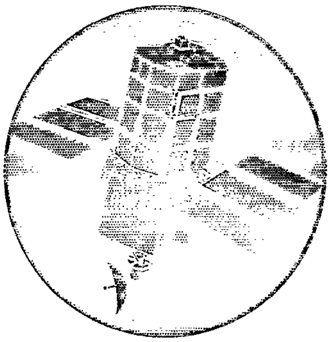
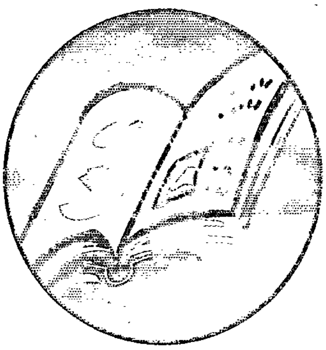
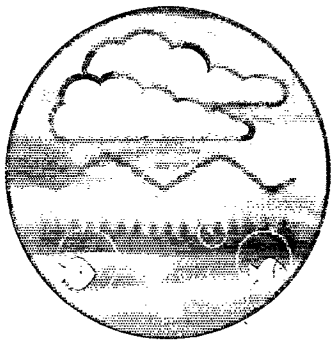
Interpretation of Optimisation in the Context of a Disposal Facility for Long-lived Radioactive Waste







Research and Development

Technical Report
P259

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ENVIRONMENT AGENCY

Interpretation of Optimisation in the Context of a Disposal Facility for Long-lived Radioactive Waste

R&D Technical Report P259

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Research Contractor

Safety Assessment Management Ltd

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R&D Technical Report P259

Interpretation of Optimisation in the Context of a Disposal Facility for Long-lived Radioactive Waste

CONTENTS

EXECUTIVE SUMMARY

Background

Guidance on the Requirements for Authorisation (the GRA[1]) issued by the Environment Agency for England and Wales requires that all disposals of radioactive waste are undertaken in a manner consistent with four principles for the protection of the public. Among these is a principle of Optimisation, that: *"The radiological detriment to members of the public that may result from the disposal of radioactive waste shall be as low as reasonably achievable, economic and social factors being taken into account."*

The principle of optimisation is widely accepted and has been discussed in both UK national policy and guidance and in documents from international organisations. The practical interpretation of optimisation in the context of post-closure safety of radioactive waste repositories is, however, still open to question. In particular, the strategies and procedures that a developer might employ to (1) implement optimisation in the siting and development of a repository and (2) demonstrate optimisation in a safety case, are not defined. In preparation for its role of regulatory review, the Agency has undertaken a pilot study to explore the possible interpretations of optimisation stemming from the GRA, and to identify possible strategies and procedures that a developer might follow.

Work programme

A review has been undertaken of UK regulatory guidance and related documents, and also international guidance, referring to optimisation in relation to radioactive waste disposal facilities. In addition, diverse examples of the application of optimisation have been identified in the international and UK performance assessment literature.

A one-day meeting was organised bringing together Agency staff and technical experts with different experiences and perspectives on the subject of optimisation in the context of disposal facilities for radioactive waste. This meeting identified and discussed key issues and possible approaches to optimisation, and specifically:

1. The meaning of optimisation – scope and strategies for optimisation – what are we trying to achieve ?

2. Application of optimisation – in waste management and repository development programmes – how is optimisation to be implemented ?

3. Demonstration of optimisation - in performance assessment, the safety case and decision making - how is optimisation to be demonstrated ?

[1] Environment Agency, SEPA and DoE NI. Disposal Facilities on Land for Low and Intermediate Level Radioactive Wastes: Guidance on Requirements for Authorisation. Environment Agency, Bristol, 1997.

This report documents the review and provides a discussion of the issues. This includes a further and more detailed examination of the issues beyond that explored in the one day meeting, and incorporates later comments by the technical experts and Agency staff.

Conclusions

The main conclusions from the study are as follows.

- A very broad interpretation should be taken of the meaning of optimisation, encompassing good decision-making throughout the repository programme, including qualitative judgements.
- Optimisation should be implemented by ensuring safety, cost and resource issues are properly considered at each decision point in the siting and development of a repository.
- The regulator should expect a developer to demonstrate optimisation by:
  (1) providing a clear record of past decisions and their basis as considered at the time, and
  (2) presenting qualitative arguments and calculations that support their design choices and compare key options still open to the developer.

The report is published by the Agency as input to the international discussion on the subject of optimisation in the context of radioactive waste disposal facilities.

Keywords
Optimisation
Radioactive Wastes
Radiological Safety Assessment
Disposal Options
ALARA
Legislation
Public exposure
Drigg

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1. INTRODUCTION

This report is prepared by Safety Assessment Management Ltd. for the Environment Agency under the terms of contract P3-033 "Interpretation of Optimisation in the Context of a Disposal Facility for Long-lived Radioactive Waste".

The objectives of the project were:

- To assist the Agency in establishing a defensible view on the interpretation of optimisation in the context of radioactive waste disposal facilities, in order to aid possible future regulatory decisions.
- To provide a basis on which the Agency may develop guidance on the interpretation of optimisation in the context of radioactive waste disposal.

The following work has been carried out:

- A brief review has been undertaken of UK regulatory guidance and advice, and also international guidance, referring to optimisation in relation to solid radioactive waste disposal facilities. In addition, diverse examples of the application of optimisation have been identified in the international and UK performance assessment literature. This work is summarised in Chapter 2 of this report, supported by Appendices I and II.
- A one-day meeting was organised bringing together Agency staff and technical experts with different experiences and perspectives on the subject of optimisation in the context of disposal facilities for radioactive waste. The aim of this meeting was to identify and discuss key issues and possible approaches to optimisation. This meeting, plus themes identified and discussed in the Agency's technical schedule and the contractor's technical proposal, form the basis for the identification and discussion of issues in Chapter 3.
- A synopsis of the issues has been made and conclusions drawn for consideration by the Agency. This is presented in Chapter 4.

This is the final report on the project. The report represents the views of the author and takes account of the views expressed by technical experts and members of Agency staff during the work. It does not necessarily represent the views of the Agency, although it will be one of the inputs that the Agency will take into account in developing its views.

The report is published by the Agency as input to the international discussion on the subject of optimisation in the context of radioactive waste disposal facilities.

2. THE UK REGULATORY BACKGROUND, INTERNATIONAL GUIDANCE AND PRACTICE

This chapter presents a brief review of UK regulatory guidance and advice, and also international guidance, referring to optimisation in relation to solid radioactive waste disposal facilities. Relevant paragraphs from selected documents are reproduced in Appendix I. In addition, diverse examples of the application of optimisation are identified from the international and UK performance assessment literature. Descriptions of these examples are given in Appendix II.

2.1 The UK Regulatory Background

The following documents are identified as setting the UK regulatory background to the interpretation of optimisation in the context of solid radioactive waste disposal:

- Command 2919 "Review of Radioactive Waste Management Policy" [HM Government 1995] which describes government policy;
- the Environment Agency's "Guidance on Requirements for Authorisation" (GRA) [Environment Agency et al. 1997] which provides the definitive regulatory guidance in this area;
- the NRPB's "Board Statement on Radiological Protection Objectives for the Land-based Disposal of Solid Radioactive Wastes" [NRPB 1992] which was a source of reference for the above-mentioned GRA document;
- the report of the RWMAC/ACSNI Study Group on "Site Selection for Radioactive Waste Disposal Facilities and the Protection of Human Health" [RWMAC/ACSNI Study Group 1995].

Relevant extracts from these documents are reproduced in Appendix I.

2.1.1 HM Government, Command 2919

Cm 2919 includes 4 paragraphs (§67-70) under the heading "Optimisation" and a further 3 paragraphs (§71-73) under the heading "Threshold for Optimisation". These are all within a section on "Discharge of Airborne and Liquid Waste" (§63-73). However, §71 and 72 appear to be of some relevance.

§71 refers to HSE's Tolerability of Risk (ToR) study [HSE 1992] which recognised that there is an upper limit beyond which an individual risk would be intolerable, regardless of benefit to society, and a lower level, below which the risk is negligible in comparison with other every-day risks and, therefore, broadly acceptable. The intermediate area is the "tolerability" region in which risks are tolerable only if they are as low as reasonably practicable (ALARP), i.e. to reduce them would involve disproportionately high cost[2].

In §72, the Government proposed to introduce a lower bound for optimisation for radioactive waste discharges at an annual risk of death of around one in a million (10^{-6}) or less. It is noted that while an annual risk of 10^{-6} is not altogether negligible, it is a level which, with certain provisos, does not generally worry us or cause us to alter our behaviour[3].

Within the section on "Disposal of Solid Waste" (§74-87) the only relevant statements are in §78. Here it is stated that a risk target (of 10^{-6} y^{-1}) should be used as an objective in the design process and, where the regulator is satisfied that best practicable means have been adopted and the estimated risks to the public are below this target, then no further reductions in risk should be sought. If, however, the estimated risk is above this target, then the regulators will need to be satisfied that not only is an appropriate level of safety assured, but also that any improvements in safety could be achieved only at disproportionate cost.

2.1.2 Environment Agency, Guidance on Requirements for Authorisation (the GRA)

The GRA defines both "as low as reasonably achievable" (ALARA) and "best practicable means" (BPM) (see Appendix I). ALARA[4] refers to reduction of doses and risks, whereas BPM refers to management and engineering controls.

The primary statement regarding optimisation is in Chapter 5 "Principles for the Protection of the Public", wherein §5.8 and 5.9 define and explain a principle as follows:

"5.8 Principle No. 3 - Optimisation (as low as reasonably achievable)

> The radiological detriment to members of the public that may result from the disposal of radioactive waste shall be as low as reasonably achievable, economic and social factors being taken into account.

5.9 In submissions related to the design and operation of a disposal facility, the applicant for authorisation should show that the best practicable means are being employed to ensure that the radiological detriment to members of the public, both before and after withdrawal of control over the facility, will be as low as reasonably achievable when viewed against wider perspectives, including recognition of competing claims on limited economic resources and that there is no risk-free option for managing radioactive waste. Demonstration of optimisation will entail showing that, among other things, the safety case has a sound scientific and technical basis and that good

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2 Note that the tolerability region is defined in terms of individual risk although, typically, other measures of radiological impact, and other factors, might be evaluated in order to achieve optimisation of protection.

3 Nevertheless, a regulator might choose to take action at even lower levels of individual risk. For example, when the decision to ban sales of beef on the bone was taken, the best estimate of risk to an individual was assessed as very low, less than 10^{-6}, yet a ban was placed. Presumably, this decision took account of the significant uncertainties in the estimate of risk and the potentially large exposed population.

4 At the time of the Sizewell Inquiry, a view was put forward that ALARP referred to the control of radioactive discharges, or other sources, whereas ALARA referred to exposures. Thus, if discharges were ALARP then exposures would be ALARA. This distinction seems not to have been taken up, however, as indicated in HSE's definition of the tolerability region. Rather, in the UK, the terms seem to be used interchangeably with the HSE favouring the term ALARP and the Environment Agency favouring ALARA. In effect, ALARA with the proviso "social and economic factors taken into account" can be seen as equivalent to ALARP.

engineering principles are being applied in facility design, construction, operation and closure."

Chapter 6 expands on this slightly, notably in §6.12, 6.14, 6.23 and 6.25. In summary, §6.14 repeats much of §72 in Cm 2919, §6.23 sets requirement R3 on "Use of best practicable means" and §6.25 addresses this requirement in respect of the period after withdrawal of control. In particular, §6.23 specifies use of BPM as the means of ensuring doses and risks are ALARA, and §6.25 states that the developer should consider variants to design for their effects on long-term radiological risk, and gives guidance on meeting requirement R3. For the chosen design, if the risk to a representative member of a potentially exposed group is:

– above the target of 10^{-6} y^{-1} – "the developer should show the design is optimised such that any additional measures which might reasonably be taken to enhance the performance of the chosen design would lead to increases in expenditure, whether in time, trouble or money, disproportionate to the reduction in risk."

– below the target of 10^{-6} y^{-1} – "where the Agency can be satisfied that the safety case has a sound scientific and technical basis, that good engineering principles and practice are being applied in facility design, construction, operation and closure, . . . , then no further reductions in risk need be sought."

2.1.3 NRPB, Board Statement on Radiological Protection Objectives for the Land-based Disposal of Solid Radioactive Wastes

The NRPB Board Statement proposes the use of criterion curves (§67 to 70) which incorporate the ToR concepts of acceptability, see Figure 2.1[5], and includes a section on "Optimisation" (§71 to 75 and summarised in §90-91).

The section on Optimisation notes the difficulties over use of collective doses in respect of exposures in the far future when human population size and behaviour are highly uncertain. It suggests, however, that a cost-benefit analysis (for example) could still be used in comparative sense. The use of multi-attribute decision-aiding techniques is suggested so that more reliable indicators, for example fluxes, could be used. The document notes that there would still be a problem of assigning weights if these fluxes were to be compared with "real" detriments, for example, worker doses. Finally, it is suggested that probability and consequence components of risk should be given separate consideration in optimisation studies.

[5] The interpretation and application of constraint curves as originally discussed by the ICRP, and later by the NRPB are compared and analysed in [Thorne 1997]. Thorne notes that the NRPB appears to have misunderstood the guidance given in ICRP Publication 46 [ICRP 1985]. This provided curves that define the maximum probability that can be permitted for estimated doses of different magnitudes, and emphasised that these are properly used in conjunction with radiological impact analyses for scenarios expressed in terms of the probability of occurrence and the maximum dose associated with it, i.e. point estimates. The NRPB presented similar curves but with a different interpretation: NRPB 1992 stated that the curve took the form of a plot of the probability that a dose D will be exceeded versus D, for a particular time or time period, i.e. allowing a comparison of a distribution of cumulative probability of dose against the criterion curve.

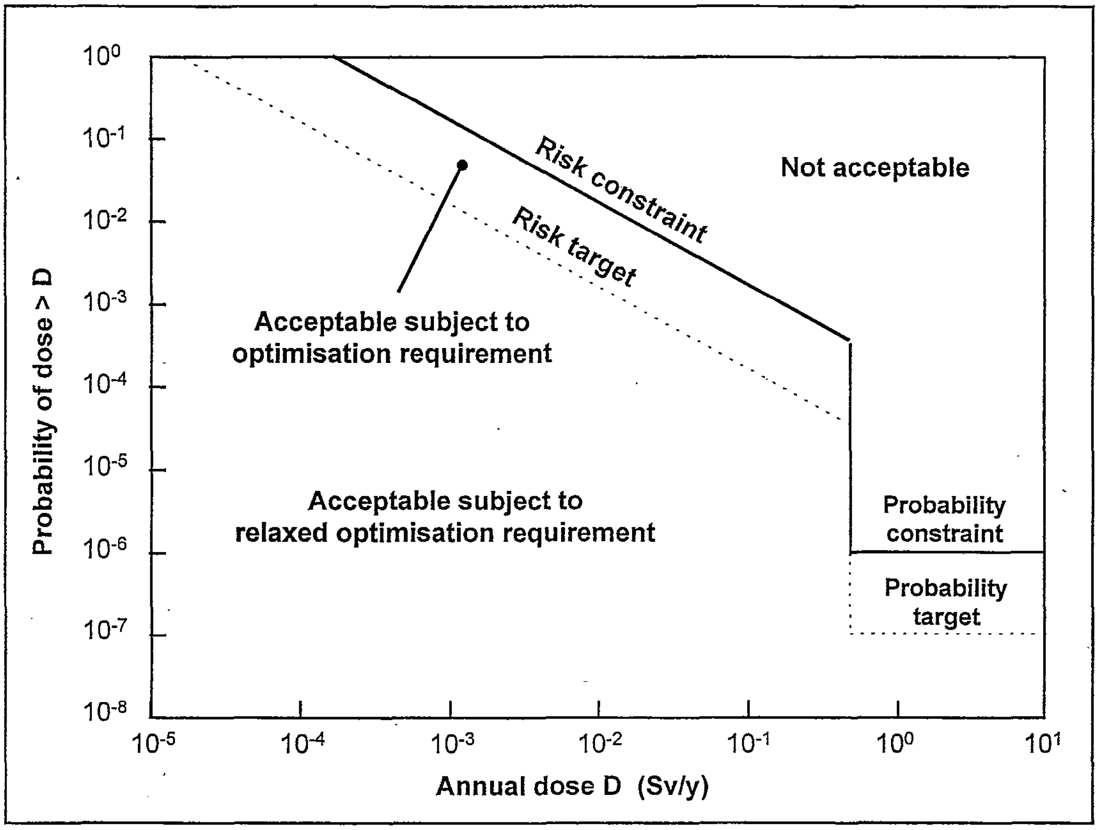


Figure 2.1: Criterion curves from the NRPB Board Statement [NRPB 1992].

2.1.4 RWMAC/ACSNI Study Group Report

The RWMAC/ACSNI Study Group did not address optimisation directly. The Group concluded in §3, however, that the approach to safety, the terminology used and the standards set in respect of geological disposal facilities should be those of the ToR. The group set out its interpretation of ToR in the context of waste repositories in §3.37 and further explained and commented on this in §3.38-39. In particular, it noted that there was evidence from the Cleator Moor Hearing that the public regarded a level of risk of one in a million as a maximum acceptable figure rather than a lower bound of the tolerability region.

The Group further concluded, in §6, that the ToR criteria cannot be directly applied in the early site selection process stages and that derived, equivalent criteria based directly on known geological and hydrogeological characteristics should be used. Some specific characteristics are suggested in §(v) of Section 7.3 (see Appendix I)[6]. The Study Group also noted that the uncertainty in any estimate of population risk would be so large that it would not be possible to discriminate between waste disposal options, and it is therefore not a useful quantity (§3.44). More recently, this view has also been expressed by the ICRP, see Section 2.2.1.

6 Although these characteristics are relevant to performance, it must be commented that none could be "known" in respect of a real site, but rather would have to be judged based on limited measurements and geological hypotheses.

2.2 International Guidance

2.2.1 ICRP guidance

The International Commission on Radiological Protection (ICRP) is the primary international source of reference on matters related to radiological protection. The modern system of radiological protection of Justification, Optimisation and Limitation was set out in ICRP Publication 26 [ICRP 1977], wherein the Optimisation element is expressed in terms of ALARA:

> "all exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account".

This system of radiological protection, and the importance of optimisation, is retained in the more recent general recommendations of the ICRP in Publication 60 [ICRP 1991]. Also relevant are Publication 46 [ICRP 1985], which sets out radiation protection principles for the disposal of radioactive waste, and Publication 64 [ICRP 1993], which sets out a conceptual framework in respect of potential exposures. Potential exposures are defined as exposures not certain to occur, and later guidance has made it clear this includes future exposures from radioactive waste disposal.

The ICRP has acknowledged that Publication 46 is rather theoretical and has not been very influential in practice. A Task Group under ICRP Committee 4 is currently working to produce a document on the application of radiological protection principles to disposal of solid wastes that will supplement or replace ICRP 46 [Sugier 1997]. In addition, a Task Group under the Main Commission has prepared a report on radiological protection policy for the disposal of radioactive waste which was adopted by the Commission in May 1997 as Publication 77 [ICRP 1997].

The guidance from ICRP is thus in a state of flux. In this section, therefore, we note some of the statements related to optimisation in Publications 60 and 64 which we assume will remain valid, and also anticipate likely guidance with respect to optimisation based on statements in Publication 77 and also statements made in presentations on ongoing ICRP Task Group work to OECD/NEA conferences and meetings[7].

In Publication 60, the optimisation of protection is discussed: in general terms in §117-121; with respect to public exposure in §186-187; and with respect to potential exposures in §203. Significant statements are:

> "The broad aim should be to ensure that the magnitude of the individual doses, the number of people exposed, and the likelihood of incurring exposures where these are not certain to be received are kept as low as reasonably achievable, economic and social factors being taken into account." (§117).

> "The judgements involved in optimising protection are not purely quantitative - they involve preferences between detriment of different kinds and between deployment of resources and health effects." (§119).

7 The author attended presentations by Mme Sugier, Leader of the relevant Task Group under Committee 4, to NEA PAAG and RWMC meetings in September 1997 and March 1998 respectively.

> "The process of optimising protection . . . is essentially source-related and should first be applied at the design stage of any project." (§120).
>
> " . . . benefits and detriments are unlikely to be distributed through society in the same way. Optimisation . . . may thus introduce substantial inequity between one individual and another. This inequity can be limited by incorporating source-related restrictions on individual dose . . . dose constraints . . . For potential exposures, the corresponding concept is the risk constraint. (§121).
>
> "The main aim of constrained optimisation in public exposure should be to develop practical restrictions on the source of exposure, e.g. in the form of restrictions on the release of radioactive waste to the environment." (§187).

Publication 64 repeats and paraphrases relevant material from ICRP 60, e.g. in §33 and 44, but also goes a little further in explaining optimisation in the context of potential exposures, thus:

> "The ultimate level of safety applied to a radiation source results from a choice among feasible alternative options. Those . . . making decisions should satisfy themselves that the most appropriate safety option under the prevailing circumstances has been selected. As safety measures are increased, the occurrence, probability or the potential radiological consequences themselves will logically be decreased. However, if the next increment of safety requires a deployment of resources or causes an increase in the social cost that is disproportionate to the resultant reduction in the probability or the magnitude of the radiological consequence, it is not in society's interest for that step to be taken. The safety measures can then be said to be optimised and the remaining risks to be as low as reasonably achievable, economic and social factors having been taken into account." (§45).

Relevant paragraphs from ICRP Publication 77 on radiation protection policy for the disposal of radioactive waste are reproduced in Appendix I. In summary:

- The Commission believes few recent radioactive waste management decisions have been based on consideration of radiation exposures (§7).
- Optimisation of protection has the broad interpretation of doing all that is reasonable to reduce doses (§17).
- The Commission's emphasis has been on the qualitative specification of optimisation (§37), and is more subtle and judgmental than implied by differential cost-benefit analysis (§38).
- The basic role of the concept of optimisation . . . is to engender a state of thinking - "Have I done all that I reasonably can to reduce the radiation doses?" (§39).
- The annual individual effective dose to a critical group for normal exposure and the annual individual risk to a critical group for potential exposure will together provide an adequate input to a comparison of the limiting detriment to future generations with that which is currently applied to the present generation (§69).

The issues related to application of optimisation of protection to solid radioactive waste disposals have been considered by the ICRP Task Group revising ICRP Publication 46. The main issues identified in the proceedings of the Cordoba conference [Sugier 1997] are:

- difficulty in performing conventional optimisation[8] as future collective dose cannot be estimated reliably;
- the uncertainties can mask the differences between the various options under consideration;
- the long delay between cost outlay and benefit expected from protection options;
- decision makers tend to maximise rather than optimise protection; this is in response to the uncertainties, the sensitivity of public opinion and the difficulty of finding sites.

In response to these issues, Sugier indicated that the Task Group believed:

- optimisation should be approached as an exercise in common sense (and this is consistent with ICRP 60 recommendations);
- reference could be made to sound engineering practice, i.e. can reductions in radiation dose and risk be achieved through engineering measures that can be implemented in a cost-effective manner;
- the relevance of collective dose estimates should be addressed.

The author's understanding of the current ICRP views based on a recent presentation to the NEA RWMC[9] is as follows.

- Waste disposal does not require justification which applies to the total practice, e.g. of nuclear power production. (Only existing and future practices require justification, and current and future wastes from those practices are a factor to consider in deciding whether they are justified.)

- Exposures to members of the public due to solid radioactive waste disposal are always potential exposures and not amenable to control by classical radiological protection methods. Dose limits cannot be applied since doses cannot be verified. Rather, emphasis must be placed on optimisation within dose constraints, which are more flexible source-related concepts.

- Optimisation is recognised as largely judgmental and should be seen as a pragmatic process of evaluating existing technologies and selecting an appropriate solution with regard to sound waste management principles.

- Several endpoints might be considered for performance calculations. Estimated future doses should, however, be seen as indicators of safety, rather than actual doses received.

- Collective dose is not a useful quantity when considering exposures in the future because of uncertainty in individual doses, and in the number and characteristics of exposed individuals. Health detriments should not be calculated because of uncertainty in the dose-health detriment relationship in the future.

8 Meaning in the classical radiological protection sense, for example, using collective doses and formal cost-benefit analysis, see [ICRP 1989].

9 30th Meeting OECD/NEA Radioactive Waste Management Committee (RWMC), 12-13 March 1998, Paris.

- In the case of releases due to natural processes, a risk-orientated approach is appropriate, but risk should be disaggregated into dose and probability. In the case of human intrusion, uncertainties are such that the recommended path is to reduce the likelihood and limit consequences of intrusion, e.g. through design and siting.

2.2.2 IAEA guidance

A discussion of optimisation is included as an Annex to IAEA Safety Series 60 "Criteria for Underground Disposal of Radioactive Waste" [IAEA 1983]. Therein is stated:

> "It is important to recognise that optimisation is not a precise numerical requirement but rather a means of assisting responsible authorities in arriving at decisions."

An inconclusive discussion follows which does, however, identify some of the problems in applying optimisation to post-closure safety. These problems include inherent uncertainties in predictions, treating low-probability high-consequence events, definition of the time period of concern, whether cost discounting should be applied, and whether very small doses should be neglected.

More recently, the subgroup under the IAEA International Radioactive Waste Management Advisory Committee (INWAC) on "Principles and Criteria for Radioactive Waste Disposal" has identified optimisation as a key issue requiring consideration and has issued a brief review of its application to radioactive waste disposal [Chapter 3 in IAEA 1996]. This review is based on ICRP recommendations from Publications 60 and 46 (see above) and makes relatively little in the way of references to practical application. Moreover, the overall tone is very negative, noting in the case of:

- radiological impact evaluation - "the uncertainties . . . make formal optimisation difficult";
- disposal options - "the choice . . . will not be significantly influenced by optimisation";
- repository design - "there may be little scope for optimising radiation protection with barriers being chosen with more regard to their effect than to their cost";
- siting analysis - "the scope for optimisation is limited in the context of siting".

This negative view seems to be because, based on ICRP Publication 46, a rather narrow view of optimisation as a quantitative optimisation of radiological protection has been taken. The INWAC subgroup conclude:

> "Although the principle of optimising radiation protection is valid and appropriate in the context of radioactive waste disposal, a detailed quantitative optimisation procedure does not usually play a major role in the decision-making process. However, a judgmental and qualitative optimisation is certainly included in the development of detailed repository design options, in planning for their operation and during the operational phase, in particular, to ensure that all reasonable or practical opportunities to reduce doses are explored. In summary, the optimisation of protection principle is valid, but its application has to be adapted to what is achievable in practice."

2.3 Examples of Optimisation in Performance Assessment

Most performance assessments (PAs) focus on evaluating the performance of a given option, and the author is not aware of a study in which a systematic demonstration of optimisation of a repository system has been attempted. Several illustrations exist, however, of optimisation at particular decision points, or for specific aspects, of a repository programme. Appendix II presents examples of optimisation from the international PA literature and also from work sponsored by HMIP. These indicate the possible breadth for illustration of optimisation in PA. The cases presented are:

– application of multi-attribute analysis to determine the 'best practical environmental option' (BPEO) for the management of low and intermediate-level radioactive waste in the UK, with special attention to a comparison of sea disposal to land-based options [DoE 1986];

– an example of multi-attribute analysis to assist the choice between candidate sites, from USDOE's study of sites nominated for characterisation for deep geological disposal of spent fuel and HLW in the USA [USDOE 1986];

– an example of optimisation with respect to scientific knowledge, from Nagra's development of a repository concept for disposal of HLW in Opalinus Clay in Switzerland [Nagra 1988];

– an example of optimisation of repository layout, from AECL's Postclosure Assessment of a Reference System for disposal of spent fuel in plutonic rock in Canada [Goodwin et al. 1994];

– an example of comparison of alternative waste management options based on PRA, from an assessment of options for management of wastes disposed in the Dounreay shaft in Scotland, carried out by HMIP on behalf of HMIPI [RM Consultants 1990];

– an investigation of the influence of the extent of site investigation on estimated radiological performance, from HMIP's study based on a synthetic geological model of the Harwell site in Oxfordshire [Mackay 1993].

In addition, examination of the design decisions in developing nuclear fuel waste disposal systems show these decisions usually have a basis in optimisation with respect to scientific knowledge and confidence in engineering performance, e.g. see Chapter 6 in [SAM 1996].

It can be observed that, even where quantitative analysis is performed, the calculations do not provide unequivocal answers that one option is necessarily better than another. Rather, as stated by the US National Academy of Sciences: ". . . the principal usefulness of the (multi-attribute utility) method is to illuminate the factors involved in a decision, rather than to make the decision itself" [USDOE 1986], and, as in the UK DoE BPEO report, the technique is a "decision-aiding, not a decision-making tool" [DoE 1986].

Even in the more technical areas of engineered barrier design and repository layout, illustrated in Appendix II with examples from Switzerland and Canada, there is no quantitative trade off between added costs and improvements in performance. Rather, reasonable and practical design modifications are considered and qualitative or quantitative evaluations are made to see whether these might offer significant improvements in estimated performance or confidence in estimated performance.

The trial investigation of the sensitivity of risk estimates to the extent of site investigation carried out by HMIP offers a warning with regard to any attempt to optimise a site investigation programme. Here a failure to fully explore possible hydrogeological models of the site, or overconfidence in the first model adopted, led to a situation where additional data produced more precise, but not more accurate, estimates of performance.

Several textbooks have been written on the subject of decision analysis, e.g. [Watson and Buede 1987] and studies have been made of the formal use of quantitative risk assessment in decision making, e.g. [HSE 1989]. HMIP commissioned a study of the feasibility of mathematical methods for assessing BPM in the context of post-closure radiological assessment [Laundy 1992], although this was exploratory and at a somewhat theoretical level.

The use of analysis to support decision making in respect of siting and development of a geological repository is currently an active topic internationally. At the current stage of development, only general advice can be given based on PA experience. For example, within the NEA RWMC/PAAG Working Group draft document [NEA 1998a], the issue is expressed in terms of an incremental decision-making process in which sufficient confidence must be achieved at each stage to justify the commitment, whether in terms of time, money or human resources, of proceeding to the next stage. Thus:

> "The planning, construction, operation and closure of a deep geological repository typically proceeds in incremental stages. The decision makers within the implementing and regulatory organisations, as well as the wider technical community and the general public, should have sufficient confidence in the prospect of achieving a facility with an acceptable long-term safety to support a decision to proceed from one development stage to the next. In particular, confidence should be sufficient to justify the commitment of resources that the next stage is likely to involve."

3. IDENTIFICATION AND DISCUSSION OF THE ISSUES

3.1 Basis and Scope

This chapter identifies and discusses issues related to the interpretation of optimisation in the context of the post-closure safety of disposal facilities for long-lived radioactive waste. The chapter draws on the Agency's Technical Specification for the Work, Safety Assessment Management Ltd.'s Technical Proposal and results of a one-day meeting convened to discuss key issues and possible approaches to optimisation[10].

Optimisation in the context of the post-closure safety of radioactive waste disposal is different from the traditional understanding and application of optimisation to operational aspects of nuclear installations. This is because of the long time periods before a member of the public or the environment is exposed - thus, it must be assumed, there will be no monitoring of radioactivity releases or exposures, nor ability to control releases or take remedial actions - and also because there is considerable uncertainty about the long-term performance of the engineered and natural barriers and future events that might affect them - so that the effectiveness of siting and design measures aimed at improving performance are difficult to judge.

The Agency needs to be aware of possible interpretations of optimisation stemming from the GRA, and also possible strategies and procedures that a developer might employ to (1) implement optimisation in the development of a repository and (2) demonstrate optimisation in a safety case. At this stage, however, the identification and discussion of issues remains relatively open. This is because, ultimately, it will be the responsibility of the developer to show that disposals will be carried out in accord with the Principles and Requirements set out in the GRA, including that of optimisation.

This document is only concerned with the approach that the Agency may take in judging the optimisation of protection afforded to members of the public and the environment in the post-closure period. It is recognised that the Nuclear Installations Inspectorate (NII) will demand optimisation of protection in respect of doses to workers and also immediate doses to members of the public, and the Agency will also be concerned to optimise protection of members of the public and the environment in the operational period. These issues are not addressed here, although the interplay between these possibly competing requirements will need to be considered in due course.

The focus of the discussion is on optimisation as applied to the long-term safety of a deep underground repository for long-lived radioactive wastes, although much of the discussion may also apply to near-surface disposal facilities.

[10] The one-day meeting was held at Environment Agency offices on 16/2/98. It was attended by Mr. R.A. Yearsley and Dr. R.E. Smith, Environment Agency; Dr. J. Fitzpatrick, RM Consultants Ltd.; Mr. A. Martin, Alan Martin Associates; Mr. P.A. Sims, Building Research Establishment; Dr. M.C. Thorne, Electrowatt Engineering (UK) Ltd. (now of AEA Technology plc.); Mr. T.J. Sumerling, Safety Assessment Management Ltd..

The chapter is structured around three high-level issues or questions posed to participants at the one-day meeting:

1. The meaning of optimisation – scope and strategies for optimisation – what are we trying to achieve?

2. Application of optimisation – in waste management and repository development programmes – how is optimisation to be implemented?

3. Demonstration of optimisation - in performance assessment, the safety case and decision making - how is optimisation to be demonstrated?

3.2 The Meaning of Optimisation

The principle of optimisation is widely accepted in radiological protection. The meaning of the principle and consequent requirements in the context of disposal facilities for radioactive waste are outlined in the GRA in general terms, see Section 2.1. The practical interpretation is still open to question, especially as applied to post-closure safety of a repository.

Paraphrasing Principle No. 3 of the GRA, the radiological detriment to members of the public that may result from disposals must be ALARA. Difficulties arise, however, because:

- the actual radiological detriment is unknown and can only be estimated, and the validity and meaning of estimated doses and collective doses into the far future are questionable;
- the radiological detriment might be received over very long time periods and to different generations;
- releases from a repository are liable to occur both as prolonged gradual releases and, possibly, as more rapid releases of uncertain timing and magnitude which may be difficult to compare.

ICRP documents usually refer to *all* doses being ALARA, e.g. including worker doses, but the GRA refers specifically to *members of the public*. This is deliberate and can be interpreted as follows. In general, ALARA refers to optimising radiological impacts and this is to be done with "social and economic factors taken into account". This heading might include non-radiological impacts on health, including conventional accidents, i.e. a general interpretation of the ALARA principle can be taken in which radiological and non-radiological impacts are both important to the decision, although they may be calculated separately and weighted differently. The form of words in the GRA then implies that doses to members of the public are to be calculated separately and, possibly, weighted differently from occupational doses. Worker doses and non-radiological hazards of various kinds[11] may still be relevant to the decision, but doses to members of the public are picked out for special attention and are not to be summed with other impacts.

[11] For example, conventional worker accident risks are liable to be important for a deep underground repository and should certainly be included within the term "social and economic factors".

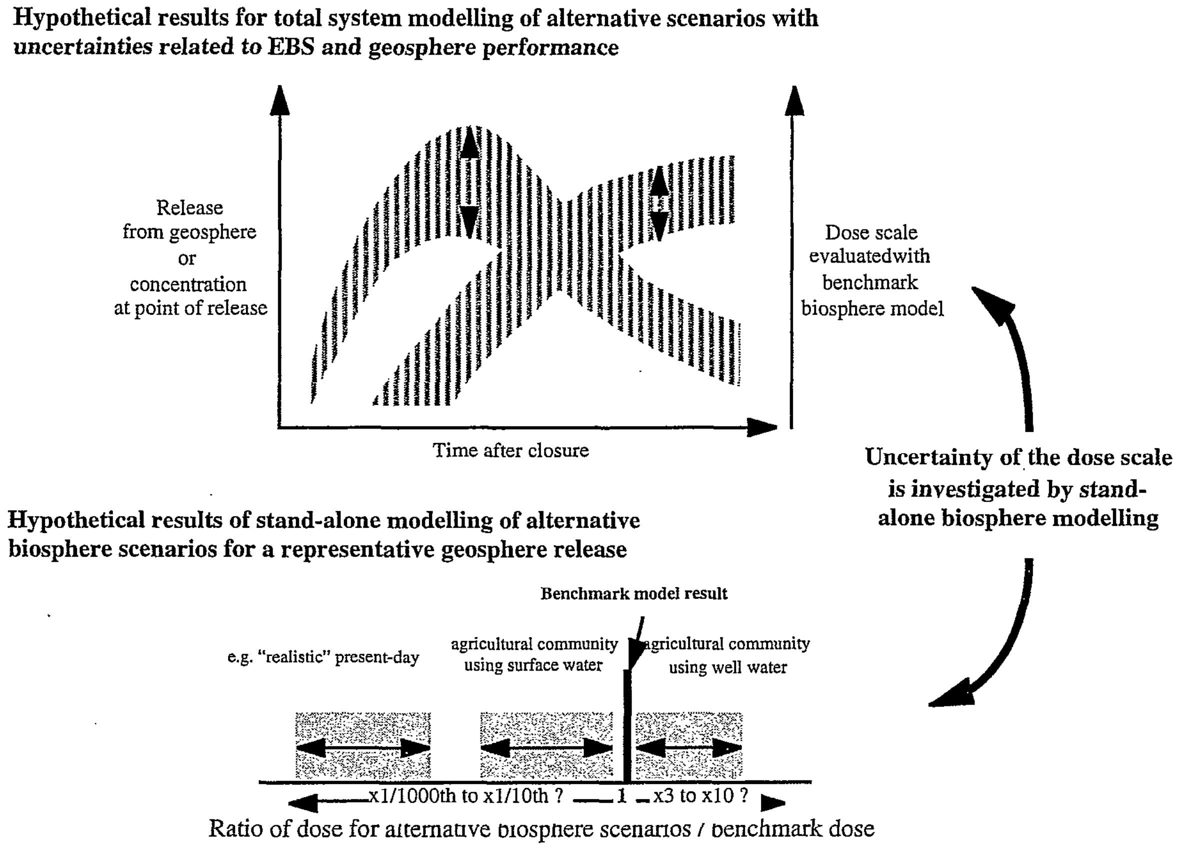
3.2.1 Radiological detriment or surrogate measures

Conventional optimisation studies in radiological protection deal with the optimisation of collective doses within individual dose constraints. The ICRP indicates, however, that estimated individual doses in the far future can be regarded only as indicators, and the use of collective doses is questionable due to inherent uncertainties, especially in human behaviour and characteristics [ICRP 1997]. Thus, even neglecting the problem of assigning costs to future health detriments, formal cost-benefit analysis in which monetary value is assigned to estimated radiological detriments is ruled out. A more qualitative approach to optimisation, in which alternative options are considered with respect to the relative effect in reducing surrogate measures related to radiological detriment can still be taken.

The NRPB, for example, suggest that radionuclide fluxes might be a more robust measure in optimisation studies [NRPB 1992], and various authors have developed this theme, e.g. [Miller 1998]. However, since there is no objective method of assigning value to radionuclide fluxes or similar surrogate measures[12], there seems little value in adopting such measures to support optimisation. Rather, providing spurious uncertainty is not included in dose estimates via inappropriate modelling, it is preferable to use dose or radiological risk estimates, the significance of which are more directly understood. In particular, using dose or radiological risk estimates as an endpoint in optimisation studies, not only the relative reduction in impact, but also the nearness of dose estimates to any target or constraint can be appreciated. An order of magnitude reduction in an estimate may be relatively meaningless if the estimate is already orders of magnitude below any dose/risk target, but could be significant if the base case estimate is of the same order as the dose/risk target.

A subgroup of the NEA PAAG has considered the treatment of the biosphere within repository system analyses [NEA 1998b]. This group proposes that only uncertainties related to repository and geosphere performance should be folded into system analyses, and that uncertainties related to the biosphere should be investigated separately, see Figure 3.1. This has the benefit that more weight is placed on evaluating and incorporating uncertainties related to the near field and geosphere, over which the developer has some control via siting and design, whereas performance and uncertainties related to the biosphere, over which the developer has little control, is treated in a more illustrative fashion. Such an approach is appropriate when generating dose estimates to be used in demonstrating optimisation.

[12] See IAEA 1994a which identifies several alternative safety indicators for use in repository safety assessment.



Understanding of the uncertainty related to the engineered barrier system (EBS) and geosphere can guide design, siting and data acquisition programmes, which can potentially improve safety, or at least reduce the uncertainty in estimates of performance. Although different hypotheses concerning the nature of the biosphere and of human behaviour in the far future can be made, these are speculative, and the uncertainty is irreducible.

Therefore, it may be convenient to separate these two parts of the assessment. Results for alternative EBS/geosphere scenarios, expressed as a dose scale calculated using a benchmark biosphere model, provide a basis for more objective illustrations of safety, and discussion of design and siting options. Results for alternative biosphere scenarios, expressed relative to results of the benchmark model, provide illustrations of the range of uncertainty in dose estimates. A key requirement is to check that the chosen benchmark model, e.g. drinking of first accessible and potable source of groundwater at 2 l d^{-1}, is reasonably conservative within this range.

Figure 3.1: Schematic illustration of the separate evaluation of uncertainties related to the EBS/ geosphere and the biosphere [after NEA 1998b].

3.2.2 The focus of optimisation

The optimisation principle demands that, however measured, radiological detriment is ALARA. Considering repository performance, at least four separate factors can be identified:

(a) actual future performance - which is unknown, or at least subject to a wide range of uncertainties, some of which may be reducible and some not;

(b) estimated performance - which is the result of quantitative modelling and may incorporate some classes of the above mentioned uncertainties, but not all uncertainties, and may incorporate both known[13] and unrecognised biases of various kinds;

(c) confidence in estimated performance - meaning the scientific confidence in the models and data which is not represented directly in numerical estimates;

(d) confidence in, and robustness of, design - meaning the extent to which a proposed design can be implemented in practice and can be relied on to behave as expected.

Ideally, we might wish to optimise (a), but this is not an option. Mathematical methods might be implemented to optimise (b), but if this path is followed the importance of (c) and (d) must not be over-looked. Put simply, it is pointless to optimise a measure that is not itself robust and has not folded in an appropriate range of uncertainties. For this reason, any treatment of optimisation must focus first on (d) and then on (c). Confidence that a system can be built and will perform as designed is more important than achieving an absolutely best design, if that design is liable to be unpredictable or relies on scientific processes that are less certain. Illustration or demonstration of optimisation might later be supported by performance calculations, i.e. factor (b).

3.2.3 Confidence in system design

The first stage in developing an optimised repository system must be selection of an appropriate repository concept. In the case of deep geological disposal, this involves selection of a host rock type and development of an engineered barrier system that is consistent with the host rock conditions and complements the natural safety barrier offered by the geology. At an early stage, several alternative repository concepts might be developed and investigated in parallel.

Classically, a potential repository location (or generic site type) is selected, an outline design is proposed consistent with rock type, and the design is refined as more information on site characteristics become available. Alternatively, an engineered barrier concept that is considered to be feasible in several different geological environments may be proposed first, e.g. cementitious control of near-field chemical environment proposed by Nirex, and this design refined to be compatible with particular site characteristics as these are defined. The dimensions of openings, need for rock support and load-bearing linings would differ between rock types, however, so that a generic repository design suited to any geological environment cannot be proposed. It is possible to investigate the potential of alternative geological

[13] For example, deliberately introduced conservatisms, see Section 3.2.4.

environments and alternative engineered barrier options in parallel, but optimisation can only take place when the various components of the system are considered together.

International research and experience has identified the general geological environments likely to be most suitable for the development of a repository, e.g. plutonic and compact volcanic rocks, evaporites especially rock salt, and argillaceous sediments, and designs principles have been elaborated for all these rock types, e.g. see [Sumerling and Smith 1998]. Beyond this, good engineering principles should be applied in developing the design for the specific environment. In particular, components and materials should be chosen in view of their longevity and reliability under repository conditions. Natural analogues may be especially useful in providing evidence for this. Radical concepts should be avoided unless there is confidence that the radical element will have significant positive benefits, and simple easily predictable designs may be preferred over more complex designs.

Traditionally, geological repositories have been described as nested, independent multi-barrier systems, e.g. using a Russian doll analogy. More recent experience of design and performance assessment indicates this analogy is not appropriate. It is better to view the various natural and engineered barriers and features as complementary rather than independent. In the normal course of future processes and events, it is expected that all components may make some contribution to safety. It is important, however, that there is a low probability of any event that could significantly undermine several safety barriers. Recognising this, the GRA document refers to the desirability of a multi-factor safety case, rather than a multi-barrier system.

3.2.4 Confidence in estimated performance

The basis of confidence in estimated performance must be a sound scientific understanding of the relevant features events and processes (FEPs), and a thorough methodology by which to identify relevant FEPs, construct mathematical models at appropriate spatial and temporal scales, and obtain and select appropriate data for use in the models.

Probabilistic or deterministic calculation techniques can be used to propagate uncertainties that can be represented via probability density functions or alternative input data values (parameter uncertainty). Attention must also be given to uncertainties and biases not explicitly included in the quantitative modelling process. These include uncertainty due to possible omission of features, events or processes (sometimes called scenario uncertainty) and also uncertainty over the representation of selected FEPs in assessment models (model uncertainty), e.g. see [NEA 1997].

Before using assessment models to demonstrate optimisation, it is important to consider the level of uncertainty or bias incorporated in the models. In particular, assessment models often include deliberate conservatisms[14] introduced for reasons of modelling convenience or caution. These may distort the relative importance of different components of the system. In this case, the optimisation calculations relate to the performance of the hypothetical model system, not necessarily to the potential performance of the actual disposal system.

14 In the context of PA, 'conservative' is used to describe an assumption, model or calculation arranged such that the radiological impact will not be underestimated.

3.2.5 Strategy for optimisation

In attempting to optimise a repository, a developer might choose to design a repository so that either:

(a) the radionuclides are released at a slow, steady rate such as to ensure that doses, albeit small ones, are received at the surface over a long period, but that the inventory of the repository falls to an innocuous level by the time that performance estimates become very uncertain, or

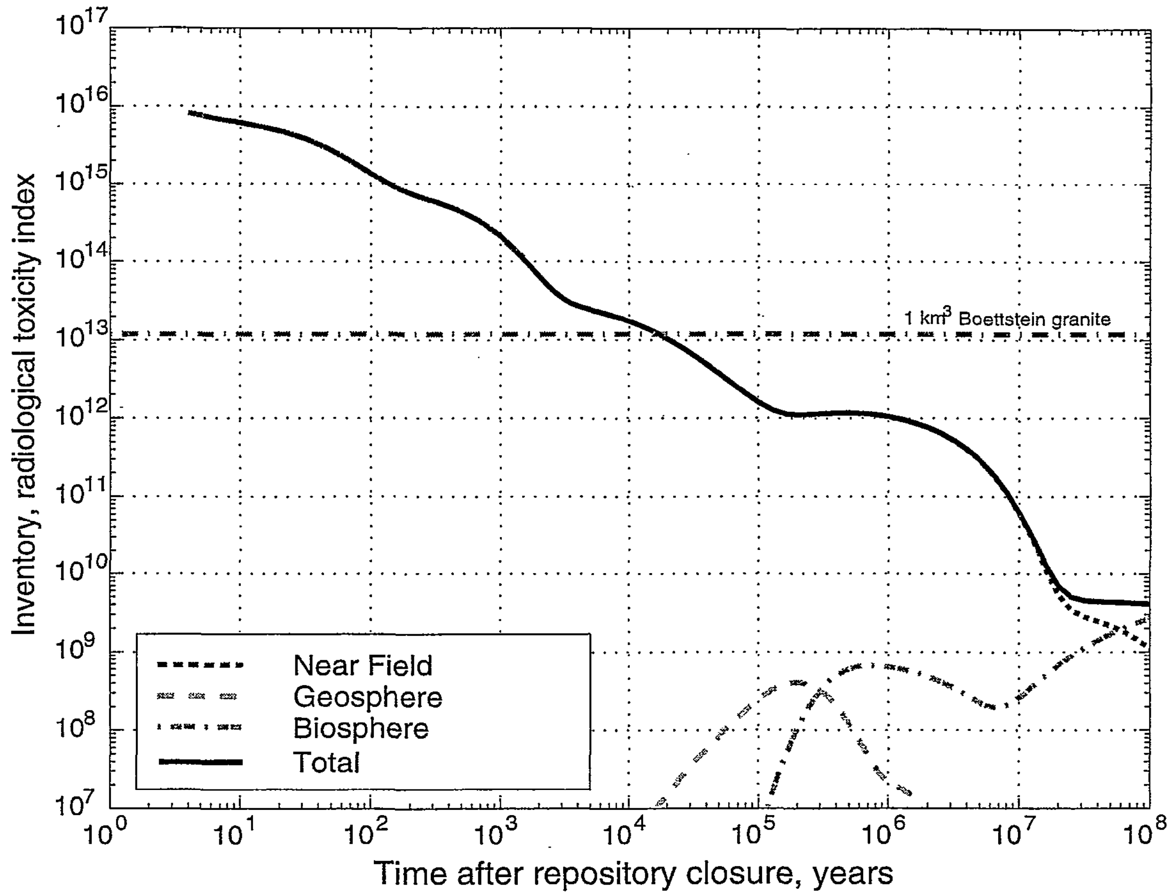
(b) the release of radionuclides is prevented or minimised for as long as possible, avoiding radiological impacts at early times, but at the risk of a possible large release at some time in the future.

If individual dose were the only criteria, then it is possible that an optimum solution might be reached following course (a). However, if a time- or population-integrated measure is adopted then it seems less likely that (a) could be optimum.

A principle of well-managed disposal of long-lived radioactive waste to achieve near 100% containment during a first period of between a few hundred or thousands of years (depending on waste type), because during this time radioactive decay can significantly reduce both the number of radionuclides that remain in significant quantities and the total radiological potential hazard. Beyond this time some release may be unavoidable and, in this later period, thought should be given as to whether a system that degrades gradually but slowly is preferable to one which offers containment for longer but is liable to sudden failure[15].

The extent to which geological disposal systems can be successful in providing containment is illustrated by Figure 3.2. This compares the total radiological toxicity of wastes within a HLW repository with toxicity of calculated leakage from the engineered barriers to the geosphere and into the biosphere; this is based on results from the Kristallin-I safety assessment [Nagra 1994]. Almost all of the radiological toxic potential of the repository (which is dominated by transuranic nuclides with uranium daughters contributing at late times) decays within the engineered barriers. Less than one millionth of the radiotoxicity present at closure ever escapes to the biosphere, even after 10 million years.

[15] Consideration of the disposal of waste in anhydrite deposits provides an example. Provided the anhydrite remains dry then effectively no release is possible. However, under some conditions anhydrite can undergo rapid hydration (gypsification) with associated volume increase and fracturing. Anhydrite deposits, originally considered as a potential repository host rock in Switzerland, have now been discounted for this reason.



Based on results from the Kristallin-I safety assessment [Nagra 1994], the figure shows: (1) the total radionuclide inventory, (2) the radionuclide inventory retained in the engineered barriers (near field), (3) the radionuclide inventory within the geosphere, and (4) the cumulative inventory released into the biosphere. All results include the ingrowth of radioactive daughters and are expressed as a radiological toxicity index based on the doses that would be received if the activity were to be ingested by a human individual.

Even after 10,000 years, when the total radiotoxicity of HLW radionuclides is equivalent to the natural radioactivity contained in 1 km^3 of the host granite considered, less than one millionth of the total residual toxicity of HLW radionuclides has left the engineered barriers. Only at times beyond 10 million years, does the total radiotoxicity released into the biosphere become a significant fraction of the total remaining. At this time, the residual radiotoxicity is less than one millionth of that present at closure. (Figure supplied by Nagra).

Figure 3.2: The total radiological toxicity of a HLW repository and calculated toxicity of release as a function of time.

In general, the major part of the toxic potential of a repository for long-lived radionuclides is associated with shorter-lived fission/activation products (which can be entirely contained by physical barriers) and actinide elements (which can be contained within well-controlled chemical barriers). The major contribution to dose in the biosphere, however, is contributed by long-lived poorly-sorbed fission and activation products such as I-129 and Cl-36, e.g. see [Nirex 1997].

Leakage implies flow of a carrier medium, typically groundwater. This same flow implies potential degradation of chemical and physical barriers. The risk is that the effects of degradation will not be uniform but exhibit a cliff edge effect, e.g. a gradual chemical change past some critical point at which a different range of chemical species are mobilised. "Leaky" repositories might be acceptable for some specific classes of waste, e.g. some low-level wastes, but are unlikely to be acceptable for transuranic or intermediate-level wastes. Also, some monitored leakage might be acceptable during an operational phase (as at Drigg) but this situation would need to be remedied or reduced to trivial levels at closure.

The Nirex cement repository concept can be thought of as a repository design that simultaneously contains the more radiotoxic actinide elements by chemical constraints, while allowing slow leakage by diffusion of certain long-lived poorly sorbed fission/activation products. It would, however, be a mistake to present this as a deliberate attempt to allow slow leakage of radionuclides. The Parliamentary Office of Science and Technology (POST) review [POST 1997] failed to appreciate the advantages of chemical barriers over physical barriers (longevity and reliability) and consequently criticised the use of the chemical barrier by Nirex. The public and general scientific audiences are also likely to consider that a deliberately "leaky" repository is counter to the principle of containment usually assumed in geological disposal.

Nevertheless, provided effective containment is provided for an initial period during which shorter-lived radionuclides decay, there may be advantages in a repository design that allows gradual and slow release thereafter, rather than a rapid release. The details are liable to be host rock and repository design specific, however, and may be a result of choices made for other reasons, rather than a deliberate attempt to manage releases in the long term.

3.2.6 Quantities and domain for optimisation

The normal radiological protection procedure for public exposures is to set limits and constraints in terms of annual dose to an individual, and seek to optimise on collective dose integrated over a defined population(s) and time period(s), within individual dose constraints. The ICRP's own comments indicate a lack of confidence in collective dose estimates, but the principle would appear to be that total impacts, integrated over appropriate temporal and spatial domains, should be minimised, constrained by individual dose rates.

One approach to demonstrating optimisation, therefore, would be to use estimates of individual dose rate as a function of time to show that dose constraints were not exceeded, and use an integrated measure of, say, total radionuclide toxicity released up to some future time (or times) to demonstrate the design was such as to reasonably minimise this quantity. Complications arise because of the inherent uncertainties in long-term future performance calculations. For example, it may be shown that, although the mean dose rate is below a dose constraint or target, there is a small probability that the value will be exceeded. In this case, it may be considered more important to reduce the probability of exceeding the constraint, rather than to reduce the integrated measure.

A possible view is that, for a geological disposal system, apart from a small population dwelling very near to the point of release into the biosphere, most of the possible individual doses due to long-term releases are likely to be very small, and these small doses could be neglected. In this case, it is only left to look at doses to members of exposed groups (hypothetical critical groups) which are usually calculated for geological disposal systems. However, small individual doses can only be neglected if they are of no concern to the exposed individual and also of no concern to the regulator. Very small risks to a large population may still constitute a public health concern and therefore deserve consideration.

The ICRP appear to conclude (see Section 2.2.1), that the annual individual effective doses and risks provide an adequate input to post-closure radiological safety studies. Notwithstanding, the acknowledged uncertainty over the estimation and meaning of population doses and risks in the far future, it would be consistent with the requirements of the GRA to also calculate post-closure population doses and/or risks integrated over appropriate time periods and postulated populations. These would inform the regulatory judgement and, for example, might be compared with estimated collective dose from alternative waste management strategies or from nuclear power operations.

3.2.7 Optimisation as a process

Partly because of the difficulties of defining appropriate endpoints for optimisation, and also because a geological waste repository will be a one-of-a-kind development, optimisation cannot rely on a demonstration at licensing. Rather, it must be a process of continuing iterative and incremental decision-making throughout the development of the repository, where each set of decisions provides guidelines or constraints for the subsequent stage of a project.

As stated in ICRP Publication 64 [ICRP 1995]:

> "The ultimate level of safety . . . results from a choice among feasible alternatives. Those . . . making decisions should satisfy themselves that the most appropriate safety option under the prevailing circumstances has been selected."

and in ICRP Publication 77 [ICRP 1997]:

> "the basic role of optimisation . . . is to engender a state of thinking - have I done all that I reasonably can to reduce the radiation doses?"

The choices made in developing a repository (e.g. of site, site investigation strategy, engineering options, emplacement strategy etc.) will be made over a long period of time with increasing knowledge and, perhaps, increasing technical opportunities along the way. Therefore, the final system is unlikely to be the "best" that could be envisaged at any single point in time. Rather, early decisions will result in commitments in terms of money and human resources that cannot be undone or recovered. The aim is to make good, robust decisions in the light of the information available at each stage. Comparatively long periods of time may be needed for research, site investigation and performance assessment, in order to ensure that a sufficient level of confidence has been reached to reasonably take the next step, involving a step up in commitment of resources (e.g. the move from desk studies to detailed site investigation, or subsequent moves to sinking of an exploratory shaft, development of an URL, excavation of underground caverns etc.).

In studying geological systems (or any natural system), it is often observed that the situation may appear to become more complex, or even more uncertain, as investigations proceed. Investigations at any site are liable to reveal features that are less than optimum or counter to prior expectation. The challenge, then, is whether underground engineering, optimisation of location within a site or modification of other barriers can sufficiently mitigate or avoid these features, since abandoning the site (or engineering concept) will entail writing-off substantial commitments and will not guarantee finding more suitable geological situations elsewhere. This indicates that a measure of caution and awareness of project risk must be exercised in making decisions. For example, in choosing a site there should be confidence that there is a sufficient volume of host rock present, so that the design could be adapted to avoid unexpected features that might be encountered.

3.3 Application of Optimisation

As indicated in Section 3.2.7, optimisation must be seen as an ongoing process and that process must start early, with key decisions being justified and consideration given to their long-term safety implications. At any decision point, long-term safety issues may not be the decisive factor but they should be considered explicitly.

The following stages or areas where optimisation might play a role are identified:

- definition of long-term waste management strategy;
- development of waste disposal concepts;
- development of waste package specifications;
- selection of sites for disposal facilities;
- site investigation strategy;
- development of safety case and supporting research;
- layout and design within a site;
- post-emplacement monitoring, retrievability and repository closure.

In practice, these stages may overlap and there may be some iteration between stages.

3.3.1 Long-term waste management strategy

In the UK, the definition of broad strategy for the long-term management of radioactive waste is the role of government, e.g. see [HM Government 1995]. This, however, does not obviate the need for a developer to present the arguments in support of their particular proposals as part of the broad strategy. In particular, even if disposal is seen as the preferred long-term management approach in the national strategy, the need for a specific facility and timing of its development are key issues to be addressed by the developer. This information may be particularly important to gaining public and local government acceptance for the proposals.

3.3.2 Waste disposal concepts

There is substantial international experience in developing waste disposal concepts and considerable consensus on what might constitute good geological attributes[16], for example:

- low tectonic/seismic and volcanic activity;
- stagnant or slow-moving groundwater, or absence of free groundwater, e.g. in the case of rock salt;
- favourable hydrochemistry, e.g. reducing groundwaters;
- good sorption capacity of host rock or component minerals;
- absence of geological resources that might encourage accidental disturbance of the repository.

Details of waste disposal concepts will be country specific – to take advantage of natural geological opportunities – and also case specific. It is helpful to set out a safety concept, i.e. a qualitative description of the natural and engineered barriers, their key functions and identification of the key processes that will be relied on to provide for safety. Important features of this safety concept are likely to be that

- the engineered design is suited to the geological environment;
- the system offers both physical and chemical containment through a variety of complementary barriers;
- no expected processes or events can be identified that will simultaneously cause all barriers to fail or seriously degrade.

The POST report [POST 1997] criticised the Nirex chemical containment concept on account of the partial nature of the barrier compared to physical containment. On the other hand, effectively indefinite physical containment, e.g. in copper-sheathed or special alloy containers, cannot be contemplated except for low-volume, high-activity wastes such as spent fuel or vitrified high-level wastes, because of the high cost of materials and container fabrication. Even then, events can be envisioned, e.g. shearing under glacial loading, that would lead to the failure of any physical containment system. The time scales over which physical containment can be relied on are likely to be limited to between a few hundred and a few thousand years depending on the site and repository design. The evidence of natural analogues, however, is that chemical containment can operate over much longer time scales and is less susceptible to disruption. Hence, a combination of physical and chemical barriers is desirable and, in the long term, it may be the chemical barriers that are most reliable.

3.3.3 Waste package specifications

For the waste producers, optimisation must start with waste minimisation and control of the characteristics and packaging of wastes, with regard to operational health and safety, cost and compatibility with disposal routes, e.g. see [Beveridge 1998]. A difficulty arises because waste producers may be under pressure to immobilise wastes now in standard packages to achieve passive safety during storage, while they must also have in mind issues of long-term

16 See IAEA 1994b which provides guidance for identifying and selecting suitable geological disposal sites for radioactive waste.

safety, so that at some time in the future the wastes will be accepted for disposal under conditions that are not yet fully specified.

The repository developer/owner will generally work with the waste producers to develop waste package specifications, which will be based on assumptions about the disposal facilities that exist or that they expect to develop. Specifications are generally framed in view of the characteristics of waste arising, available conditioning processes, transport and storage considerations, and only very general principles of eventual stability in a repository. Optimisation with respect to long-term safety cannot be considered in advance of detailed information on the associated repository design, location and performance. Thus, the waste package specifications become a boundary condition for the repository design which the applicant develops.

In the UK, waste package specifications are developed to apply to wastes as they are currently being produced; waste acceptance criteria will only be defined when a disposal facility exists, taking account of the characteristics and estimated performance of the particular facility. In general, waste package specifications are believed to be conservative with respect to eventual waste acceptance criteria, in part, because the package specifications must be such that the packaged wastes should still able to satisfy possible acceptance criteria even after a period of prolonged storage.

At the stage of waste disposal authorisation, the Agency will set conditions on the authorisation which are likely to be related to waste acceptance criteria developed by the applicant. If the developer eventually puts forward a repository design that differs substantially from that assumed at the time that waste package specifications were developed, then a thorough re-examination would be required of the suitability of existing wastes types for disposal in the facility, and wastes may have to be processed or re-packaged before being accepted for disposal.

3.3.4 Site selection

In no country, has the selection of potential sites for a radioactive waste repository been based on technical optimisation. Certain geological environment types may be preferred for technical reasons, but the experience is that sites are chosen for reasons of historical use (e.g. on or near existing nuclear or military sites), geographic convenience, demographic and political factors. Increasingly, local public acceptance is seen as the most critical factor, e.g. in the site selection approaches in Sweden and Canada [EAP 1998].

If alternative sites are selected which have very different geologies, then some broad qualitative distinctions may be made. For example, in Switzerland, four sites with differing geologies were short-listed as possible sites for development of a repository for low-level and short-lived medium level waste [Nagra 1992]: Piz Pian Grand (granite), Bois de la Glaive (anhydrite), Oberbauenstock (marl under limestone) and Wellenberg (marl). In the selection study, the Piz Pian Grand site was marked down because of inconvenient location and transport routes, Bois de la Glaive was marked down because of uncertainty over long term behaviour of anhydrite as disturbed by repository construction. Of the two marl sites, Wellenberg was preferred as a first site for investigation because it represented an easier prospect for geological investigation than Oberbauenstock.

In Finland, where first 5 and then 3 sites have been investigated, all in ancient plutonic basement rock, it has been stated that differences within sites and associated uncertainties, are more important than differences between sites so that a ranking based on post-closure performance analysis is not meaningful [Vieno and Nordman 1996]. In the USA, cost appears to have been the key factor in selecting the Yucca Mountain site, see Section B2, Appendix II.

In the UK, Nirex enacted a national survey procedure to identify first general regions of potentially suitable geology, then specific sites within these regions, e.g. [Chapman and McEwen 1991]. The decision to focus first on Dounreay and Sellafield was, however, related to a claimed "measure of local public support" [Nirex 1989] and later, when focusing on Sellafield, that transport of waste could be minimised. Given that a large proportion of the wastes to be disposed arises or currently resides at the Sellafield site, it is a logical decision to first investigate the potential of the Sellafield region. It might have been better, however, if this decision had been more explicitly stated and supported[17].

Overall, it is unlikely that optimisation of long-term safety will play a role in selection of candidate sites in the UK since the level of information available ahead of site selection is unlikely to reliably distinguish the long-term safety potential of alternative sites, and, it will be argued, a large number of sites could fulfil long-term safety requirements. Once a candidate site is selected, however, long-term radiological safety could be a factor in identifying and selecting potential repository locations in the vicinity of the site and, depending on the site, this might include consideration of different geological and hydrogeological situations.

3.3.5 Site investigation strategy

It can be calculated that, even drilling one hundred 10 cm diameter boreholes into a 1 km^2 area of rock, which would be regarded as excessive, less than 10^{-8} (one millionth of one percent) of the rock will be sampled. Thus, however extensive an investigation is made, there will still be a very large degree of uncertainty regarding the site characteristics. A site investigation strategy must be developed that provides sufficient quality and quantity of information to support PA calculations and reduce uncertainty to a tolerable level. What constitutes a tolerable level will depend on the complexity of the geological situation, the extent to which the safety of the repository relies on the geological characteristics, and also the types of wastes to be disposed, notably their radionuclide content and toxicity. Mackay [1993] advises, see Section B6, Appendix II, that a minimum objective for a site investigation programme must be to establish the true macroscopic conceptual model.

Adequate characterisation of plutonic and volcanic rock sites can be problematic due to the natural heterogeneity and presence of fractures and intrusions at a range of scales. Indeed, opponents of Nirex criticised the Sellafield site as being too complex to be properly characterised, and the Inspector's report from the RCF Public Inquiry concluded that Nirex did not understand the "extreme complexity" of the potential repository zone [POST 1997]. Investigations in low permeability sediments also bring problems, however, e.g. in

[17] Subsequently, the Secretary of State for the Environment stated in his decision to reject the Nirex appeal against refusal of planning permission for the RCF that, in any major development proposal that represents a milestone towards the design and construction of the repository, the Environment Statement should address the question of alternatives and explain and justify why a particular location had been chosen in preference to others [POST 1997].

developing appropriate measurement techniques, interpretation of measurements, and understanding the role of coupled chemical-hydraulic processes and hydraulic disequilibria. Different rock types each bring their particular challenges and opportunities, e.g. see [Sumerling and Smith 1998], and in the UK, which has a mixed geology, it would be unwise to limit options by dismissing a given rock type as too difficult to pursue *a priori*.

A very detailed knowledge of site-specific geological characteristics should not, in any case, be necessary in order to make preliminary calculations of repository safety. Indeed, if safety depends critically on very specific geological characteristics then, it can be argued, this is either not a very good site or repository concept. In particular, a well-designed set of engineered barriers can reduce the requirements on the geology to providing sufficient stability and limiting water inflow such that the engineered barriers operate effectively, e.g. see [Nagra 1994]. This reduces the requirements on site investigation at the stage of demonstrating the concept and, thus, can give confidence that long-term safety can be achieved. If, at a later stage, the flow and transport properties of the host rock and other units can be characterised by site investigation, and these characteristics indicate a significant natural barrier potential, then the engineered barriers may be reduced or optimised to that degree necessary to complement the natural safety of the site[18].

The core of a good site investigation strategy must be a plan of the information that will be obtained tied to the specific use that will be made of the information – to develop the safety case or for technical feasibility and design. Sufficient time needs to be allowed to obtain and interpret data, and assess the implications in PA, before pressing ahead with developments that could limit the opportunities for data acquisition, e.g. by disturbing the natural hydrogeological regime. Complementarily, the excavation of shafts and underground openings, and monitoring of consequent changes, provide opportunities to obtain important data and test models. Such excavations should be planned as part of the investigation programme so that advantage can be taken of the opportunities.

3.3.6 The safety case and supporting research

As indicated earlier, a sound scientific understanding of the relevant features, events and processes (FEPs) is an essential foundation of a repository safety case. It will not, however, be necessary to understand all FEPs at the same level of detail or to represent all FEPs in the safety case. The basic safety concept and PA calculations can give guidance on what are the key features and processes that must be characterised and relied on to construct a safety case, and this knowledge can guide allocation of research budgets. Some processes, while complex and scientifically interesting, may have little impact on final safety, or their effects can be reasonably bounded in safety assessment calculations. Of course, as understanding increases, then previously neglected processes may be recognised as having significant effects that must be investigated. At earlier stages, however, attention should be focused on those features and processes that are expected to provide adequate safety, plus any FEPs with the capacity to undermine key safety-relevant processes.

If research is to be optimised, it is important that it is justified in terms of the PA and safety case that is required; research interests should not be allowed to dictate the safety case that

[18] Alternatively, it could be considered that the originally designed engineered barriers, plus the confirmed site characteristics, represent BPM. In this case a reduction of engineered barrier could only be justified if parts of the engineered barriers were found to be redundant within the geological environment.

can be presented. In the WIPP project, a sharp shift in research management was achieved in the mid-1990s when a formal system of research prioritisation was begun [Prindle et al. 1996]. All research had to be justified in terms of the support it could bring to the PA calculations required to demonstrate compliance, and researchers could not argue the case for further resources in a given field on scientific interest or reputation.

In deciding the level of science to incorporate into performance assessment, there is sometimes a tendency to try to create a fully scientifically-based description of the evolution of the repository system and its environment. There are, however, substantial uncertainties in calculating environmental behaviour into the far future, so that such calculations must always be illustrative to a large degree. In addition, it is not a good idea to fold in details of scientific knowledge that are themselves at the limits of current scientific understanding and are liable to be the subject of debate. Rather, it is better to produce a safety case that relies, as far as possible, on well-known and well-characterised processes, where there is a strong scientific consensus on their nature and appropriate representation, e.g. see [McCombie et al. 1991]. Ideally, it may be desirable to have several lines of calculational arguments, some including more detailed scientific understanding and some including only a limited number of processes and simple models.

3.3.7 Layout and design within a site

The layout and design of a repository within a site is an area where much can be done to optimise the performance of a repository. For example, if a siting area is sufficiently extensive, then the repository might be placed so as to increase the groundwater travel time to the nearest discharge zone, e.g. see [Davison et al. 1996], or location in a zone of stagnant groundwater surrounded or beneath conducting faults may be possible, e.g. see [SKB 1991]. Commonly, calculated performance depends critically on the thickness of good quality rock that can be guaranteed in the transport path, e.g. see [Goodwin et al. 1994][19]. Therefore, disposal tunnels or caverns should be sited so as to avoid significant fracture zones, more permeable seams etc. (this may also be desirable for geotechnical reasons). In several programmes, "respect distances" are specified or calculated as design constraints.

A general point here is that optimisation at one stage generates the design constraints that are used in the next. There is a continuing tension between the fluidity in design implied by optimisation and the need for designers to work to a clear and coherent set of design guidelines. A staged approach should be followed in which optimisation at one stage is used to set guidelines for the next stage, thus optimisation is progressively focused towards a final design goal.

Typical issues to be considered include the following.

- Location and orientation with respect to hydrogeological regime - location such as to maximise groundwater travel times to any discharge zone or in groundwater stagnation zones may be preferred.

- Depth of the repository - at depth, permeabilities may be lower and fractures closed; costs may increase, however, or the temperature may be higher causing problems for operation and thermal design.

[19] Also see Section B4, Appendix II.

- Segregation/waste allocation - it may be desirable from a long-term safety perspective to locate wastes of special characteristics, e.g. high actinide and/or organic content, in separate vaults or even separate geological locations; this, however, will have implications for costs, excavation schedule and operations.

- Tunnel and shaft seals - their location and construction, will be an important factor in ensuring that effective use is made of the natural isolation capacity of the site.

3.3.8 Post-emplacement monitoring, retrievability and repository closure

Studies of the opportunities and uses of post-emplacement monitoring have indicated that post-emplacement monitoring is likely to have no practical benefit to the long-term safety of a deep repository since the time period over which safety-relevant changes are expected to occur or radionuclides are released is so long. In addition, post-emplacement monitoring is likely to demand quite sophisticated remote sensing technology, the long-term reliability of which remains to be proven. Thus, there is a risk that the system would fail to deliver the required information reliably, or its maintenance could interfere with the conditions preferred for long-term safety. Nevertheless, in several countries post-emplacement monitoring is contemplated, or will be required by regulation, mostly as a reassurance measure and to increase public confidence.

Similarly, studies of possibilities for facilitating retrievability by keeping repository tunnels or disposal caverns open for an extended period after waste is emplaced, show that this is liable to introduce an additional set of complicating processes not beneficial to the demonstration of long-term safety. Yet, possibilities for keeping repositories open for extended periods are being considered, mostly motivated by public and ethical concerns, thus creating a long-term monitored underground storage facility rather than disposal facility.

It seems likely that decisions in this area will be driven by public acceptability and, possibly, greater understanding of the application of ethical principles, such as sustainability and the precautionary principle, to waste management. Given the uncertainty on this issue, consideration should be given to repository design and management options that could facilitate monitoring and retrievability while still providing for long-term safety.

3.4 Demonstration of Optimisation

There are at least two elements to the demonstration of optimisation that should be expected from a developer.

1. Since optimisation is interpreted primarily as a process of sound decision-making with awareness of safety and resource implications, then a clear record of the decisions and their basis should be maintained.

2. Analyses should be presented to explain and support past decisions and also to investigate and compare options that are still open to the developer.

The regulator cannot change past decisions, but can seek to ensure the current and future programme or operation is well managed and leads to safe disposals, see Figure 3.3. This includes consideration of remedial actions if necessary (intervention in ICRP terms). The regulator may not be able to change the effects of past decisions but can ensure that where past decisions have turned out to be less than optimal, the effects are mitigated by future decisions and actions.

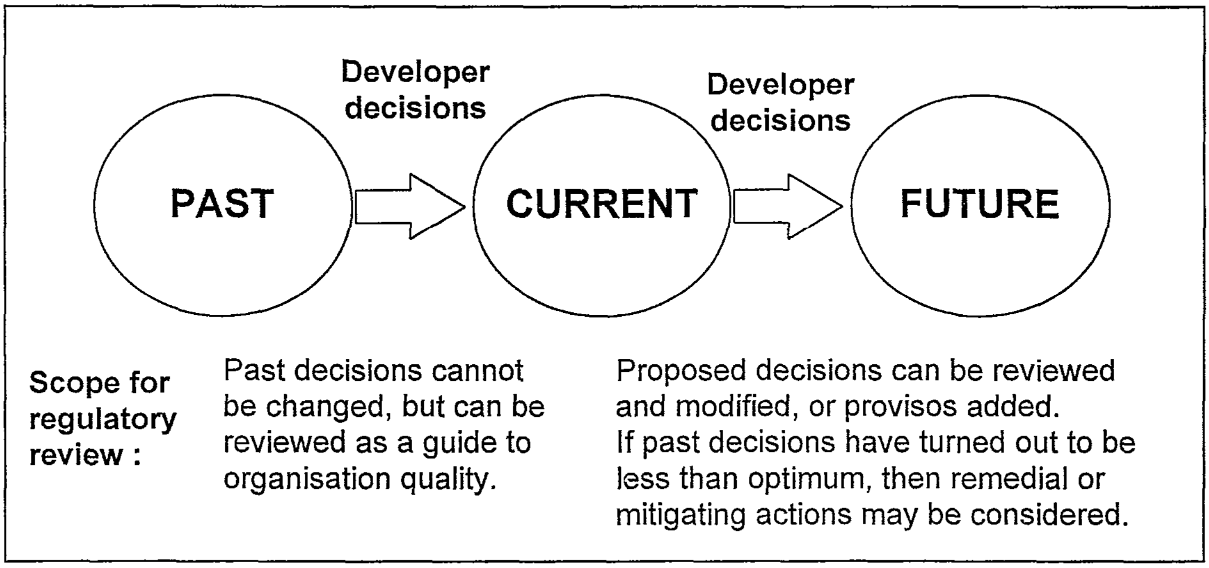


Figure 3.3: Scope for regulatory review of a developer's decision process.

3.4.1 Demonstration in the decision-making process

Under current UK law, the Environment Agency has no statutory power to act unless an application under RSA 1993 to dispose of radioactive wastes has been made; this need not happen until a relatively advanced stage of a repository development project. The GRA, however, indicates that the Agency would favour a staged application process in which a developer communicated and discussed their proposals early. The Agency would then be able to undertake interim reviews of proposals and supporting draft safety submissions, and give interim views to the developer.

Any limitation on the early involvement of a regulator in a repository programme is a potential cause for concern. If optimisation is regarded as a prospective process, without revisiting of previous decisions, a regulator could be presented with a highly developed option as a *fait accompli*. This seems to be a strong argument for a staged application procedure, particularly from the point of view of the developer, since it would be very much within the regulator's power to refuse to grant an operating license. Thus, the developer may prefer a staged application process in order to reduce the commercial risk.

Past decisions

In developing a repository programme, decisions are made against the background of current knowledge and technical capability. A regulator should expect a developer to provide evidence of sufficient evaluation of options and a logical decision process enacted in the past.

The regulator should not seek to revisit these decisions with the benefit of hindsight, but equally the developer should present the evaluation and key factors as they influenced the decision at the time, not a post-justification of the decision. Thus, the regulator can judge whether the developer has followed a logical and justified path in evaluating options and decision-making in the past. This will act as a guide to organisational quality of the developer and also confidence, or not, that the developer is pursuing an appropriate programme.

Proposed decisions

For proposed decisions, a regulator should expect to see an identification and evaluation of options open to the developer, a description of the decision process, and the results of the proposed decision together with an identification of those factors most critical to the decision and discussion of the related uncertainties.

Except in the case of application for authorisation to dispose of wastes, the responsibility for the decision remains primarily with the developer, including the evaluation of project risk. The developer should have sufficient confidence that the proposed course can eventually lead to the development of a repository that can provide adequate conditions for the safe disposal of radioactive wastes, and takes the financial risk that this may not be the case. The regulator should be able to acknowledge, or not, that the decision appears justified in the light of current information, and should give guidance on those open issues that are currently perceived as most critical, e.g. alternative options that might be investigated, processes that appear to deserve further attention, and areas in which uncertainties should be reduced.

3.4.2 Demonstration in the safety case

It is the responsibility of the developer to identify the options to be evaluated, to present appropriate evidence (including reasoned arguments and quantitative analysis) that safety and resource issues have been considered, and show that a reasonable decision has been reached. The methods adopted, and scope of analysis, will depend on the stage of repository development, the PA methodology adopted and the importance of the decision point. It is likely that a more explicit treatment of optimisation will tend to lead to less emphasis on a central total system analysis, and more emphasis on selected subsystem analyses and evaluation of multiple lines of argument in the safety case. Optimisation of long-term protection may only play a subsidiary role at some stages, e.g. site selection, but may be a more important factor at other stages.

Repository design is an area in which the repository developer can do much to achieve optimisation with respect to long-term performance. (Design, here, includes developing the safety concept, the choice of geological location within a potential site area, optimisation of layout and concept at a location, as well as the choice of engineered barriers and excavation/construction techniques and schedule.) Consequently, this is the area on which a regulator could focus their review, to examine what, in principle, might be done, the options considered by the developer and the reasons for the choices made.

The options for the siting and design of a repository for radioactive waste are constrained by various criteria that ensure that:

- the various barriers that delay and attenuate the release of radionuclides to the human environment operate as planned,
- the units that comprise the repository host rock are of sufficient extent to house the required amount of waste,
- the barriers, operating as designed, deliver sufficient safety (e.g. to meet regulatory guidelines),
- the barriers are not unduly subject to processes that might undermine safety (i.e. there is good confidence that the barriers will operate as designed),
- construction and operation of the repository is both safe and practicable, and
- costs are not prohibitive.

In determining whether a design option (a given combination of "design variables") satisfies these criteria, account must be taken of various properties of the disposal system that are fixed features:

- of the site and host rock. i.e. the structural, hydrological and physico-chemical properties of the rock,
- of the waste, i.e. the type and amount of waste for disposal.

Table 3.1 defines a possible hierarchy of levels of design variables that might, with development, be used to review repository designs developed by an applicant. This begins, at Level 1, by identifying very broad design decisions and then examines progressively more detailed decisions.

- Level 1 variables define the basic design concepts consistent with the available host geology or geologies (e.g. tunnel, cavern or silo designs, chemical control strategy, depth options).
- Level 2 variables define general design options and the properties and behaviour required of repository components (e.g. package design life, whether or not cavern/silo liner is required), without specifying the materials to be used (e.g. steel, concrete, grades of material).
- Level 3 variables define more detailed design options, including the materials to be used, for example, for the waste containers and backfill.
- Level 4 variables define additional options, including engineering measures to avert possible disruptive scenarios (e.g. long-term cavern stability measures, tunnel and shaft seal design).

Table 3.1: A hierarchy of levels of design variables that might be used to review an applicant's repository design.

Optimisation will be demonstrated in a safety case primarily through clear presentation of the design process according to a well-defined methodology. Beyond this, quantitative modelling studies may be able to illustrate relative performance of rather broad options but is unlikely to be a sharp enough tool to differentiate more minor design options. Thus, the logic of decisions, and supplementary calculations to confirm their adequacy, are just as important a part of the safety case as system calculations which quantify overall safety levels and demonstrate compliance with regulatory targets.

4. SYNOPSIS AND CONCLUSIONS

4.1 Context and Aim of this Study

Guidance on the Requirements for Authorisation (the GRA) issued by the Environment Agency for England and Wales requires that all disposals of radioactive waste are undertaken in a manner consistent with four principles for the protection of the public. Among these is a principle of Optimisation, that: *"The radiological detriment to members of the public that may result from the disposal of radioactive waste shall be as low as reasonably achievable, economic and social factors being taken into account."*

The principle of optimisation is widely accepted and has been discussed in both UK national policy and guidance and in documents from international organisations. The practical interpretation of optimisation in the context of post-closure safety of radioactive waste repositories is, however, still open to question. In particular, the strategies and procedures that a developer might employ to (1) implement optimisation in the siting and development of a repository and (2) demonstrate optimisation in a safety case, are not defined.

In preparation for its role of regulatory review, the Agency has undertaken this study to explore the possible interpretations of optimisation stemming from the GRA, and to identify possible strategies and procedures that a developer might follow.

The text that follows recalls key points and conclusions from the preceding chapters.

4.2 Regulatory Background, International Guidance and Practice

The UK regulatory background (see Section 2.1)

The requirement to ensure protection is optimised is incorporated in the UK government radioactive waste management policy, and follows the framework set out in the HSE's Tolerability of Risk study.

The GRA sets out the Principles for protection of the public and the Requirements that an applicant would be expected to fulfil in order to gain authorisation. In particular, Principle No. 3 on Optimisation (quoted above) is set, and Requirement R3 is made that 'best practicable means' (BPM) shall be employed to ensure any radioactive releases are such that doses to members of the public and risks to future populations are 'as low as reasonably achievable', economic and social factors being taken into account (ALARA).

Figure 4.1 shows an outline procedure for the optimisation of long-term protection in the case of a radioactive waste disposal facility, derived from the GRA.

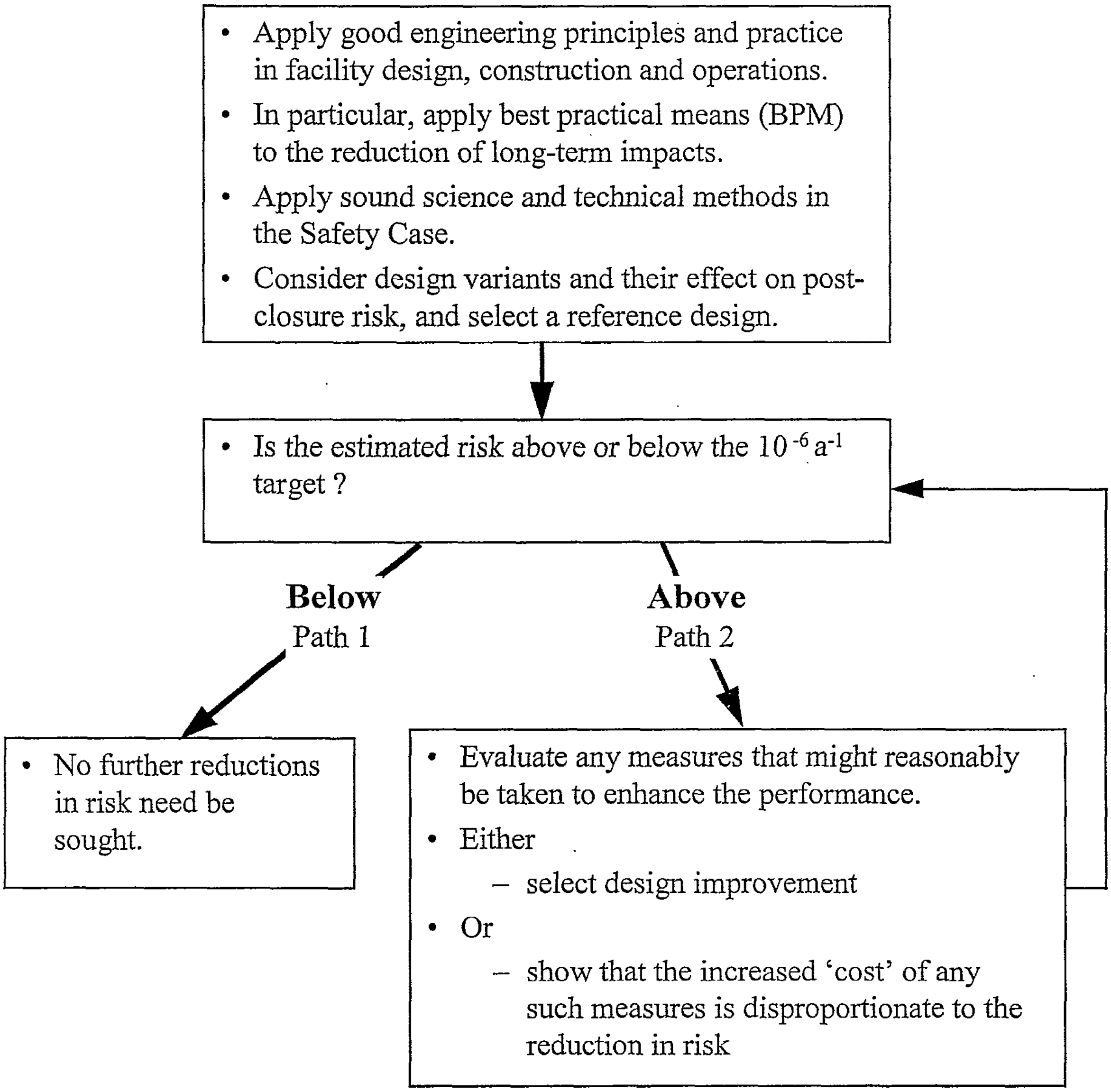


Figure 4.1: An outline procedure for the application of the optimisation principle derived from the GRA.

Optimisation in relation to solid waste disposal is discussed in advice from the NRPB, although this may be considered to be mainly superseded by later guidance from the ICRP, see below. The RWMAC/ACSNI Study Group report noted the public may regard a risk of one in a million as a maximum acceptable figure rather than a lower bound of the tolerability region; thus Path 2 in Figure 4.1 might not be acceptable, especially for a new facility.

International guidance (see Section 2.2)

The ICRP system of radiological protection, including optimisation, applies to solid radioactive waste disposal activities but with some difficulties mainly related to uncertainties over the reliability and interpretation of dose and risk estimates at long times in the future.

The ICRP considers that exposures to members of the public due to solid radioactive waste disposal are always potential exposures and not amenable to control by classical radiological protection methods. Dose limits cannot be applied since doses cannot be verified. Rather, emphasis must be placed on optimisation within dose constraints. The ICRP has stated that the basic role of optimisation is to engender a state of thinking: "have I done all that I reasonably can to reduce the radiation doses?" It is recognised that optimisation is largely judgmental and should be seen as a pragmatic process of evaluating existing technologies and selecting an appropriate solution with regard to sound waste management principles.

Although estimated future individual doses should be seen as indicators of safety, rather than actual doses, ICRP consider that annual individual doses and risks to appropriate critical groups will provide an adequate input to a comparison of the limiting detriment to future generations with that which is currently applied to the present generation. Collective dose is not a useful quantity for optimisation studies because of the uncertainties in individual dose and in the number and characteristics of exposed individuals.

An IAEA working group has reviewed the application of optimisation in the context of solid radioactive waste disposal. It noted that, although the principle of optimisation is valid and appropriate, a detailed quantitative optimisation procedure does not usually play a major role in the decision-making process. Judgmental and qualitative optimisation is, however, certainly included in the development of repository designs and operations.

Examples of optimisation in performance assessment (see Section 2.3)

Most performance assessments (PAs) focus on evaluating the performance of a given option. It appears that a systematic demonstration of optimisation of a repository system has not yet been attempted. Several illustrations exist, however, of optimisation at particular decision points, or for specific aspects, of a repository programme, e.g. development of waste management strategy, choice of disposal site, development of system design and repository layout. From these, it can be observed that, even where quantitative analysis is performed, the calculations do not provide unequivocal evidence that one option is better than another. The main value of the analysis is, rather, to illuminate the factors involved in a decision.

The current trend in PA is away from static demonstrations of safety towards recognising the role of analysis as a decision-aiding technique at key stages of repository development programme. Thus, the key question to be answered by a safety analysis is whether a sufficient level of confidence has been reached to justify the commitment of resources that the next stage of the programme is likely to involve. This is consistent with a more explicit emphasis on optimisation achieved via well-founded decision making during the programme, see below.

4.3 Resume of the Issues

Optimisation in the context of the post-closure safety of radioactive waste disposal is different from the traditional application of optimisation to operational aspects of nuclear installations. This is because of the long time periods before a member of the public or the environment is exposed (thus, it must be assumed, there will be no monitoring of radioactivity releases or exposures, nor ability to control releases or take remedial actions) and, also, because there is considerable uncertainty about the long-term performance of the engineered and natural barriers and future events that might affect them (so that the effectiveness of siting and design measures aimed at improving performance are difficult to judge).

Three high-level issues or questions have been identified and discussed. These are:

1. The meaning of optimisation – scope and strategies for optimisation – what are we trying to achieve?

2. Application of optimisation – in waste management and repository development programmes – how is optimisation to be implemented?

3. Demonstration of optimisation - in performance assessment, the safety case and decision making - how is optimisation to be demonstrated?

Key statements and conclusions from the discussion are summarised below.

4.3.1 The meaning of optimisation

Radiological detriment or surrogate measures (see Section 3.2.1)

The ICRP indicate that the calculation of collective doses in the far future is questionable and it has been suggested that other measures, such as radionuclide flux, might be a more robust measure in optimisation studies. However, since there is no objective method of assigning value to such surrogate measures, there seems to be little value in adopting them to support optimisation. Individual dose or radiological risk estimates seem preferable as an end point in optimisation studies because, not only the relative reduction in impact, but also the nearness to any target or constraint, can be appreciated.

The focus of optimisation (see Section 3.2.2)

There is significant uncertainty in estimating the long-term impacts from a repository for long-lived radioactive wastes. Confidence that a system can be built and will perform acceptably is more important than achieving a theoretically best design. Thus, optimisation should focus first on confidence and robustness of design (meaning the extent to which a proposed design can be implemented in practice and can be relied on and behave as expected), and then on confidence in the estimated performance (meaning the scientific confidence in the models and data applied). Performance calculations may be used later to illustrate any quantitative difference between design variants and indicate that the chosen design option leads to acceptably low long-term radiological consequences.

Confidence in system design (see Section 3.2.3)

Good engineering principles should be applied in developing a repository design for the specific geological environment. In particular, components and materials should be chosen in view of their longevity and reliability in repository conditions.

The various natural and engineered barriers and features should be viewed as complementary rather than independent. It is important that there is a low probability of any event that could significantly undermine several safety barriers, i.e. the safety case should be multi-factor.

Confidence in estimated performance (see Section 3.2.4)

The basis of confidence in estimated performance must be a sound scientific understanding of the relevant features, events and processes (FEPs), and a thorough methodology by which to identify relevant FEPs, construct mathematical models at appropriate spatial and temporal scales, and obtain and select appropriate data for use in the models.

Before using assessment models to demonstrate optimisation, it is important to consider the level of uncertainty or bias incorporated in the models, especially deliberate conservatisms, since these may distort the relative importance of different components of the system.

Strategy for optimisation (see Section 3.2.5)

A disposal system might be designed so that either the radionuclides are released at slow, steady rate so that the inventory falls over time, or so that the release of radionuclides is minimised for as long as possible.

A general design principle for the disposal for long-lived radioactive waste is to achieve a high level of containment during an early period, during which radioactive decay will reduce the radiological hazard. Thereafter, there may be advantages in a system that degrades gradually, or allows slow release, rather than one that is liable to sudden failure allowing more rapid release. The details, however, are liable to be host rock and design specific rather than a deliberate attempt to manage releases in the long term.

Quantities and domain for optimisation (see Section 3.2.6)

The ICRP optimisation principle requires that ***all*** doses should be as low as reasonably achievable and this is usually implemented by minimising population doses within individual dose constraints. Complications arise because of the uncertainties in long-term performance calculations. For example, it may be considered important to reduce the probability that individual constraints are exceeded, as well as reducing global measures.

The ICRP appear to conclude that the individual doses and risks provide an adequate input to post-closure radiological safety studies. Nevertheless, it would be consistent with the requirements of the GRA to also calculate post-closure population doses and/or risks. These would inform the regulatory judgement and, for example, might be compared with estimated collective doses from alternative waste management strategies or from nuclear power operations.

Optimisation as a process (see Section 3.2.7)

For a geological repository, optimisation cannot rely on a demonstration at licensing. Rather, it must be a process of iterative and incremental decision-making throughout the development of the repository. The aim is to make good, robust decisions in the light of the information available at each stage. Each set of decisions will provide guidelines for the subsequent stages of the project.

The final disposal system is unlikely to be the "best" that could be envisaged at any single point in time. Early decisions will result in commitments in terms of money and human resources that cannot be undone or recovered. Investigations may reveal features that are less than optimum or counter to prior expectation. The challenge, then, is whether underground engineering, optimisation of location within a site, or modification of other barriers can sufficiently mitigate or avoid these features, since abandoning a site (or engineered concept) will entail writing off substantial commitments and will not guarantee finding more suitable geological situations elsewhere.

4.3.2 Application of optimisation

Long-term waste management strategy (see Section 3.3.1)

The definition of broad strategy for the long-term management of radioactive waste is the role of government. The developer, however, still needs to present the arguments in support of their particular proposals as part of the broad strategy. The need for a specific facility and its timing are key issues to be addressed, and this information may be important to gaining public and local government acceptance for the proposals.

Waste disposal concepts (see Section 3.3.2)

It is helpful to set out a safety concept, i.e. a qualitative description of the natural and engineered barriers, their key functions and identification of key processes that will be relied on to provide for safety. Important features of this safety concept are likely to be that:

- the engineered design is suited to the geological environment;
- the system offers both physical and chemical containment through a variety of complementary barriers;
- no processes or expected events can be identified that will simultaneously cause all barriers to fail or seriously degrade.

Using high-specification waste packages, e.g. copper-sheathed or special alloy containers, to provide extended physical containment can only be contemplated for low-volume, high activity wastes such as spent fuel or vitrified high-level waste. The time scales over which more conventional steel or concrete packages can be relied to provide containment are likely to be limited to between a few hundred and a few thousand years. The evidence of natural analogues, however, is that chemical containment can operate over much longer time scales and is less susceptible to disruption.

Waste package specifications (see Section 3.3.3)

Waste package specifications are generally framed in view of the characteristics of waste arising, available conditioning processes, transport and storage considerations, and only very general principles of eventual stability in a repository. Thus, optimisation will be mainly with respect to operational safety, and the waste package specifications become a boundary condition for future repository design.

In the UK, waste package specifications are developed to apply to wastes as they are currently being produced; waste acceptance criteria will only be defined when a disposal facility exists.

At the stage of waste disposal authorisation, the Agency will set conditions on the authorisation which are likely to be related to the waste acceptance criteria developed by the applicant. If, however, the developer puts forward a repository design that differs substantially from that assumed at the time that waste package specifications were developed, then a thorough re-examination would be required of the suitability of existing waste types for disposal in the facility, and wastes may have to be processed or re-packaged before being accepted for disposal.

Site selection (see Section 3.3.4)

In no country, has the selection of potential sites for a radioactive waste repository been based on technical optimisation. Certain geological environment types may be preferred for technical reasons, but the experience is that sites are chosen for reasons of historic use, geographic convenience, demographic and political factors. Local public acceptance is increasingly seen as the most critical factor.

Optimisation of long-term safety is not expected to play a large role in the selection of candidate sites in the UK, since the level of information available ahead of detailed site investigation is unlikely to reliably distinguish the long-term safety potential of alternative sites. Once a candidate site is selected, however, long-term radiological safety could be a factor in identifying possible repository locations in the vicinity of the site, and this may include consideration of different geological and hydrogeological situations.

Site investigation strategy (see Section 3.3.5)

The site investigation should provide sufficient quality and quantity of information to support PA calculations and reduce uncertainty to a tolerable level. What constitutes a tolerable level will depend on the complexity of the geological situation and the extent to which safety relies on the geological characteristics. Different rock types each bring their particular challenges and opportunities, and in the UK, which has a mixed geology, it would be unwise to limit options by dismissing a given rock type as too difficult to pursue *a priori*.

The core of a good site investigation strategy must be a plan of the information that will be obtained tied to the use that will be made of the information. Sufficient time needs to be allowed to obtain and interpret data, before pressing ahead with developments that could limit the opportunities for data acquisition. Complementarily, the excavation of shafts and underground openings, and monitoring of consequent changes, provide opportunities to obtain data and test models, and should be planned as part of the investigation programme.

The safety case and supporting research (see Section 3.3.6)

The safety concept and PA calculations can give guidance on what are the key features and processes that must be characterised and relied on to construct a safety case, and this knowledge can guide allocation of research budgets. Research should be justified in terms of the support it can bring to the PA and safety case, research interests should not be allowed to dictate the safety case that can be presented.

It is not a good idea to fold into the safety analysis details that are at the limits of current scientific understanding and are liable to be the subject of debate. Rather it is better to produce a safety case that relies on well-known processes, where there is scientific consensus on their nature and appropriate representation. It may, however, be desirable to have several lines of calculational argument, some including more detailed scientific understanding and some including only a limited number of processes and simple models.

Layout and design within a site (see Section 3.3.7)

This is an area where much can be done to optimise the performance of a repository. The repository should be arranged to take advantage, as far as possible, of the natural geological safety potential of the site, e.g. by observing respect distances to faults and locating the repository so as to maximise groundwater travel times. Typical issues to be considered will include location and orientation with respect to hydrological regime, the depth of repository, segregation of wastes, and tunnel and shaft seals.

Monitoring, retrievability and repository closure (see Section 3.3.8)

Post-emplacement monitoring is unlikely to have practical benefits to the long-term safety of a deep repository because the time period over which safety-relevant changes are expected to occur is so long. Nevertheless, such monitoring may be contemplated as a reassurance measure. Similarly, repository tunnels or disposal caverns may be kept open for extended periods in order to improve retrievability. This will introduce an additional set of complicating processes that may not be beneficial to long-term safety.

Decisions in this area are liable to be driven by public acceptability and, possibly, greater understanding of the application of ethical principles to waste management. Given there may be a demand, consideration should be given to incorporating measures to monitor and facilitate retrievability while still providing for long-term safety.

4.3.3 Demonstration of optimisation

There are at least two elements to the demonstration of optimisation that should be expected from a developer.

1. Since optimisation is interpreted primarily as a process of sound decision-making with awareness of safety and resource implications, then a clear record of the decisions and their basis should be maintained.

2. Analyses should be presented to explain and support past decisions and also to investigate and compare options that are still open to the developer.

The regulator cannot change past decisions, but can seek to ensure the current and future programme or operation is well managed and leads to safe disposals. This includes the consideration of remedial actions, if necessary, through which the regulator can ensure that where past decisions have turned out to be less than optimal, the effects are mitigated by future decisions and actions.

Demonstration in the decision-making process (see Section 3.4.1)

The GRA indicates that the Agency favour a staged application process in which a developer communicates and discusses their proposals early. The Agency will then be able to undertake interim reviews of proposals and supporting draft safety submissions, and give interim views to the developer. The developer may also prefer a staged application process in order to reduce the commercial risk.

Past decisions

The developer should provide evidence of sufficient evaluation of options and a logical decision process enacted in the past. The regulator should not seek to revisit these decisions with the benefit of hindsight, but equally the developer should present the evaluation and key factors as they influenced the decision at the time, not a post-justification of the decision. Thus, the regulator can judge whether the developer has followed a logical and justified path in evaluating options and decision-making in the past.

Proposed decisions

For proposed decisions, a regulator should expect to see an identification and evaluation of options open to the developer, a description of the decision process, and the results of the proposed decision together with an identification of those factors most critical to the decision and discussion of the related uncertainties.

Except in the case of an application for authorisation to dispose of wastes, the responsibility for the decision remains primarily with the developer. The developer should have sufficient confidence that the proposed course can eventually lead to the development of a repository that can provide adequate conditions for the safe disposal of radioactive wastes. The regulator, should be able to judge whether the decision appears justified in the light of current information, and give guidance on those open issues currently perceived as most critical.

Demonstration in the safety case (see Section 3.4.2)

It is the responsibility of the developer to identify the options to be evaluated, to present appropriate evidence (including reasoned arguments and quantitative analysis) that safety and resource issues have been considered, and show that a reasonable decision has been reached. The methods adopted, and scope of analysis, will depend on the stage of repository development, the PA methodology adopted and the importance of the decision point.

Repository design is an area in which the repository developer can do much to achieve optimisation with respect to long-term performance. (Design, here, includes developing the safety concept, the choice of geological location within a potential site area, optimisation of layout and concept at a location, as well as the choice of engineered barriers and excavation/construction techniques and schedule.) Consequently, this is the area on which a regulator could focus their review, to examine what, in principle, might be done, the options considered by the developer and the reasons for the choices made.

Optimisation will be demonstrated in a safety case primarily through clear presentation of the design process according to a well-defined methodology. Beyond this, quantitative modelling studies may be able to illustrate relative performance of rather broad options but is unlikely to be a sharp enough tool to differentiate more minor design variants. Thus, the logic of decisions, and supplementary calculations to confirm their adequacy, are just as important a part of the safety case as system calculations which quantify overall safety levels and demonstrate compliance with regulatory targets.

4.4 Overall Conclusions

The main conclusions from the study are as follows.

- A very broad interpretation should be taken of the meaning of optimisation, encompassing good decision-making throughout the repository programme, including qualitative judgements.
- Optimisation should be implemented by ensuring safety, cost and resource issues are properly considered at each decision point in the siting and development of a repository.
- The Agency should expect a developer to demonstrate optimisation by:
  (1) providing a clear record of past decisions and their basis as considered at the time, and
  (2) presenting qualitative arguments and calculations that support their design choices and compare key options still open to the developer.

This report is published by the Agency as input to the international discussion on the subject of optimisation in the context of radioactive waste disposal facilities.

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Appendix I:

Extracts from UK Regulatory and International Guidance Documents

This appendix presents extracts from UK regulatory and guidance documents and from international guidance documents that refer to optimisation in the context of a disposal facility for long-lived radioactive waste. Extracts are included from the following documents:

A1. Command 2919 "Review of Radioactive Waste Management Policy" [HM Government 1995] which describes government policy;

A2. the Environment Agency's "Guidance on Requirements for Authorisation" (GRA) [Environment Agency et al. 1997] which provides the definitive regulatory guidance in this area;

A3. the NRPB's "Board Statement on Radiological Protection Objectives for the Land-based Disposal of Solid Radioactive Wastes" [NRPB 1992] which was a source of reference for the above-mentioned GRA document;

A4. the report of the RWMAC/ACSNI Study Group on "Site Selection for Radioactive Waste Disposal Facilities and the Protection of Human Health" [RWMAC/ACSNI Study Group 1995];

A5. ICRP Publication 77, "Radiological Protection Policy for the Disposal of Radioactive Waste" [ICRP 1998].

A1. Cm 2919: Review of Radioactive Waste Management Policy, July 1995

71 The risks that people are prepared to accept and the degree to which risk is perceived vary considerably from individual to individual. The HSE has conducted a considerable amount of work on tolerable and acceptable levels of risk, culminating in the publication of *The Tolerability of Risk from Nuclear Power Stations* (TOR), originally issued in 1988 and updated in 1992. This recognised that there was an upper limit beyond which a risk would be intolerable, regardless of the benefit which society derived from the activity involved, and a lower level, below which the risk was negligible in comparison with the other risks we run in our daily lives and therefore broadly acceptable. The area in between was the ALARP or "tolerability" region, in which risk is tolerable only if it is as low as reasonably practicable (ALARP) - i.e. to reduce it further would involve disproportionately high cost.

72 The Government proposes to introduce a threshold, or lower bound for optimisation, for radioactive waste discharges similar to the area of broadly acceptable risk recognised in TOR - i.e. an annual risk of death of around one in a million (10^{-6}) or less. As the HSE points out, an annual risk of 10^{-6} is not altogether negligible: it is broadly the same as that of death from electrocution in the home (and is about a hundred times less than the annual average risk of dying in a traffic accident). But it is a level of risk which, provided there is a benefit to be gained and proper precautions are taken, does not generally worry us or cause us to alter our ordinary behaviour in any way.

78 In the Government's view, the nature of the disposal system makes it less amenable to such quantified risk assessments than is the case, for example, for new nuclear reactors. Reliance cannot be placed exclusively on estimates of risk to determine whether a disposal facility (or a nuclear plant) is safe. While such calculations can *inform* a judgement about the safety of a facility, other technical factors, including ones of a more qualitative nature, will also need to be considered in arriving at the decision. The Government therefore confirms the preliminary conclusion of the review that it is inappropriate to rely on a specified risk limit or risk constraint as the criterion for determining the acceptability of disposal facility. A risk target, however, should be used as an objective in the design process and this should be a risk of 10^{-6}/y of developing either a fatal cancer or a serious hereditary defect. Where the regulators are satisfied that best practicable means have been adopted by the operator to limit risks and the estimated risks to the public are below this target, then no further reductions in risk should be sought. However, if the estimated risk is above this target, then the regulators will need to be satisfied not only that an appropriate level of safety is assured, but also that any further improvements in safety could be achieved only at disproportionate cost.

A2. The GRA: Guidance on Requirements for Authorisation, January 1997

CHAPTER 2 - GLOSSARY

As low as reasonably achievable (ALARA)

Radiological doses or risks from a source of exposure are as low as reasonably achievable when they are consistent with the relevant dose or risk standard and have been reduced to a level that represents a balance between radiological and other factors, including social and economic factors; the level of protection may then be said to be optimised.

Best Practicable Means (BPM)

Within a particular waste management option, the BPM is that level of management and engineering control that minimises, as far as practicable, the radiological impact of the option whilst taking account of a wider range of factors, including cost-effectiveness, technological status, operational safety, and social and environmental factors. In determining whether a particular aspect of the proposal represents the BPM, the Agencies will not require the applicant to incur expenditure, whether in money, time or trouble, which is disproportionate to the benefits likely to be derived. Where it is demonstrated that BPM has been applied, doses or risks may be regarded as ALARA.

CHAPTER 5 - PRINCIPLES FOR THE PROTECTION OF THE PUBLIC

5.8 Principle No. 3 - Optimisation (as low as reasonably achievable)

The radiological detriment to members of the public that may result from the disposal of radioactive waste shall be as low as reasonably achievable, economic and social factors being taken into account.

5.9 In submissions related to the design and operation of a disposal facility, the applicant for authorisation should show that the best practicable means are being employed to ensure that the radiological detriment to members of the public, both before and after withdrawal of control over the facility, will be as low as reasonably achievable when viewed against wider perspectives, including recognition of competing claims on limited economic resources and that there is no risk-free option for managing radioactive waste. Demonstration of optimisation will entail showing that, among other things, the safety case has a sound scientific and technical basis and that good engineering principles are being applied in facility design, construction, operation and closure.

CHAPTER 6 - RADIOLOGICAL REQUIREMENTS

6.12 Requirement R2 - Period after control is withdrawn (risk target).

After control is withdrawn, the assessed radiological risk from the facility to a representative member of the potentially exposed group at greatest risk should be consistent with a risk target of 10^{-6} per year (i.e. 1 in a million per year).

6.14 In the 1995 White Paper (Ref. 8), the Government stated that reliance cannot be placed exclusively on estimates of risk to determine whether the facility is safe. Whilst such calculations can inform a judgement on the safety of the facility, other technical factors, including some of a more qualitative nature, will also need to be considered. (See Chapter 9 for further discussion). The Government therefore considers it inappropriate to rely on a specified risk limit or risk constraint as an acceptance criterion for disposal facility after control is withdrawn. It is, however, considered appropriate to apply a risk target in the design process. Where the Agency is satisfied that good engineering and good science have been adopted by the operator and that the estimated risk to the public is below this target, no further reductions in risk will be sought. However, if the estimated risk is above the target, the Agency will need to be satisfied not only that an appropriate level of safety is assured, but also that any further improvements in safety could be achieved only at disproportionate cost.

6.23 Requirement R3 - Use of best practicable means

The best practicable means shall be employed to ensure that any radioactivity coming from a facility will be such that doses to members of the public and risks to future populations are as low as reasonably achievable (ALARA - see Glossary).

After withdrawal of control

6.25 Where appropriate, the developer should also consider variants to the design for their effect on radiological risk to potentially exposed groups for the period after withdrawal of control over the facility. In order to focus attention on those features of the disposal facility that influence radiological detriment and are amenable to regulatory control, the result of varying the key design parameters should be assessed. If for the chosen design the risk to a representative member of the potentially exposed group of greatest risk is above the target of 10^{-6} per year, the developer should show that the design is optimised such that any additional measures which might reasonably to taken to enhance the performance of the chosen design would lead to increases in expenditure, whether in time, trouble or money, disproportionate to the reduction in risk. The demonstration of optimisation should also take into account any other relevant benefits and detriments. However, where the Agency can be satisfied that the safety case has a sound scientific and technical basis, that good engineering principles and practice are being applied in facility design, construction, operation and closure, and that the risk to potentially exposed groups is below the target, then no further reductions in risk need be sought.

A3. NRPB Board Statement on Radiological Protection Objectives for the Land-based Disposal of Solid Radioactive Wastes, 1992

Optimisation of protection

71 This advice relates only to the period after closure of a waste disposal site. However, for the purposes of optimisation, it should be remembered that it will also be necessary to consider factors relating to the design, construction and operational periods, such as costs and occupational doses.

72 The main radiological input to optimisation studies has generally been the total (integrated) collective dose, as a surrogate for the total health detriment incurred. For optimisation studies relating to solid waste disposal, however, the use of collective dose is far from ideal. Even with relatively short (in solid waste disposal terms) integration times, the post-disposal collective dose to members of the public is so dependent on detailed assumptions about the biosphere, human behaviour and population size that such calculations must be treated with extreme caution. In fact they can be treated as no more than indicators.

73 One exception to this recommendation is the case of relatively simple optimisation studies related to the detailed design of a disposal facility, where (for example) cost-benefit analysis may be used to compare options which are, to a large extent, similar. In such situations, even though the absolute values of collective dose are not likely to be reliable, *comparisons* between collective doses for different options are likely to be. However, even in these cases, care will be required in assigning a monetary value to a quantity of detriment which is uncertain.

74 More generally, the use of multiattribute decision-aiding techniques (such as multiattribute utility analysis) should reduce the need for absolute values of health detriment, and therefore it may be possible to use a more reliable surrogate which avoids the problems of making specific assumptions about the biosphere and human behaviour. There are a number of possibilities, including calculating the 'virtual collective dose', i.e. the collective dose which would be delivered to a chosen reference population in a chosen reference model, or the total radionuclide flux across some specified boundary (weighted according to the nature of the nuclides). Even with a more 'well-behaved' surrogate for health detriment, however, the problem of how to weight this measure of detriment against 'real' detriments (e.g. worker doses) and costs remains.

75 Society's perception of low consequence, high probability events tends to differ fundamentally from that of high consequence, low probability events. Therefore, when individual risks are used in optimisation studies, the probability and consequence components (see paragraph 55) should always be given separate consideration.

Optimisation of protection

90 All risks, to individuals and populations, should be kept as low as reasonably achievable, economic and social factors being taken into account.

91 Calculations of collective dose (or societal risk), for input to optimisation studies, extending far into the future are unlikely to be reliable, and therefore such calculations are not, in general, recommended.

92 When individual risk is used as an input for optimisation studies, separate consideration should be given to the probability and dose elements of risk.

93 Demonstration that risks are ALARA should be based on quantitative arguments, except for the time period beyond about 1 000 000 years, when qualitative arguments should be used.

A4. RWMAC/ACSNI Study Group Report: Site Selection for Radioactive Waste Disposal facilities etc., March 1995

3. The approach to safety, the terminology used and the standards set should be those of the Tolerability of Risk (TOR).

6. The TOR criteria cannot be directly applied in the early selection process stages and the Study Group thus recommends the development of derived, equivalent criteria based directly on known geological and hydrogeological characteristics. The Study Group has illustrated its thinking by reference to an illustrative index based on groundwater return time, but other indices should also be developed, covering, for example, sorptive geological properties and disruptive processes.

Chapter 3: Human Health Protection Criteria

3.37 The Tolerability of Risk concept and terminology introduced by the HSE is appropriate and relevant to radioactive waste repositories. In the context of waste repositories its essential features can be restated as follows:

- the maximum acceptable risk of fatal cancer to a member of the public from a repository is one in a hundred thousand per year; this risk constraint corresponds with a dose constraint of 0.3 mSv;
- below this maximum acceptable risk, risks should be reduced to a level as low as reasonably achievable (ALARA), but if the risk of fatal cancer to a member of the public is less than one in a million per year then the risk can be considered to be acceptable and the ALARA requirement can be relaxed;
- if the performance of the repository is such that the risk is above one in a million per year, then the onus is on the developer to demonstrate that it would require a disproportionate amount of resources to reduce the risks further.

3.38 It seems reasonable and consistent that the levels of risk regarded as broadly acceptable and just tolerable for a waste repository should be no different from the levels considered broadly acceptable and just tolerable for any other nuclear plant. Both represent imposed risks rather than voluntarily accepted risks, and both concern risks from actual or potential exposure to radioactive material. It is possible that the risks posed by a radioactive waste repository are regarded with more concern by the public because the risks will accrue to future generations rather than to the current generation, and because the risks are less reliably predictable (because, for example, of geological uncertainty) than the relatively well understood risks from other nuclear plants. It is certainly true that the confidence limits placed on an estimate of the risk arising from a radioactive waste repository will be wider than those for the risks from other nuclear plant, particularly at long times in the future. However, this should be taken into account in the way the potential risks are estimated and assessed rather than by applying different criteria of acceptability.

3.39 Nevertheless, the application of the Tolerability of Risk concept to radioactive waste repositories is not yet well understood by the public. The introduction of the concept in the DoE Consultation Document, and, in particular, the suggestion that a risk above one in a million per year would be acceptable if it was shown that further reductions in risk could only be achieved at disproportionate cost, is perceived by some contributors to the hearing at Cleator Moor as a weakening of the criterion set out in the "Green Book" that this level was an appropriate target for a repository. A level of risk of one in a million per year is generally regarded as acceptable (indeed, it is considered to be an acceptable level by Friends of the Earth). However, the evidence from the hearing is that the public regard it as a maximum acceptable figure rather than the lower boundary of a tolerable region. Thus, although the Study Group sees no reason for not adopting the same risk levels for all nuclear plant, including repositories, it recommends, from its experience at the hearing, that more consideration needs to be given to the intolerable or unacceptable risk level for waste repositories.

3.44 Most safety criteria focus on individual risk rather than risks to populations. The uncertainties in the estimation of population risk are even larger than those in the estimation of individual risk. While it may be possible to postulate the behaviour of individuals or small groups of individuals and so make an estimate of the risks to which they may be exposed, it is impossible to estimate the number of individuals who may be exposed. The uncertainty in any estimate of population risk would be so large that it would not be possible to discriminate between waste disposal options, and it is therefore not a useful quantity when evaluating the safety of waste repositories.

Chapter 7: Response to the Terms of Reference and Other Conclusions

7.3 Site selection

(v) With this in mind the Study Group has suggested that a small number of indices be established to characterise the safety aspects of potential areas. These aspects include:

- stability against natural disruptive events
- hydrogeology

- chemical and geochemical properties, including good retention properties
- mechanical and thermal properties
- depth and volume of the host rock
- proximity to natural resources.

The evaluation of such indices would enable areas to be ranked in provisional safety order. Criteria for these indices, based on the fundamental risk criteria, would enable areas to be disqualified as being unlikely to be safe enough.

A5. ICRP Publication 77: Radiological Protection Policy for the Disposal of Radioactive Waste, adopted May 1997

4. Policies for Waste Disposal

(7) In recent years, national policies for radioactive waste management have not commonly been derived from the Commission's recommendations. Few recent radioactive waste management decisions have been based on the resultant radiation exposures or on the probability of such exposures. There has been increasing pressure for the adoption of policies described by labels such as 'best available technology' or 'best available technology not entailing excessive costs'. The term 'best available' has usually implied best from the environmental viewpoint regardless of cost. The addition of 'not entailing excessive cost' brings the concept closer to the Commission's advice to keep doses as low as reasonably achievable (ICRP 1991), but involves costs only when they are becoming excessive. These policies fall short of achieving the optimisation of protection.

5. Difficulties in the Application of the Current Policy

(17) The optimisation of protection has the broad interpretation of doing all that is reasonable to reduce doses. In some ways it is unfortunate that the shorthand label 'optimisation of protection' lost the adjective 'reasonable' in the phrase 'as low as reasonably achievable'. Furthermore, optimisation of protection has become too closely linked to differential cost benefit analysis.

6. The Commission's Policy for Waste Disposal

6.1 The Framework of Radiological Protection

The optimisation of protection

(37) Much of the Commission's emphasis has been on the qualitative specification of the optimisation of protection. This calls for the individual doses, the number of people exposed, and the likelihood of potential exposures all to be kept as low as reasonably achievable, economic and social factors being taken into account. This concept has been developed over the years. As early as 1971, the Commission decided to provide an explanation of this qualitative approach and, in *Publication 22* (ICRP, 1973), accepted a

quantitative cost-benefit approach. This was restated in a less flexible form in *Publication 26*, the 1977 Recommendations of the Commission (ICRP, 1977). The quantitative aspects of the optimisation of protection were again emphasized in *Publication 37* (ICRP, 1983).

(38) In fact, the Commission's policy is more subtle and judgmental than is implied by differential cost-benefit analysis, which depends only on a comparison of the value attributed to reductions in collective dose and the incremental costs of protection.

(39) This broader view was expressed in Paragraph 18 of *Publication 55* (ICRP, 1989) as is indicated by the following extract. 'The basic role of the concept of optimisation of protection is to engender a state of thinking in everyone responsible for control of radiation exposure such that they are continually asking themselves the question "Have I done all that I reasonably can to reduce these radiation doses?".'

(40) This view was confirmed in Paragraph 112 of *Publication 60* (ICRP, 1991), and again by the following sentence in Paragraph 117.: 'If the next step of reducing the detriment can be achieved only with a deployment of resources that is seriously out of line with the consequent reduction, it is not in society's interest to take that step . . . '.

6.2 The Application of the Framework of Protection to Waste Disposal

(52) In both the justification of a practice and the optimisation of protection, the presentation of collective dose contributed by very wide ranges of individual dose should be separated into blocks of limited ranges of dose and time. The aggregation of these blocks of collective dose into a single value may be misleading, because it deprives the decision maker of the option of taking account of the individual dose and of the distribution of collective dose in time.

(55) In the optimisation of protection, some relaxation of the requirement for comprehensive summation may be possible. If all the available protection options are likely to deliver similar collective doses beyond some distance or beyond some time in the future, these components of the collective dose will play no part in the choice of option. They need not be estimated. Furthermore, the optimisation of protection should be based on a broad judgement of what is reasonable. Collective dose is only one input to the process.

6.2.5 The protection of future generations

(67) There are also ethical questions in judging the importance of possible harm to future generations from decisions taken in the present. The Commission can only indicate the implications of some of the options for presenting the analysis of future risks and to add some general suggestions.

(68) There are at least three quantities that may be relevant to these judgements. These are the total detriment imposed on a population over many generations, the total detriment imposed on a defined generation, and the detriment imposed annually, or over a lifetime, on individuals represented by one or more hypothetical critical groups. Any one of these quantities could be claimed to indicate the degree of protection of future generations.

(69) The Commission suggests that the annual individual effective dose to a critical group for normal exposure and the annual individual risk to a critical group for potential exposure will together provide an adequate input to a comparison of the limiting detriment to future generations with that which is currently applied to the present generation.

References to section A5.

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Appendix II:

Examples of Optimisation in Waste Management Decision Making and Performance Assessment

This appendix presents examples of optimisation from the international performance assessment literature and also from work sponsored by HMIP. These are presented in order to indicate the possible breadth for demonstration of optimisation in PA. The cases presented are:

B1. application of a multi-attribute analysis to determine the 'best practical environmental option' (BPEO) for the management of low- and intermediate-level radioactive wastes [DoE 1986];

B2. an example of multi-attribute analysis to assist the choice between candidate sites, from USDOE's study of sites nominated for characterisation for deep geological disposal of spent fuel/HLW [USDOE 1986];

B3. an example of optimisation with respect to scientific knowledge, from Nagra's development of a repository concept for disposal of HLW in Opalinus Clay [Nagra 1988];

B4. an example of optimisation of repository layout, from AECL's Postclosure Assessment of a Reference System [Goodwin et al. 1994];

B5. an example of comparison of alternative waste management options based on PRA, from HMIP's assessment of options for management of the Dounreay shaft [RM Consultants 1990];

B6. an investigation of the extent of site investigation on estimated radiological performance, from HMIP's study based on a synthetic geological model of the Harwell site [Mackay 1993].

B1. Application of multi-attribute analysis to determine the 'best practical environmental option' for management of wastes

The UK had disposed of packaged solid radioactive waste in the deep ocean since 1949 and, in the years prior to 1983, had carried out annual disposals under the OECD/NEA multi-lateral consultation and surveillance mechanism at an internationally agreed site in the North-East Atlantic. In 1984, the Holliday report recommended that sea disposal of radioactive waste should not be resumed until a comparison of sea-disposal with land-based alternatives had been completed and that government should make a comparative assessment of all disposal and storage options for LLW and ILW with a view to establishing the 'best practical environmental option' (BPEO) - a concept originating in the 5th report of the Royal Commission of Environmental Pollution, 1976. This prompted the Department of the Environment (DoE) to carry out such an assessment which was published in March 1986 [DoE 1986].

Over 70 different types of LLW and ILW were identified in over 400 waste streams, and the quantity of each waste type expected to require storage or disposal was assessed under a range of assumptions about nuclear power and fuel reprocessing strategies. For each type of waste, the study compared the following options:

- disposal of packaged waste in the deep ocean (sea disposal);
- burial in trenches on land (near-surface disposal);
- disposal in deep mined cavities on land (geological repository);
- disposal in boreholes under the coastal seabed;
- long-term monitored storage on land.

To compare the options, a multi-attribute decision analysis procedure was employed. This considered a range of economic and radiological impacts, see Figure B.1, and four different sets of weights, chosen to cover a range of perceived views extending from a strong desire to minimise cost, to preferences to minimise risks, local impacts, or widespread environmental dispersion of radioactivity.

Application of this procedure showed that a preferred option could be identified for most LLW types whichever set of weights was used. It was also clear, from consideration of health risks to individual members of the public, that much of the more radioactive and long-lived ILW would require deep disposal, whichever set of weights was used. These conclusions were insensitive to changes in assumed costs and calculated radiological impacts within the range of uncertainty on these parameters. Among the conclusions were the following.

- For every type of waste, several options are practical and would comply with safety limits.
- Of these, long-term storage is the least attractive on economic and radiological grounds. It would only be considered attractive if an ability to retrieve wastes easily was an overriding concern, and the reversibility of disposal options was considered inadequate.
- On economic and radiological grounds, an optimum strategy would involve early use of all disposal options, including sea disposal.

- The BPEO for most LLW and some short-lived ILW is near-surface disposal, as soon as practicable, in appropriately designed trenches.
- ILW with higher alpha-emitting radionuclide content than acceptable for near-surface disposal or sea disposal will require deep underground disposal, although no preference was established between disposal in on-land cavities and off-shore boreholes.
- If future sea disposal operations are carried out it could be the preferred option for about 15% of ILW wastes likely to arise by 2030.

In the event, sea-disposal operations were not resumed. Although Nirex's first proposals for near-surface disposal facilities were for both LLW and short-lived ILW, the ILW component was later removed, and in 1987, a decision was made to focus on the search for a site for deep disposal of both LLW and ILW. Subsequently, the planned Nirex repository volume was reduced to mainly ILW with only a very minor LLW component, and in 1997, the decision of the Secretary of State to uphold Cumbria County Council's refusal of planning permission for the RCF effectively blocked Nirex's deep repository programme.

Thus the DoE report has not been very influential in practice. However, as noted in the report, the objective of the BPEO assessment was to identify alternative strategies for storage and disposal of LLW and ILW which would be optimum from a number of different view points, but the report "is a decision-aiding, not a decision-making tool".

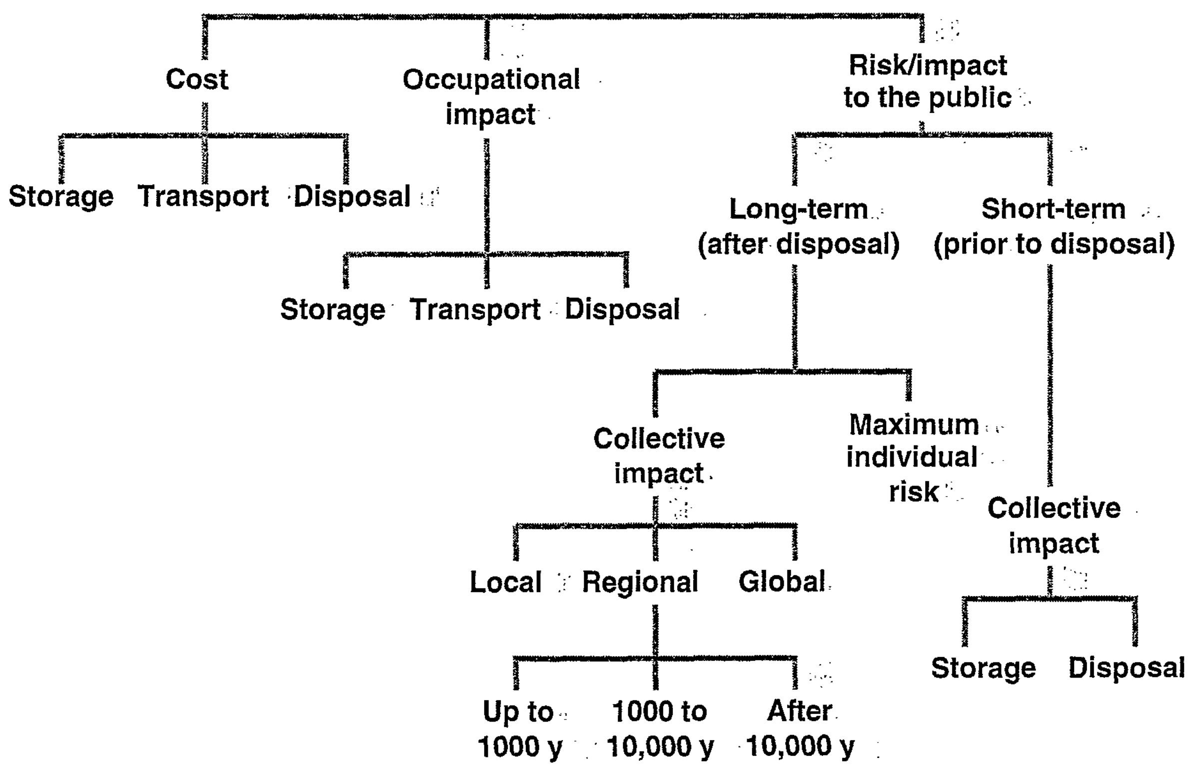


Figure B.1: A structure of economic and radiological impacts pertinent to comparative assessments of waste management options.

B2. An example of multi-attribute analysis of candidate sites

In the USA, the search for potential repository sites for spent fuel/high-level waste disposal began in earnest in the mid 1970s, and the general process by which selection would occur was specified in the Nuclear Waste Policy Act of 1982.

The USDOE undertook a process of screening in four stages: (1) a survey of geological provinces leading to selection of potential suitable regions; (2) a survey of regions narrowing to areas; (3) a survey of areas narrowing to locations (usually not more than 100 square miles); and (4) a survey of locations narrowing to sites (generally smaller than 10 square miles). This led, in 1983, to the selection of nine potentially acceptable sites for a repository location, see Figure B.2.

The next step mandated by the Act, was that at least five sites suitable for characterisation should be nominated and not fewer than three sites recommended to the President for detailed characterisation. To achieve this, the USDOE selected 5 sites as representative of differing geohydrological settings and carried out detailed draft Environmental Assessments (EAs) for each, see Table B.1. In order to form a basis for the recommendation to the President, a formal multi-attribute utility analysis of the five sites was carried out; this considered postclosure performance, preclosure impacts and costs [USDOE 1986].

The postclosure analysis indicated all five sites appeared capable of providing exceptionally good radiological protection for at least 100,000 years after closure. The performance of four sites was virtually indistinguishable with the Hanford site just discernibly less favourable than the other four. The confidence in performance was highest for the three salt sites.

The preclosure analysis indicated, with regard to health and safety, the differences amongst the sites were attributable to waste transportation and non-radiological repository worker fatalities due to accidents, although the differences were small. Differences in environmental and socio-economic impacts were also small. The largest differences were in regard to costs, with over 4 billion US dollars difference between the most and least favourable of the sites.

Table B.2. shows the overall postclosure and preclosure analysis rankings of the five sites and a composite ranking based on postclosure and preclosure factors. These rankings were said to be relatively stable for a wide range of sensitivity analysis of factor weights, with costs being the dominant factor. The Board on Radioactive Waste Management of the National Academy of Sciences noted that "This recognition of the heavy dependence on cost reinforces the Board's judgement that the principal usefulness of the multi-attribute utility method is to illuminate the factors involved in a decision, rather than to make the decision itself." [USDOE 1986, Appendix H].

In the event, the President decided that, in order to focus limited scientific resources, a detailed characterisation should be made at a single site, and the Yucca Mountain site was selected.

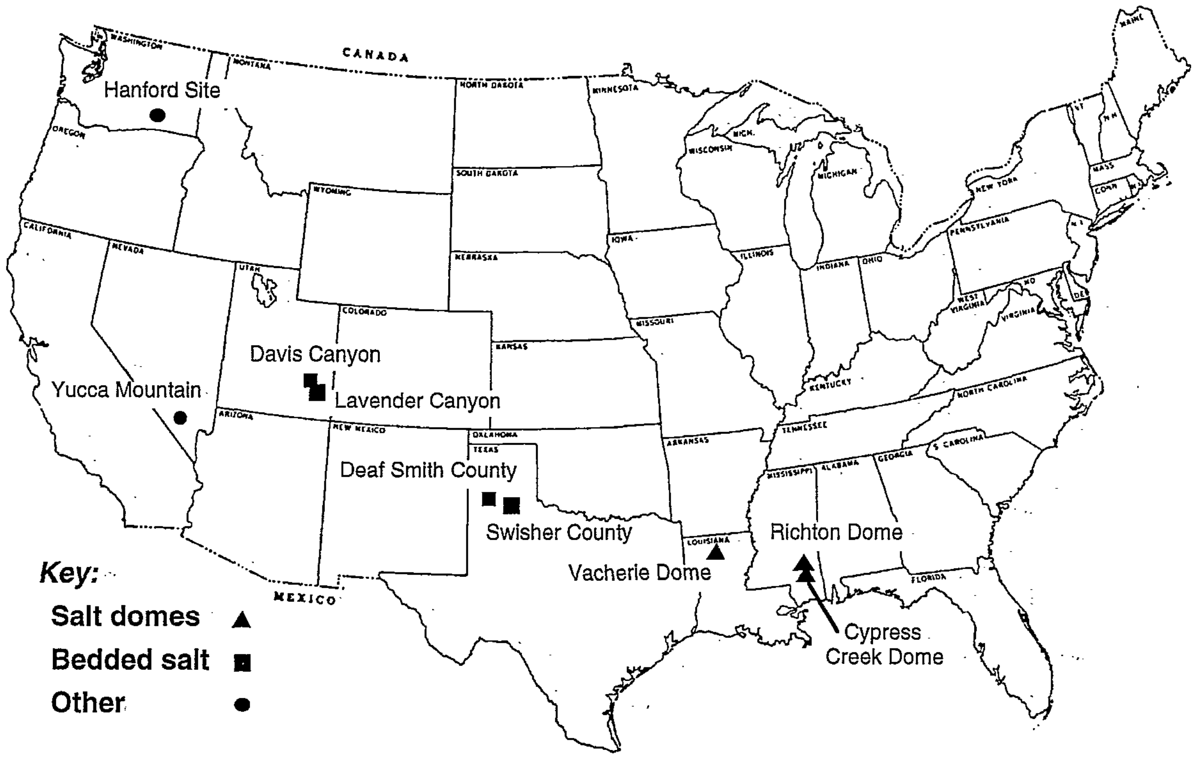


Figure B.2: Potentially acceptable sites for the first repository [USDOE 1986].

Geohydrologic setting	Host rock	Site
Columbia Plateau	Basalt flows	Reference repository location at the Hanford Site, Washington
Great Basin	Unsaturated tuff	Yucca Mountain, Nevada
Permian Basin	Bedded salt	Deaf Smith County, Texas
Paradox Basin	Bedded salt	Davis Canyon, Utah
Gulf Coastal Plain	Salt dome	Richton Dome, Mississippi

Table B.1: Geohydrologic settings and candidate sites for characterisation.

Overall postclosure analysis ranking	Overall preclosure analysis ranking	Composite ranking
Davis Canyon	Yucca Mountain	Yucca Mountain
Richton Dome	Richton Dome	Richton Dome
Deaf Smith	Deaf Smith	Deaf Smith
Yucca Mountain	Davis Canyon	Davis Canyon
Hanford	Hanford	Hanford

Table B.2: Postclosure, preclosure and composite rankings from the multi-attribute analysis.

B3. An example of optimisation with respect to scientific knowledge

In the reference repository design currently being considered for disposal high-level vitrified waste and spent fuel in Opalinus Clay in Northern Switzerland, wastes in cast steel containers will be placed centrally in tunnels of about 2.4 m diameter surrounded by a thick bentonite buffer. This is based on the design developed in Project Gewähr 1985 and elaborated for Opalinus Clay in preliminary assessment studies [Nagra 1988], see Figure B.3(a). In this design, the thick bentonite buffer is expected to fulfil a key safety function, principally that:

- the low permeability and chemical characteristics of the bentonite ensure a stable chemistry around the wastes so that radionuclide solubility limits can be relied on;

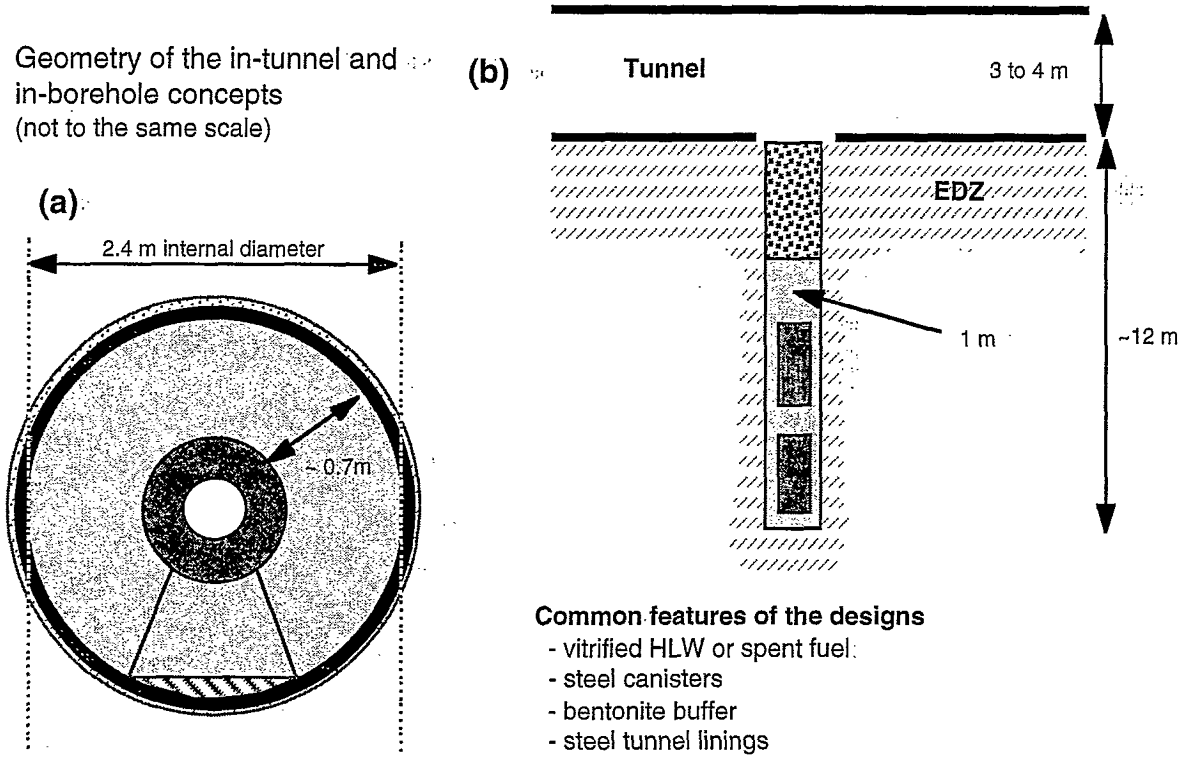
- the plasticity and microporous structure of the bentonite ensure that any colloids formed near the waste are entrapped and cannot migrate to the enter the host rock.

Geotechnical conditions in the Opalinus clay (an indurated mudstone) may demand that load-bearing tunnel linings are installed soon after excavation. Pre-cast concrete sections or in-situ-cast concrete would usually be the preferred materials for tunnel lining on account of cost and experience of use. However, cement leachate can cause deleterious mineralogical changes in bentonite which might adversely affect its properties. In the Nagra reference repository design, therefore, steel section linings are selected for the disposal tunnels [Nagra 1988].

The introduction of the steel (or any) liner to the design leads to the need to consider additional features and processes in long-term safety assessment, e.g. potential for voids between the liner and host rock, chemical reactions of liner materials with the host clay or bentonite, formation of steel corrosion products, volume changes and gas generation.

An alternative design has, therefore, been considered in which waste containers would be placed in vertical unlined boreholes in the floor of the tunnels see Figure B.3(b). This would allow the bentonite buffer around the waste containers to be placed in direct contact with the host rock and would enable the waste to be placed at a distance from the uncertain physical and chemical processes associated with the tunnel linings. In an extreme case, if necessary, the tunnel linings could be removed at closure and the tunnels backfilled, e.g. with a sand-bentonite mix. Although technically more complex and costly to implement, either of these solutions would result in a simpler near-field system, the long-term behaviour of which might be estimated with more confidence.

The possible designs under consideration incorporate several choices that have, or could be, made. These choices are made, or options considered, not because they offer a theoretically improved performance that could be demonstrated by performance assessment, but because they reduce the need to take account of processes about which there is a significant scientific uncertainty.



The in-tunnel emplacement concept was originally developed for Project Gewähr 1985 for the case of disposal of HLW in self-supporting tunnels in crystalline rock. A reference design has been elaborated for disposal of HLW/spent fuel in Opalinus Clay considering a smaller tunnel diameter and tunnel linings as would be required in clay. Uncertainty over the quantitative significance of processes that might occur at the host rock-tunnel lining-bentonite buffer interfaces has led to the definition of an alternative design based on in-borehole emplacement; in this design there is no liner between the bentonite buffer and host rock.

Figure B.3: Possible alternative arrangements for the emplacement of vitrified HLW and spent fuel in clay.

B4. An example of optimisation of repository layout

The AECL method of post-closure assessment includes a stage of studying design constraints. In the AECL "Postclosure Assessment of a Reference System" [Goodwin et al. 1994] several potential design modifications including thicker buffer around waste containers, thicker containers and more durable container material were investigated quantitatively. The most significant improvement in performance was achieved by modifying the layout of disposal rooms (the vault) to provide greater isolation from a nearby geological feature.

In the assessment, the underground repository is placed hypothetically at 500 m depth at the Underground Research Laboratory site of the Whiteshell Research Area. It is conservatively assumed that a major low-angle dipping fracture zone (LD1) extends to below repository depth to intercept the vault plane (although more recent information from the site indicates that this is not the case). Preliminary deterministic calculations for this hypothetical repository indicated that radiological impact would be dominated by releases from the vault sectors above the zone LD1 and also that the maximum impact is very sensitive to the distance between the zone LD1 and the closest assumed position of waste disposal rooms. Three options were examined: to move the vault farther away from fracture zone LD1; to adjust the vault dimensions, moving rooms closest to LD1 out to the sides; to eliminate all or parts of some vault rooms nearest to LD1.

For detailed analysis, the third option was chosen, see Figure B.4. Deterministic calculations with median values of parameters showed that

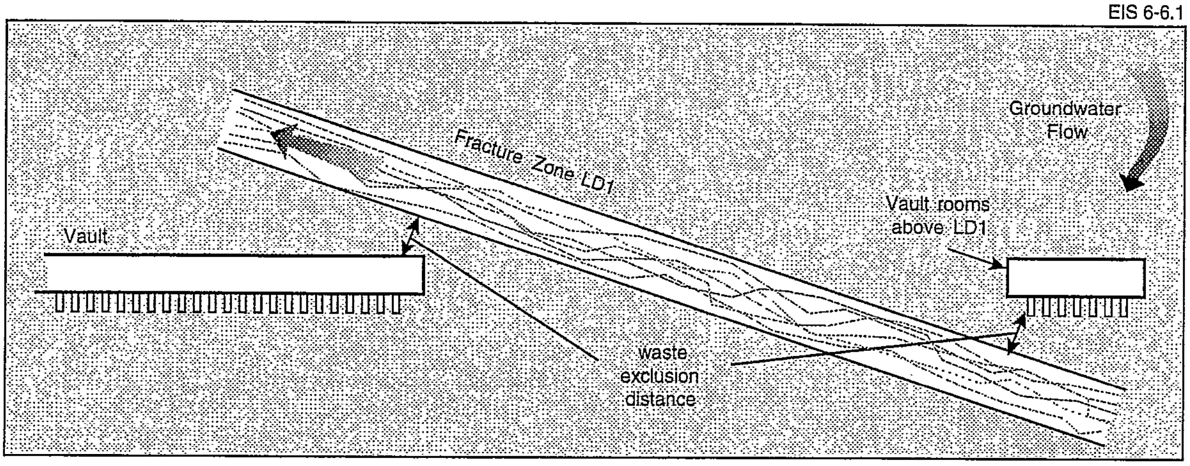
- increasing the waste exclusion distance from about 30 to 50 m reduced calculated dose from I-129 (the dominant nuclide) by 13 orders of magnitude at 10,000 years and by almost one order of magnitude at 100,000 years;

- removing vault rooms above LD1 reduced calculated dose from I-129 by almost 6 orders of magnitude at 10,000 years and by 2 orders of magnitude at 100,000 years.

Even stronger reductions were seen for Tc-99 and C-14.

Therefore, for the detailed postclosure assessment, a "derived constraint" was applied, i.e. a reduced area vault was considered in which the vault rooms above the zone LD1 were eliminated and an exclusion distance of about 50 m was imposed between the zone LD1 and the nearest disposal rooms.

Vertical crossection view



The fracture zone LD1 is assumed to be present at the depth of the hypothetical repository. Deterministic calculations are performed with and without the vault rooms above LD1 and for different waste exclusion distances. These show that impact is substantially reduced if (a) vault rooms above LD1 are eliminated and (b) the waste exclusion distance is at least 50m. These are adopted as design constraints in the design of the Reference Disposal System considered in probabilistic simulations.

Figure B.4: Application of design constraints to the hypothetical repository layout at the URL site considered in AECL's postclosure assessment of a reference disposal system [Goodwin et al. 1994].

B5. An example of comparison of alternative waste management options

At AEA Dounreay, the authorised disposal of radioactive waste to a 65m deep shaft, close to the shoreline cliffs, took place until 1977. Contaminated water (leachate) is pumped from the shaft to keep the water level in the shaft below the authorised limit of -0.12m OD, with the intention of preventing radioactivity migrating in groundwater from the shaft through the rock to the nearby cliffs and foreshore. The leachate is then discharged to sea with other effluent from the site.

In 1988-90 HMIP undertook a study, on behalf of HMIPI, to compare the postclosure radiological risks of various engineering alternatives to the then current management regime [RM Consultants 1990]. A number of options, spanning a wide range of approaches were proposed and ranked, subjectively, against radiological and non-radiological criteria. Three were considered to merit detailed assessment:

- Option 1 - Continued Pumping. As pumping cannot be continued indefinitely, this option was assessed only to provide a hypothetical base case against which to compare the others.
- Option 2 - Top Plug. The shaft would be capped at waste level with a substantial plug.
- Option 3 - Grout Curtain. In addition to the top plug, a grout curtain would be constructed around the shaft, with the aim of isolating it from the surrounding environment.

A probabilistic risk assessment (PRA) methodology was adopted, in which detailed deterministic studies were used to derive simple conceptual models and data sets for probabilistic analysis. Not all uncertainties were represented in the PRA. In particular, long term effects (degradation of materials, environmental change and human intrusion) were not modelled, but were given qualitative consideration. The main computer code used in both deterministic and probabilistic runs was VANDAL, which has been developed by HMIP for use in PRAs of underground waste repositories. However, for Option 1, a separate code called PUMPCASE had to be developed because VANDAL required excessive run times to model the high flow rate in the shaft. The calculations were carried out up to 30000y - an estimate of the time to the onset of the next glaciation.

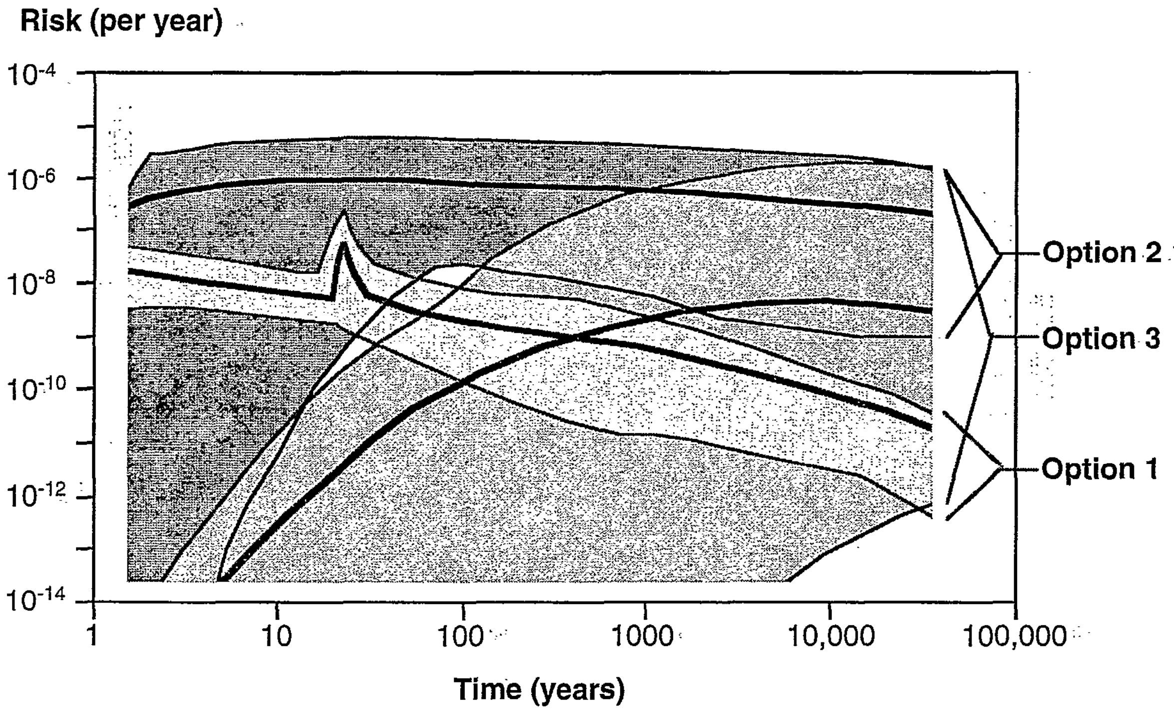
The PRA results showed wide spread with some overlap between predicted confidence intervals on risks from for all three options, see Figure B.5. Comparisons of the means of upper confidence limits predicted for each option indicated that:

- Option 2 would present risks few orders of magnitude greater than Option 1 at late times.
- Option 3 gives risks several orders of magnitude lower than either Option 1 or 2 at early times.

It was not possible to make any more precise statement of the relative merits of each option, because uncertainties in models and data which could not be incorporated within the PRA may have biased the results, for example, the effects of sea level fall, coastal erosion and degradation of the grout curtain were not included in the models.

It was concluded that, the predicted ranges of risks from all three options overlap to some extent, and when long term effects and remaining uncertainties and potential bias in the assessment are considered an unequivocal best option cannot be identified.

It was recommended that further research should address the effects of long term change and also the feasibility and cost of removing the waste from the shaft.[1]



A number of options were proposed and ranked against radiological and non-radiological criteria. Three options were considered to merit detailed assessment: (1) Continued Pumping - this was assessed to only provide a baseline against which to compare the other options; (2) Top Plug - the shaft would be capped at waste level with a substantial plug; (3) Grout Curtain - in addition to the plug, a grout curtain would be constructed around the shaft.

Figure B.5: Probabilistic analyses of risk for three options for the future management of the Dounreay shaft [RM Consultants 1990].

1 It has recently been announced that the waste will be removed from the shaft.

B6. An investigation of the extent of site investigation on estimated radiological performance.

During 1989-92, HMIP sponsored a study to investigate the relationship between amount and quality of geological data and the quality of performance assessment results. In particular, to investigate quantitatively for a specific site the sensitivity and possible bias in the results of performance assessment resulting from different levels of geological data [Mackay 1993].

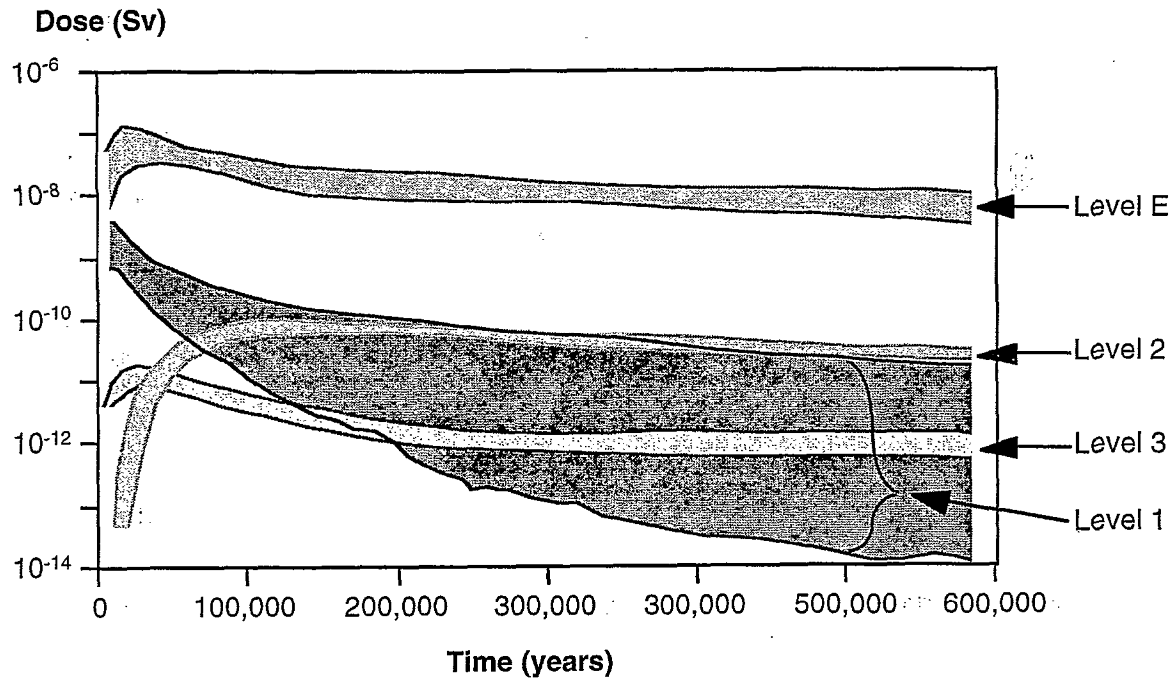
To achieve this, a computer-based synthetic model was developed of the hydrogeological regime in a 41x51 km area centred on the Harwell site. The model permitted sampling of geological and hydraulic parameters over a wide range of scales and was thus able to simulate results from geological and hydrogeological site investigation.

The synthetic site model was used to provide sampled, data to an independent team of hydrogeologists not involved in setting up the synthetic model. These sample levels comprised (1) historical sampling of the Harwell area, (2) local sampling within the hypothetical repository footprint, and (3) a more extensive regional sampling campaign. The data were used to successively establish three dimensional models of the ground water flow regime and to develop network models of flow and transport which were represented using the VANDAL PRA code. No knowledge of the synthetic site model was provided to the sampling/modelling team other than through the provision of the sample data sets.

Figure B.6 compares the VANDAL PRA results for the three sampling levels and also a VANDAL PRA based on the exact synthetic site data, Level E, developed by the synthetic site model team.

It is clear that the successive models developed by the sampling team did not converge on the "exact" solution and also seriously underestimate uncertainties present. This seems to be largely due to false assumptions by the sampling/modelling team about key features and processes determining the hydrogeological regime. In particular, a failure to represent spatial heterogeneity in subhorizontal clay layers in the region. Also, in refining their model, the sampling/modelling team used the additional data to narrow PDFs of input parameters but not to substantially re-assess their conceptual model of the site.

It was concluded that, the most important element in (the setting up of a hydrogeological model for) performance assessment is the construction of a conceptual model describing all macroscopic controls governing the flow and transport behaviour of the groundwater system. Consequently, a minimum objective for a site investigation programme must be to establish the "true" macroscopic conceptual model.



Levels 1 to 3 represent VANDAL PRA results based on successively increasing levels of sampled data from a synthetic site model. Level E represents VANDAL PRA results based on the "exact" site data. The shaded areas are the extent of the 5-95 %ile spread of results.

Figure B.6: Comparison of PRA results for successively increasing levels of site data.