 10^{7}	3.10 10^{-5}	1.01 10^{-5}
Np-237	2.82 10^{7}	1.30 10^{-4}	7.48 10^{-5}
Pu-239	4.99 10^{9}	1.10 10^{-4}	1.12 10^{-2}
Pu-242	2.83 10^{7}	1.10 10^{-4}	6.35 10^{-5}
Am-243	2.61 10^{7}	1.20 10^{-4}	6.39 10^{-5}

Thus, the total inhalation dose is estimated to be 1.14 10^{-2} Sv, almost entirely due to ^{239}Pu.

2.1.4 Radon Inhalation

Relevant data are summarised below.

λ_{Rn} = 2.10 10^{-6} s^{-1}
V_T = n x V = 5 x 0.0157 = 0.0785 m^3
f_{ex}^{Rn} = 1.0 (pessimistic assumption)
T_{Rn} = 40 h
f_{inh-Rn} = 5.26 10^{-5} Sv/y per Bq/m^3
K = 2.778 10^{-4} s^{-1} ($\equiv 1$ h^{-1})
V_1 = 10^2 m^3 (typical laboratory volume)

The value of f_{inh-Rn} is taken from ICRP Publication 50 (ICRP, 1987), Table 3.2. For an equilibrium equivalent ^{222}Rn concentration in air of C' Bq/m^3, the indoor dose rate is 1.0 10^{-8}C' Sv/h. However, this value applies to the equilibrium equivalent ^{222}Rn concentration (i.e. it assumes full equilibrium between ^{222}Rn and its short-lived daughters). The equilibrium equivalent ^{222}Rn concentration is related to the actual ^{222}Rn concentration by an F factor, which is typically 0.3 to 0.6 for indoor air. Adopting a value of 0.6, gives a dose factor of 6 10^{-9} Sv/h per Bq/m^3 or 5.26 10^{-5} Sv/y per Bq/m^3.

On the basis of the above:

$$H_{Rn} = 1.43\ 10^{-12}\ .\ S_{Ra\text{-}226} = 1.25\ 10^{-6}\ Sv.$$

2.1.5 Summary

For type A actions, a geotechnical worker examining cores is used to derive a calculational basis. Estimated doses to this worker via various routes are listed below.

Route	Effective Dose Equivalent (Sv)
External irradiation	$2.58\ 10^{-5}$
Ingestion	$1.02\ 10^{-2}$
Inhalation	$1.14\ 10^{-2}$
Radon inhalation	$1.25\ 10^{-6}$

All four routes are affected equally, and in linear fashion, by the period of exposure, which could be in error by a factor $\sim\pm 2$. External irradiation and radon inhalation are affected by the total volume of active material present in the laboratory, this could be in error by a factor $\sim\pm 5$. External irradiation is also affected by assumptions as to typical distance from the cores, this could be in error by a factor ~2 in either direction, causing a factor ~4 in either direction in the result obtained. Radon inhalation rate is affected by laboratory volume (factor $\sim\pm 3$), ventilation rate (factor $\sim\pm 3$) and fractional exhalation (unknown factor, pessimistic upper bound value of unity adopted). None of these errors is sufficiently large as to make external irradiation or radon inhalation dominate over the other two routes of exposure.

The main uncertain factor with ingestion is the mass of material ingested. This could be in error by an order of magnitude in either direction, and there are no readily available data by which the assumption made can be checked. Similarly, for inhalation, the dust load in air is the major uncertain factor. It is unlikely to be less than 0.5 the adopted value, but could be a factor of 5 higher.

2.2 TYPE B ACTIONS

In this case, the exposed individual is taken to be a householder self-sufficient in vegetable production living on the contaminated area. Ingestion of contaminated drinking water, meat, meat products and milk is not included in the calculations, though the formalism is provided above should such extension be required in future studies. Pessimistically, occupation is assumed to commence immediately after the intrusion event (as might occur if the householder had permitted an exploratory borehole to be drilled on his land).

2.2.1 Initial Levels of Soil Contamination

The soil concentration immediately after intrusion, $\sigma(\tau,\tau)$, is given by:

$$\sigma(\tau,\tau) = A_{cx}.Q(\tau)/(A_v.A_s.d_s)$$

where the various quantities are as defined in Section 1.2.

Taking a core of diameter 0.1 m, A_{cx} = 0.00785 m^2.

A_v may be taken as 4 10^6 m^2 (Volume 1, Section 6).
A_s is reasonably taken as 10^3 m^2, since this area is adequate for self-sufficiency in vegetable production.
d_s is reasonably taken as 0.3 m, corresponding to the depth typically disturbed by gardening practices, e.g. digging.

Thus:

$$\sigma(\tau,\tau) = 6.54\ 10^{-12}.Q(\tau)$$

For τ = 100 y, values of $\sigma(\tau,\tau)$ are as listed below.

Inventory at 100 y (Bq)				
Radionuclide				σ(Bq/m³)
	LLW	ILW	Total	
C-14	$2.766\ 10^{13}$	$4.792\ 10^{14}$	$5.069\ 10^{14}$	$3.32\ 10^{3}$
Cl-36	$1.820\ 10^{10}$	$5.829\ 10^{11}$	$6.011\ 10^{11}$	$3.93\ 10^{0}$
Se-79	$5.404\ 10^{9}$	$2.208\ 10^{12}$	$2.213\ 10^{12}$	$1.45\ 10^{1}$
Tc-99	$5.658\ 10^{9}$	$1.859\ 10^{14}$	$1.859\ 10^{14}$	$1.22\ 10^{3}$
Sn-126	$5.416\ 10^{9}$	$3.637\ 10^{12}$	$3.642\ 10^{12}$	$2.38\ 10^{1}$
I-129	$5.400\ 10^{9}$	$4.220\ 10^{11}$	$4.274\ 10^{11}$	$2.80\ 10^{0}$
Cs-135	$5.410\ 10^{9}$	$5.580\ 10^{12}$	$5.585\ 10^{12}$	$3.65\ 10^{1}$
Pb-210	$9.693\ 10^{10}$	$1.033\ 10^{12}$	$1.130\ 10^{12}$	$7.39\ 10^{0}$
Ra-226	$8.138\ 10^{10}$	$1.054\ 10^{12}$	$1.135\ 10^{12}$	$7.42\ 10^{0}$
Th-229	$5.400\ 10^{11}$	$4.297\ 10^{9}$	$5.443\ 10^{11}$	$3.56\ 10^{0}$
Th-230	$5.395\ 10^{11}$	$2.388\ 10^{10}$	$5.634\ 10^{11}$	$3.68\ 10^{0}$
Pa-231	$5.389\ 10^{11}$	$3.803\ 10^{10}$	$5.769\ 10^{11}$	$3.77\ 10^{0}$
U-233	$5.398\ 10^{11}$	$1.009\ 10^{11}$	$6.407\ 10^{11}$	$4.19\ 10^{0}$
U-234	$5.860\ 10^{9}$	$2.442\ 10^{13}$	$2.443\ 10^{13}$	$1.60\ 10^{2}$
U-235	$7.120\ 10^{9}$	$1.751\ 10^{12}$	$1.758\ 10^{12}$	$1.15\ 10^{1}$
U-238	$9.180\ 10^{10}$	$1.920\ 10^{13}$	$1.929\ 10^{13}$	$1.26\ 10^{2}$
Np-237	$5.507\ 10^{9}$	$3.404\ 10^{13}$	$3.405\ 10^{13}$	$2.23\ 10^{2}$
Pu-239	$1.715\ 10^{11}$	$6.023\ 10^{15}$	$6.023\ 10^{15}$	$3.94\ 10^{4}$
Pu-242	$5.589\ 10^{9}$	$3.409\ 10^{13}$	$3.410\ 10^{13}$	$2.23\ 10^{2}$
Am-243	$4.706\ 10^{8}$	$3.150\ 10^{13}$	$3.150\ 10^{13}$	$2.06\ 10^{2}$

2.2.2 External Irradiation

The initial dose rate, H_{ext} (Sv/y), is given by:

$$H_{ext} = \sigma . O_f . \sum_j y_j H_j$$

where the various symbols are as defined in Section 1.2.1. O_f is taken as unity, values of H_j are given in Section 1.2.1 and values of y_j are derived from ICRP Publication 38 (ICRP, 1983). Results are summarised below.

Radionuclide	σ	$\Sigma y_j H_j$	H_{ext} (Sv/y)
C-14	$3.23\ 10^{3}$	-	-
Cl-36	$3.93\ 10^{0}$	$2.52\ 10^{-13}$	$9.90\ 10^{-13}$
Se-79	$1.45\ 10^{1}$	-	-
Tc-99	$1.22\ 10^{3}$	-	-
Sn-126	$2.38\ 10^{1}$	$2.66\ 10^{-9}$	$6.33\ 10^{-8}$
I-129	$2.80\ 10^{0}$	$1.06\ 10^{-11}$	$2.97\ 10^{-11}$
Cs-135	$3.65\ 10^{1}$	-	-
Pb-210	$7.39\ 10^{0}$	$2.09\ 10^{-12}$	$1.54\ 10^{-11}$
Ra-226	$7.42\ 10^{0}$	$2.84\ 10^{-9}$	$2.11\ 10^{-8}$
Th-229	$3.56\ 10^{0}$	$9.26\ 10^{-10}$	$3.30\ 10^{-9}$
Th-230	$3.68\ 10^{0}$	$7.75\ 10^{-13}$	$2.85\ 10^{-12}$
Pa-231	$3.77\ 10^{0}$	$4.28\ 10^{-11}$	$1.61\ 10^{-10}$
U-233	$4.19\ 10^{0}$	$7.16\ 10^{-13}$	$3.00\ 10^{-12}$
U-234	$1.60\ 10^{2}$	$7.22\ 10^{-13}$	$1.16\ 10^{-10}$
U-235	$1.15\ 10^{1}$	$2.11\ 10^{-10}$	$2.43\ 10^{-9}$
U-238	$1.26\ 10^{2}$	$5.33\ 10^{-9}$	$6.72\ 10^{-7}$
Np-237	$2.23\ 10^{2}$	$1.29\ 10^{-9}$	$2.88\ 10^{-7}$
Pu-239	$3.94\ 10^{4}$	$3.69\ 10^{-13}$	$1.45\ 10^{-8}$
Pu-242	$2.23\ 10^{2}$	$6.22\ 10^{-13}$	$1.39\ 10^{-10}$
Am-243	$2.06\ 10^{2}$	$1.82\ 10^{-10}$	$3.75\ 10^{-8}$

Thus, the total dose rate is estimated to be $1.10\ 10^{-6}$ Sv/y, mainly from U-238 and Np-237.

2.2.3 Dust Inhalation

The initial dose rate, H_{inh} (Sv/y), is given by:

$$H_{inh} = \sigma . I_{inh} . C_d . B_d O_f / \rho_s$$

where the various symbols are as defined in Section 1.2.2.

Ambient dust loads are typically ~100 $\mu g/m^3$, but this includes a substantial proportion of material not derived directly from the underlying ground. A value of 30 $\mu g/m^3$ (3 10^{-8} kg/m^3) is adopted for C_d recognising that this could be in error by an order of magnitude in either direction.

B_d is taken as 8400 m^3/y (ICRP, 1975)
O_f is taken as unity
ρ_s is taken as 1300 kg/m^3.

Thus:

$$H_{inh} = 1.94\ 10^{-7}\ \sigma . I_{inh}$$

Using the values of σ and I_{inh} listed above (Sections 2.2.1 and 2.1.3, respectively), results are as summarised below.

Radionuclide	σ	I_{inh}	H_{inh} (Sv/y)
C-14	3.32 10^3	5.60 10^{-10}	3.61 10^{-13}
Cl-36	3.93 10^0	5.50 10^{-9}	4.19 10^{-15}
Se-79	1.45 10^1	1.70 10^{-9}	4.78 10^{-15}
Tc-99	1.22 10^3	2.00 10^{-9}	4.73 10^{-13}
Sn-126	2.38 10^1	2.30 10^{-8}	1.06 10^{-13}
I-129	2.80 10^0	4.20 10^{-8}	2.28 10^{-14}
Cs-135	3.65 10^1	1.10 10^{-9}	7.79 10^{-15}
Pb-210	7.39 10^0	3.50 10^{-6}	5.02 10^{-12}
Ra-226	7.42 10^0	2.10 10^{-6}	3.02 10^{-12}
Th-229	3.56 10^0	5.70 10^{-4}	3.94 10^{-10}
Th-230	3.68 10^0	8.60 10^{-5}	6.14 10^{-11}
Pa-231	3.77 10^0	3.50 10^{-4}	2.56 10^{-10}
U-233	4.19 10^0	3.60 10^{-5}	2.93 10^{-11}
U-234	1.60 10^2	3.50 10^{-5}	1.09 10^{-9}
U-235	1.15 10^1	3.30 10^{-5}	7.36 10^{-11}
U-238	1.26 10^2	3.10 10^{-5}	7.58 10^{-10}
Np-237	2.23 10^2	1.30 10^{-4}	5.62 10^{-9}
Pu-239	3.94 10^4	1.10 10^{-4}	8.41 10^{-7}
Pu-242	2.23 10^2	1.10 10^{-4}	4.76 10^{-9}
Am-243	2.06 10^2	1.20 10^{-4}	4.80 10^{-9}

Thus, the total dose rate is estimated to be 8.59 10^{-7} Sv/y, mainly from Pu-239.

2.2.4 Radon Daughter Inhalation

The initial dose rate, H_{Rn} (Sv/y),is given by:

$$H_{Rn} = \sigma.\chi_{Rn}.f_{inh-Rn}.O_f/\rho_s$$

where the various symbols are as defined in Section 1.2.3.

Assuming, pessimistically, that exposure is indoors in a house built over the contaminated area:

σ = 7.42 Bq/m^3 f_{inh-Rn} = 5.26 10^{-5} Sv/y per Bq/m^3 (Section 2.1.4)

O_f = 1.0 ρ_s = 1500 kg/m^3

Typical soil levels of ^{226}Ra are 0.6 pCi/g or 22 Bq/kg (NCRP, 1984), while typical indoor levels of ^{222}Rn in the UK are 23 Bq/m^3 (NRPB). Thus, χ_{Rn} may reasonably be taken as unity.

Hence, H_{Rn} = 2.54 10^{-7} Sv/y.

2.2.5 Ingestion of Soil

The initial dose rate, H_{soil} (Sv/y), is given by:

$$H_{soil} = \sigma.I_{ing}.M_s/\rho_s$$

where the various symbols are as defined in Section 1.2.5.

As for inhalation (Section 2.2.3), ρ_s is taken as 1300 kg/m^3.

Because titanium is present in high concentrations in soils [~5000 ppm, Krauskopf (1979)], but is virtually entirely excluded from plants, it is a convenient measure of soil contamination of diet and is often used as such in animal studies. For man, dietary intakes of titanium are estimated to be ~0.85 mg/d (ICRP, 1975), corresponding to 0.17 g of soil per d. Thus, M_s is taken as 0.062 kg/y and:

$$H_{soil} = 4.77\ 10^{-5}\ \sigma.I_{ing}$$

Using the values of σ and I_{ing} listed above (Sections 2.2.1 and 2.1.2), results are as summarised below.

Radionuclide	σ	I_{ing}	H_{soil} (Sv/y)
C-14	$3.23\ 10^{3}$	$5.60\ 10^{-10}$	$8.63\ 10^{-11}$
Cl-36	$3.93\ 10^{0}$	$8.20\ 10^{-10}$	$1.54\ 10^{-13}$
Se-79	$1.45\ 10^{1}$	$2.30\ 10^{-9}$	$1.59\ 10^{-12}$
Tc-99	$1.22\ 10^{3}$	$3.50\ 10^{-10}$	$2.04\ 10^{-11}$
Sn-126	$2.38\ 10^{1}$	$5.10\ 10^{-9}$	$5.79\ 10^{-12}$
I-129	$2.80\ 10^{0}$	$6.60\ 10^{-8}$	$8.81\ 10^{-12}$
Cs-135	$3.65\ 10^{1}$	$1.70\ 10^{-9}$	$2.96\ 10^{-12}$
Pb-210	$7.39\ 10^{0}$	$1.40\ 10^{-6}$	$4.94\ 10^{-10}$
Ra-226	$7.42\ 10^{0}$	$3.00\ 10^{-7}$	$1.06\ 10^{-10}$
Th-229	$3.56\ 10^{0}$	$1.10\ 10^{-6}$	$1.87\ 10^{-10}$
Th-230	$3.68\ 10^{0}$	$1.40\ 10^{-7}$	$2.46\ 10^{-11}$
Pa-231	$3.77\ 10^{0}$	$2.90\ 10^{-6}$	$5.22\ 10^{-10}$
U-233	$4.19\ 10^{0}$	$7.10\ 10^{-8}$	$1.42\ 10^{-11}$
U-234	$1.60\ 10^{2}$	$7.00\ 10^{-8}$	$5.34\ 10^{-10}$
U-235	$1.15\ 10^{1}$	$6.80\ 10^{-8}$	$3.73\ 10^{-11}$
U-238	$1.26\ 10^{2}$	$6.70\ 10^{-8}$	$4.03\ 10^{-10}$
Np-237	$2.23\ 10^{2}$	$1.10\ 10^{-6}$	$1.17\ 10^{-8}$
Pu-239	$3.94\ 10^{4}$	$9.50\ 10^{-7}$	$1.79\ 10^{-6}$
Pu-242	$2.23\ 10^{2}$	$9.00\ 10^{-7}$	$9.57\ 10^{-9}$
Am-243	$2.06\ 10^{2}$	$9.80\ 10^{-7}$	$9.63\ 10^{-9}$

Thus, the total dose rate is estimated to be $1.82\ 10^{-6}$ Sv/y, mainly from ^{239}Pu.

2.2.6 Ingestion of Vegetables

The initial dose rate, H_{veg} (Sv/y), is given by:

$$H_{veg} = \sigma.I_{ing}.CR.M_c/\rho_s$$

where the various symobls are as defined in Section 1.2.6.

A value of 0.316 kg f.w./d has been given for the typical consumption of vegetables and fruit in Europe (ICRP, 1975). Using this as a basis, M_c = 115.4 kg f.w./y. As above, ρ_s is taken as 1300 kg/m³. Thus:

$$H_{veg} = 0.0888.\sigma.I_{ing}.CR$$

Values of CR are those for the above-ground parts of non-leguminous leafy vegetables given by Jackson (1984). Values of σ and I_{ing} are as listed in Section 2.2.5. A summary of results obtained is given below.

Radionuclide	σ	I_{ing}	CR	H_{veg} (Sv/y)
C-14	$3.23\ 10^{3}$	$5.60\ 10^{-10}$	0.125	$2.01\ 10^{-8}$
Cl-36	$3.93\ 10^{0}$	$8.20\ 10^{-10}$	5.0	$1.43\ 10^{-9}$
Se-79	$1.45\ 10^{1}$	$2.30\ 10^{-9}$	0.25	$7.40\ 10^{-10}$
Tc-99	$1.22\ 10^{3}$	$3.50\ 10^{-10}$	200	$7.58\ 10^{-6}$
Sn-126	$2.38\ 10^{1}$	$5.10\ 10^{-9}$	0.1	$1.08\ 10^{-9}$
I-129	$2.80\ 10^{0}$	$6.60\ 10^{-8}$	0.1	$1.64\ 10^{-9}$
Cs-135	$3.65\ 10^{1}$	$1.70\ 10^{-9}$	0.2	$1.10\ 10^{-9}$
Pb-210	$7.39\ 10^{0}$	$1.40\ 10^{-6}$	0.1	$9.19\ 10^{-8}$
Ra-226	$7.42\ 10^{0}$	$3.00\ 10^{-7}$	0.6	$1.19\ 10^{-7}$
Th-229	$3.56\ 10^{0}$	$1.10\ 10^{-6}$	0.01	$3.48\ 10^{-9}$
Th-230	$3.68\ 10^{0}$	$1.40\ 10^{-7}$	0.01	$4.57\ 10^{-10}$
Pa-231	$3.77\ 10^{0}$	$2.90\ 10^{-6}$	0.021	$2.04\ 10^{-8}$
U-233	$4.19\ 10^{0}$	$7.10\ 10^{-8}$	$1\ 10^{-4}$	$2.64\ 10^{-12}$
U-234	$1.60\ 10^{2}$	$7.00\ 10^{-8}$	$1\ 10^{-4}$	$9.95\ 10^{-11}$
U-235	$1.15\ 10^{1}$	$6.80\ 10^{-8}$	$1\ 10^{-4}$	$6.94\ 10^{-12}$
U-238	$1.26\ 10^{2}$	$6.70\ 10^{-8}$	$1\ 10^{-4}$	$7.49\ 10^{-11}$
Np-237	$2.23\ 10^{2}$	$1.10\ 10^{-6}$	0.021	$4.57\ 10^{-7}$
Pu-239	$3.94\ 10^{4}$	$9.50\ 10^{-7}$	$6\ 10^{-5}$	$1.99\ 10^{-7}$
Pu-242	$2.23\ 10^{2}$	$9.00\ 10^{-7}$	$6\ 10^{-5}$	$1.07\ 10^{-9}$
Am-243	$2.06\ 10^{2}$	$9.80\ 10^{-7}$	0.02*	$3.59\ 10^{-7}$

* Value given as 2.0 by Jackson (1984). Reference to Coughtrey et al. (1984) indicates this to be an error.

Thus, the total dose rate is estimated as $8.86\ 10^{-6}$ Sv/y.

2.2.7 Summary

For Type B actions, a householder self-sufficient in vegetable production is used to derive a calculational basis. Estimated dose rates to this householder in the first year following intrusion are listed below.

Route	Effective Dose Equivalent Rate (Sv/y)
External irradiation	$1.10\ 10^{-6}$
Inhalation	$8.59\ 10^{-7}$
Radon daughter inhalation	$2.54\ 10^{-7}$
Ingestion of soil	$1.82\ 10^{-6}$
Ingestion of vegetables	$8.86\ 10^{-6}$

Given the characteristics of the exposed individual and the area and type of contamination, the initial dose rate from external irradiation is well-defined and sets a lower limit to the total initial dose rate. The value for inhalation is less well established because of uncertainties in the locally maintained dust load in air. Errors of up to an order of magnitude in either direction are possible. The radon daughter pathway dose rate is almost certainly over-estimated, but the degree of over-estimation is difficult to quantify. The soil ingestion pathway is critically dependent upon assumptions relating to the mass of soil ingested. The value adopted was 0.17 g/d, which could be in error by an order of magnitude in either direction. For ingestion of vegetables, the main uncertainty is in the concentration ratios adopted. In particular, Tc-99 is the dominant radionuclide and the concentration ratio adopted is almost certainly an over-estimate (Coughtrey et al., 1983). Thus, overall the initial dose rate is likely to be in the range 10^{-6} to $2\ 10^{-5}$ Sv/y.

Because of the long residence times of many of the radionuclides in soils, the initial dose rates listed above can be expected to persist for at least several decades, indeed a mean residence time in soil of ≥ 100 years seems likely for the actinides.

3. CONCLUSIONS

The most likely type of intrusion is considered to be that associated with exploratory drilling for reserves of coal or oil shale. Based on NCB data, a realistic estimate of the frequency of such exploratory drilling is 0.01 y^{-1}, indicating that it is virtually certain that exploratory drilling through the repository would occur within a few hundred years of site restrictions being lifted and planning controls having failed.

In mitigation, downhole logging of such boreholes might identify the anomalous nature of the repository and cause actions to be taken to prevent human exposures.

Limitation of exploratory drilling subsequent to site restrictions being lifted, and identification and response to the anomalous nature of the repository during exploratory drilling, require positive safety-related responses by future generations. The desire to dispense with the need for such positive safety related responses is seen as part of the rationale for deep geological disposal of radioactive wastes.

Two general types of intrusive actions are considered. Type A relates primarily to the examination of small amounts of excavated material, whereas type B relates to actions which occur after excavated material has been spread over the surface of the land or removed from the site. For type A actions, the exposed individual is taken to be a worker in a geotechnical laboratory examining cores. Estimated committed effective dose equivalents to such a worker, from the adopted inventory, are listed below.

Route	Effective Dose Equivalent (Sv/y)
External irradiation	$2.58\ 10^{-5}$
Inhalation	$1.02\ 10^{-2}$
Ingestion	$1.14\ 10^{-2}$
Radon inhalation	$1.25\ 10^{-6}$

Uncertainties in respect of these values can be summarised as follows.

Uncertainty	Scale Factor			
	External	Ingestion	Inhalation	Radon
Period of exposure	0.5 to 2.0	0.5 to 2.0	0.5 to 2.0	0.5 to 2.0
Volume of active material	0.2 to 5.0	N/A	N/A	0.2 to 5.0
Distance from cores	0.25 to 4.0	N/A	N/A	N/A
Laboratory volume	N/A	N/A	N/A	0.33 to 3.0
Ventilation rate	N/A	N/A	N/A	0.33 to 3.0
Fractional exhalation	N/A	N/A	N/A	<1
Mass ingested	N/A	0.1 to 10.0	N/A	N/A
Dust load in air	N/A	N/A	0.5 to 5.0	N/A

Thus, the total committed effective dose equivalent is estimated to be in the range $6\ 10^{-3}$ to $1.6\ 10^{-1}$ Sv, with a best estimate of $2.2\ 10^{-2}$ Sv. This dose should be taken to be incurred in the year of intrusion. Taking a risk factor of $2\ 10^{-2}\ Sv^{-1}$ and an intrusion frequency of $0.01\ y^{-1}$, the annual risk is $-4.4\ 10^{-6}$ (range $1.2\ 10^{-6}$ to $3.2\ 10^{-5}$).

For type B actions, the exposed individual is taken to be a householder self-sufficient in vegetable production living on the contaminated area. Ingestion of contaminated drinking water, meat, meat products and milk is not included in the calculations.

Estimated committed effective dose equivalents incurred by such a householder in the year following intrusion, from the adopted inventory, are listed below.

Route	Effective Dose Equivalent Rate (Sv/y)
External irradiation	$1.10\ 10^{-6}$
Inhalation	$8.59\ 10^{-7}$
Radon daughter inhalation	$2.54\ 10^{-7}$
Ingestion of soil	$1.82\ 10^{-6}$
Ingestion of vegetables	$8.86\ 10^{-6}$

Major unquantified uncertainties exist in the assumptions relating to the area and type of contamination (see Section 2.2.1). However, given that these are appropriately specified, uncertainties in the various dosimetric calculations lead to a best estimate total initial dose rate of $1.3\ 10^{-5}$ Sv/y (range 10^{-6} to $2\ 10^{-5}$ Sv/y). Given that intrusion is almost certain to happen on a timescale of centuries, comparable with radionuclide residence times in soil, the individual risk for type B actions is assessed as $\leq 4\ 10^{-7}\ y^{-1}$, i.e. an order of magnitude lower than the best estimate of the risk to the geotechnical worker and a factor of three lower than the lower bound estimate for that worker.

4. REFERENCES

Coughtrey, P.J., Jackson, D. and Thorne, M.C. (1984). Radionuclide Distribution and Transport in Terrestrial and Aquatic Ecosystems, Vol. 3, A.A. Balkema, Rotterdam.

Coughtrey, P.J., Jackson, D., Jones, C.H. and Thorne, M.C. (1984). Radionuclide Distribution and Transport in Terrestrial and Aquatic Ecosystems, Vol. 5, A.A. Balkema, Rotterdam.

Greenhalgh, J.R., Kendall, G.M., Fell, T.P. and Kennedy, B.W. (1986). The RAPID System for Information Retrieval from the NRPB Internal Dosimetry Database. NRPB-M133.

International Commission on Radiological Protection (1975). Report of the Task Group on Reference Man. Pergamon Press, Oxford. ICRP Publication No. 23.

International Commission on Radiological Protection (1983). Radionuclide Transformations: Energy and Intensity of Emissions. Annals of the ICRP, Vols. 11-13. ICRP Publication No. 38.

International Commission on Radiological Protection (1987). Lung Cancer Risk from Indoor Exposures to Radon Daughters. Annals of the ICRP, Vol. 17(1). ICRP Publication 50.

Jackson, D. (1984). Derivations and Ranges of Aquatic Organism and Terrestrial Plant Data for Use With the Biosphere Code ECOS. ANS Report No. 376-2. DoE SYVAC Technical Report TR-ANS-12. DoE Report No. DOE/RW/84.127.

Krauskopf, K.B. (1979). Introduction to Geochemistry, 2nd edit., Wiley.

National Council on Radiation Protection and Measurements (1984). Exposures From the Uranium Series With Emphasis on Radon and its Daughters. NCRP Report No. 77. Available from: NCRP, 7910 Woodmont Avenue, Bethesda, MD 20814.

National Radiological Protection Board (1987). Exposure to Radon Daughters in Dwellings. NRPB-GS6.