SKI Report 99:46

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September 1999

ISSN 1104-1374
ISRN SKI-R--99/46--SE

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September 1999

SKI Project Number 98141

9802-1
Version 1

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Report History

This document has been prepared by Galson Sciences Ltd for SKI under the terms of SKI Contract 14.9-971645/98141.

Draft 1 was dated 31 July 1998.

Draft 2 incorporated comments provided by SKI at a meeting on 1 September 1998.

The final version incorporates written comments from SKI (Christina Lilja) and comments arising from a meeting with SKI in June 1999.

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Version:	Date:	Principal Author: R.D. Wilmot	Checked by: D.A. Galson	Approved by: D.A. Galson
9802-1	29 Sept. 1999	Signature: .... Date:	Signature: .... Date:	Signature: .... Date: ....

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Summary

The objective of this report is to discuss issues that should be considered in the development of a regulatory strategy for assessing future human actions in any forthcoming license application for a deep repository for spent fuel in Sweden and for sites of other repositories.

The report comprises an outline of key issues concerning the treatment of future human actions in safety assessment, reviews of regulatory developments, recent safety assessments and supporting studies, and international initiatives on the treatment of future human actions in safety assessment, and the principal elements of a regulatory strategy.

Performance assessments (PAs) are generally accepted as providing illustrations of system performance under given sets of assumptions. The results of PAs are clearer and easier to understand if certain large uncertainties are accounted for by determining performance under several different sets of assumptions or scenarios, each of which defines a possible evolution of the disposal system.

A number of assumptions can be made that would restrict the scope of an assessment without reducing the credibility of the corresponding safety case. Reducing speculation about technological development, by assuming that the techniques used in future human activities are similar to those currently in use in the region or at similar sites, will simplify the assessment. A distinction is generally made between inadvertent and intentional intrusion, with intentional activities excluded because society cannot protect future populations from their own actions if they understand the potential consequences. A division of human activities into "recent and ongoing" and "future" activities considers not only the timing of the activities but also the degree of control or influence that can be imposed on them.

Recent and ongoing human activities are those that affect an area beyond the immediate vicinity of the disposal facility and which neither the proponent nor the regulator can influence. Examples include anthropogenic climate change and activities that have recently taken place in the vicinity of the disposal site, such as groundwater abstraction.

Future human activities are those that may take place in the vicinity of the disposal system at some time in the future and which may affect the performance of the disposal system by by-passing or affecting the characteristics of the engineered and natural barriers. Institutional controls can prevent or reduce the likelihood of any disruptive activities.

It may be inappropriate to treat recent and ongoing human activities in the same way as future human activities. Scenarios that include the occurrence of future human activities are conditional and are used to illustrate the potential behaviour of the system. Scenarios including recent and ongoing human activities are not conditional and may provide a better estimate of system performance than those that exclude such activities.

The focus of assessments of future human actions should be on longer-term doses received by groups of people who might anyway be considered in the Reference Scenario In particular, human intrusion assessments should include groups considered in assessments of groundwater releases who may receive additional doses from new pathways arising from future human actions, and groups consuming foodstuffs contaminated by radionuclides brought to the surface during or subsequent to an intrusion and dispersed into the biosphere. Members of a drilling crew that intrude into a repository do not fulfil the definition of a potentially exposed group because any intrusion would be an isolated activity not occurring on a day-to-day basis. The dose received by one individual from a specific short-term event cannot be compared with a regulatory criteria expressed as an average annual dose.

The following outline strategy is proposed as a basis for consultation on the treatment of future human actions.

- Assessments must include calculations of disposal system performance without any disruptive future human actions. These calculations should include the effects of any recent and ongoing human activities that might affect the performance of the disposal system. Additional calculations should illustrate the potential effects of disruptive human actions.

- Assessments of future human actions should be based on present-day conditions in the region of the disposal site and similar sites. Site-specific definitions of the region considered and the period examined for defining rates and frequencies should be provided by the proponent.

- Assessments should consider the long-term effects of disruption through the formation of new pathways and the dispersal of radioactive material in the biosphere. The proponent should develop and justify the scenarios analysed in an assessment.

In addition to developing guidance for the proponent on the scope and conduct of assessments, the regulator could undertake illustrative assessments in order to assure themselves that they understand the impacts of the proposed strategy. Work on both guidance and independent assessments could be support by the development of an international reference human action approach.

Sammanfattning

Syftet med denna rapport är att diskutera frågor som bör beaktas vid utveckling av principer för myndigheternas (SKIs och SSIs) bedömning av framtida mänskligt handlande i samband med kommande granskningar av ansökningar om tillstånd för slutförvaring av radioaktivt avfall i Sverige.

Rapporten omfattar en översikt av grundläggande frågor vid hantering av framtida mänskligt handlande, sammanställningar av utvecklingen på myndighetssidan, av nyligen slutförda säkerhetsanalyser och bakgrundsstudier och av internationella initiativ, samt förslag till innehåll i en myndighetsstrategi.

Säkerhetsanalyser används allmänt för att illustrera hur ett slutförvar fungerar under olika förhållanden. Resultaten av säkerhetsanalysen är klarare och lättare att förstå om vissa stora osäkerheter behandlas i särskilda scenarier, där vart och ett beskriver ett möjlig utveckling av slutförvaret och dess omgivning.

Ett antal förutsättningar kan definieras för att om möjligt begränsa omfattningen av säkerhetsanalysen utan att minska trovärdigheten hos säkerhetsredovisningen. Ett sätt att förenkla bedömningen är att undvika spekulationer om den tekniska utvecklingen genom att förutsätta att den teknik som används i framtida mänsklig verksamhet liknar den som används idag, regionalt eller på liknande platser. Man gör vanligen skillnad mellan oavsiktligt och avsiktligt intrång. De senare utesluts från fortsatt analys eftersom samhället av idag aldrig kan skydda en framtida befolkning från dess egna handlingar som den utför i medvetande om tänkbara konsekvenser. En uppdelning av mänsklig verksam-het i "pågående" och "framtida" verksamheter kan göras inte bara för att särskilja när handlingarna inträffar utan också för att avgöra vilken kontroll eller inflytande man kan ha utöva på dem. (Begreppet "pågående" inbegriper även sådana aktiviteter som inträffat relativt nyligen.)

Pågående mänskliga verksamheter är sådana som berör ett område utanför ett slutförvars omedelbara närhet och där varken den sökande eller myndigheterna har ett inflytande. Exempel härpå är såväl mänsklig klimatpåverkan som verksamheter vilka nyligen ägt rum i omgivningarna kring ett slutförvar såsom uttag av grundvatten.

Framtida mänskliga verksamheter är sådana som kan äga rum i närheten av slutförvaret vid någon gång i framtiden och som kan påverka dess funktion genom att kortsluta eller försämra egenskaperna hos de tekniska eller naturliga barriärerna. Institutionell kontroll kan förhindra eller minska sannolikheten för sådana förstörande skadliga verksamheter.

Det kan vara olämpligt att behandla pågående och framtida mänskliga verksamheter på samma sätt. Scenarier som inkluderar framtida mänsklig verksamhet är villkorliga och används för att illustrera systemets funktion i olika tänkbara situationer. Scenarier som inkluderar pågående mänsklig verksamhet är inte villkorliga och kan medge en bättre uppskattning av systemets funktion än de som inte beaktar sådan verksamheter.

Bedömningar av framtida mänskliga handlingar bör fokusera på doser till grupper av människor långt fram i tiden och som ändå bör beaktas i ett referensscenario. Bedömningen av mänskligt intrång bör inbegripa sådana grupper som kan utsättas från utläckage till grundvatten och som skulle kunna få ytterligare dos från nya transportvägar som kan uppstå till följd av framtida mänskligt handlande, liksom grupper som konsumerar födoämnen vilka kontaminerats av radionuklider som förts upp till ytan i samband med ett intrång och sedan spridits i biosfären. Medlemmarna i ett borrlag som gjort intrång i ett slutförvar är per definition inte att betrakta som medlemmar av en "potentiellt exponerad grupp" eftersom ett intrång skulle vara en isolerad verksamhet som inte inträffar dagligen. Individdosen från en isolerad kortvarig händelse kan inte jämföras med myndighetskriterier uttryckta i en medeldos på årsbasis.

Följande principer föreslås ingå i en strategi för bedömning av framtida mänskligt handlande:

- Säkerhetsanalyser måste inkludera beräkningar av hur slutförvaret fungerar utan störande framtida mänskligt handlande. Beräkningarna bör ta hänsyn till inverkan från pågående mänsklig verksamhet. Ytterligare beräkningar bör göras för att illustrera tänkbara effekter av störande mänskligt handlande.

- Säkerhetsanalyser av framtida mänskligt handlande bör grundas på dagens förhållanden i den region där slutförvaret är beläget och på liknande platser. Platsspecifik definition av regionens utsträckning och den tidsperiod som ligger till grund för bestämning av frekvenser bör anges av sökanden.

- Säkerhetsanalyser bör ta hänsyn till effekten på lång sikt av störningar genom uppkomst av nya transportvägar och spridning av radioaktivt material i biosfären. Sökanden bör utveckla och motivera de scenarier som analyseras.

Förutom att utveckla råd till sökanden rörande omfattning och utförande av säkerhetsanalyser kan myndigheterna företa egna illustrativa analyser för att förvissa sig om att en föreslagen strategi är lämplig. Arbetet med både rådgivning och oberoende säkerhetsanalyser skulle kunna ha nytta av om det utvecklades en internationell referensmetod för att hantera framtida mänskligt handlande.

1 Introduction

1.1 Background

In Sweden, the Swedish Nuclear Power Inspectorate (SKI) and the Swedish Radiation Protection Institute (SSI) regulate all nuclear activities, including the management and disposal of radioactive waste. The Swedish Nuclear Fuel and Waste Management Company (SKB) is responsible for the actual management and disposal of radioactive waste and for justifying its waste management policy and decisions.

Future human actions must be considered at a broad level in developing a policy on the long-term disposition of radioactive wastes, including in the context of an Environmental Impact Assessment (EIA). Such considerations have been one reason behind the worldwide focus on deep geological disposal of long-lived radioactive wastes, as opposed to the alternative of long-term or indefinite near-surface storage[1]. A deep geological repository is conceived as a passively safe system that does not require ongoing institutional control to ensure long-term safety. SKB is in the process of siting a deep repository for spent nuclear fuel and, as part of this work, will be preparing an EIA in which alternatives to disposal must be considered.

An important issue in the licensing of repositories is the approach to the treatment of future human actions. The regulators have already licensed SKB's repository for low-level and intermediate-level radioactive waste at Forsmark (SFR), but still requires a strategy for dealing with the issue in future licensing authorisations for a spent nuclear fuel repository. SKI has considered the issue of human intrusion in its scenario development work (Andersson et al., 1989), and in recent performance assessment (PA) activities (SITE-94, SKI, 1996). However, the performance assessment work by the regulators has not taken explicit account of the international consensus, nor have the regulators yet developed and documented a coherent regulatory strategy for dealing with future human actions for the licensing of a spent nuclear fuel repository in Sweden. Such a strategy is needed for two reasons: to inform regulatory assessment activities and to provide guidance to SKB on what would be considered acceptable in a safety case.

1.2 Objectives and Scope

The main objective of this report is to provide the Swedish regulators with the elements of a defensible regulatory strategy for dealing with human intrusion and future human actions in assessments. This regulatory strategy will need to consider the following issues:

- An overall approach for dealing with human actions in performance assessments.

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1 Considerations of intergenerational equity also suggest a policy of deep disposal rather than indefinite storage.

- The provision of guidance to SKB on acceptable approaches to the treatment of future human actions in assessments.

- The means of identifying, screening and evaluating the potential consequences of future human actions, including assumptions about future societies.

- The means of accounting for uncertainty in assessing the possible impact of future human actions on repository safety, including the effectiveness of controls.

1.3 Structure of the Report

The main content of the report is presented within the following five sections:

- Section 2 outlines key issues concerning the treatment of future human actions in safety assessments.

- Section 3 summarises a review of the status of regulatory developments in a number of OECD countries concerning the treatment of future human actions in safety assessments.

- Section 4 summarises a review of how future human actions have been treated in recent safety assessments and supporting studies in a number of OECD countries.

- Section 5 reviews and documents recent international initiatives and thinking on the treatment of future human actions in safety assessment.

- Section 6 provides specific suggestions for key elements of a regulatory strategy for the treatment of future human actions in assessments.

Two Appendices present additional detail from our review:

- Appendix A presents further details on the status of regulatory developments concerning the treatment of future human actions in safety assessments.

- Appendix B presents further details on how future human actions have been treated in recent safety assessments and supporting studies.

The material reviewed for Sections 3-5 and Appendices A and B is current through August 1998. Although additional safety assessments (e.g., in Finland and the United States) and draft regulations (e.g., United States) have been published since then, or are about to be published (e.g., in Japan and Sweden), we are not aware of anything in these recent developments that would change the overall picture presented here.

2 Evaluating the Impacts of Future Human Actions

This Section discusses some important issues regarding the treatment of human actions and the assumptions required in assessing their impact. The first subsection considers the institutional controls that may be used to reduce the effect of human actions. Subsequent subsections discuss issues associated with the scope of PAs and the definition of human action scenarios, inadvertent versus intentional human actions, and the selection of exposed groups for consequence models.

These discussions provide a background to the reviews of regulations in countries outside Sweden (Section 3) and the treatment of human actions in recent assessments (Section 4). These issues are also addressed in the recommendations for elements of a proposed regulatory strategy (Section 6).

2.1 Institutional Controls

The term ***institutional controls*** includes a variety of measures intended to prevent or inhibit human activities in the vicinity of a disposal site. Institutional controls may be "active", involving a continued presence at the site, or "passive", involving the presence of markers or the retention of information concerning the site on maps and in archives.

Two types of human activities may be affected by institutional controls:

- Disruptive human activities - those that may lead to earlier releases of radionuclides to the biosphere than would otherwise occur.

- Non-disruptive activities - those that may increase exposure to radionuclides that have already reached the biosphere through natural processes.

The potential for either of these types of human activities to result in higher doses is significantly greater for near-surface repositories than for deep repositories. For example, there are many more human activities that penetrate to the depth of a near-surface repository than reach the depths typical of a deep repository. Institutional controls that reduce the extent of these activities in the period immediately after disposal, when the waste is most radioactive, will therefore be more important for near-surface repositories.

The time-scales involved in the migration of radionuclides from a deep repository to the biosphere are generally far longer than the period over which any type of institutional controls can be assumed to be effective. In contrast, the shorter pathways for radionuclide transport to the biosphere from near-surface repositories mean that institutional controls may still be effective in reducing doses to populations in the vicinity of the repository. Once again, therefore, the establishment of institutional controls is more important for near-surface repositories than for deep repositories.

The post-closure safety of a sealed deep repository should not in general be dependent upon institutional controls. Institutional controls are likely to be important for near-surface repositories, and if there is a proposed interval between waste emplacement and sealing of a deep repository[2]. Institutional controls for deep repositories may also be proposed in order to provide additional levels of assurance. Assumptions regarding the effectiveness of institutional controls are therefore potentially relevant for assessments of both near-surface and deep repositories.

Active institutional control of the disposal site can prevent or detect any local disruptive activities through on-site security and surveillance, but there is no consensus on the period for which active controls can be relied upon. The periods of effective institutional controls assumed in regulations and in recent PAs are outlined in Section 3 and 4 of this report. Similarly, while there is general recognition that a variety of passive control measures should be taken (NEA, 1995a), it is impossible to quantify their effectiveness. This uncertainty compounds the large uncertainties already associated with human actions taking place.

Guidance from the regulator as to the period over which institutional controls can be assumed to be effective would address a significant source of uncertainty. Guidance on the value of passive controls in reducing intrusion rates would also reduce undue speculation.

2.2 Scope of a Safety Case

Whatever institutional controls are put in place, human actions have the potential to affect the performance of deep geologic repositories, and must therefore be considered in any safety case. The safety case must provide assurance that the long-term performance of the overall system will satisfy appropriate national and international safety criteria.

A safety case comprises a wide range of both quantitative and qualitative elements. An important element is a performance assessment (PA) that evaluates the overall behaviour of the disposal facility taking account of all sources of uncertainty. PAs provide illustrations of system performance under given sets of assumptions (NEA, 1991), and the results of PAs are clearer and easier to understand if certain large uncertainties are accounted for by determining performance under several different sets of assumptions or scenarios, each of which defines a possible evolution of the disposal facility.

A primary set of assumptions considers the evolution of the repository without disturbance from future human actions and unlikely natural events. This is variously referred to as the "undisturbed performance scenario", the "base case scenario", the "central scenario", or the "reference scenario". We mainly use the term "undisturbed performance scenario" in this report. The features, events and processes (FEPs) included in this scenario are commonly determined by systematically screening a comprehensive list of FEPs. FEPs may be excluded because they are considered to be outside the scope of the assessment, because they have a low probability of occurrence, or because they are assessed to be of low consequence to system performance. The effects of low-probability

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2 Reliance on institutional controls during such an interval, intended to allow for possible retrieval of wastes, may be contrary to the general principle that the society benefiting from a technology should not impose burdens associated with this technology on future generations.

events that could increase releases of radionuclides from the repository, or affect the transport of radionuclides through the engineered or natural barriers, may be considered in additional scenarios.

Scenarios that consider future human actions can be defined either by screening a comprehensive FEP list or through an ***a priori*** decision concerning potential future activities. The range of possible future human actions is large and indeterminate, and the probability of their occurrence is impossible to determine, so screening cannot define which human activities may occur at a particular site in the future. This makes future human actions particularly difficult to address in the assessment of a safety case.

In general, the proponent of a particular disposal facility will undertake a series of PAs during the concept approval, site selection, repository design, optimisation, and licensing cycle. The extent to which human actions are considered in these PAs will vary with the purpose of the PA. During site selection, for example, the resource potential of different regions may be considered, and assessments conducted as part of optimisation may consider the effects of different design elements on the consequences of an intrusion. The scope of these assessments is the responsibility of the proponent.

The regulator, who may undertake independent assessments for insight into some of the key issues concerning safety, will judge the adequacy of any assessment submitted as part of a safety case, and assess the results against the established regulatory target or limit. The proponent remains responsible for the scope of such an assessment. However, because there is a wide range of assumptions that can be made regarding the treatment of human actions, guidance from the regulator would be helpful in ensuring that potential impacts, including those related to human actions, are adequately addressed in a PA.

2.3 Scenario Development

In this Section, we discuss issues associated with the scale of human actions to be included in assessments, and with future societal and technological developments and their influence on the definition of scenarios.

2.3.1 Recent, ongoing, and future human actions

A division of human actions into "recent and ongoing" and "future" actions considers not only the timing of the actions, but also the degree of control or influence that can be imposed on them. At the beginning of the assessment period, other factors require consideration, and it is useful to make a further subdivision of human actions into "global" and "local" actions.

Recent and ongoing human activities are those that affect an area beyond the immediate vicinity of the disposal facility and which neither the proponent nor the regulator can easily influence. These include **global human activities** that have a large-scale or even global influence, such as anthropogenic climate change arising from the release of greenhouse gases into the atmosphere. They also include **local human activities** that have recently taken place in the vicinity of the disposal site, such as groundwater abstraction, together with any local human activities that are certain to continue for some period after repository closure.

In contrast, **future human activities** are activities that may take place in the vicinity of the disposal site at some time in the future and which may affect the performance of the repository by by-passing or affecting the characteristics of the engineered and natural barriers. Future human activities having a large-scale and potentially global influence, such as nuclear war, are not considered in decisions on repository safety.

Because they have already occurred or are certain to occur, it may be inappropriate to treat recent and ongoing human activities in the same way as future human activities. Scenarios that include the occurrence of future human activities can only illustrate the potential behaviour of the system. Scenarios that include recent and ongoing human activities, whether local or global, may provide a better estimate of expected system performance than those that exclude such activities.

Guidance from the regulator as to which human actions should be assessed, and on the treatment of recent and ongoing human activities, both local and global, would ensure that assessments provide appropriate estimates of system performance.

2.3.2 Future Societal and Technological Development

Analyses of the effects of future human actions require assumptions about future behaviour patterns and about the disruptive processes themselves. Patterns of human behaviour are controlled in part by technological development and in part by climatic conditions. As an example illustrating the role of climate, it can be noted that within the next hundred thousand years, disposal sites in Sweden are expected to be covered by an ice-sheet once or several times depending on location. During the period of cooling climate prior to glaciation, human populations will probably decrease and human activities become less extensive. The assumption of present-day demography would probably provide a reasonable bounding analysis for the extent of future human actions during this period. Assessments of the effects of drilling may require information on borehole diameter and drilling techniques. Assumptions about these factors should be consistent with the types of drilling currently used in the types of activities under consideration.

Reducing speculation about technological development, by assuming that the techniques used in future human activities are similar to those currently in use in the region of the disposal site or at similar sites, would simplify the assessment. Whereas such simplifications may be desirable for regulatory decision making, there may still be a need for the regulator to anticipate the types of philosophical considerations concerning possible societal evolution that could be put forward by other stakeholders in the debate on repository safety. In particular, discussion on possible societal evolutions and their implications for intrusion scenarios could be necessary to satisfy public concerns.

2.4 Inadvertent and Intentional Human Actions

Inadvertent future human actions are defined (NEA, 1995a) as:

> *Those in which either the repository or its barrier system are accidentally penetrated or their performance impaired, because the repository location is unknown, its purpose is forgotten, or the consequences of the actions are unknown.*

Inadvertent future human actions have been considered in many assessments (see Section 4).

Conversely, intentional future human actions are defined (NEA, 1995a) as those actions for which:

> *…future intruders are aware of the waste and the consequences of disturbing the repository or its barrier system…*

It has been argued that current society cannot protect future societies from their own actions if the latter understand the potential consequences of their activities (NEA, 1995b). This argument has been used to reduce the range of potential future human actions considered in assessments by excluding intentional disruption of the repository.

The distinction between inadvertent and intentional intrusion is more complex if the repository design concept includes the potential for retrievability. In this case, the safety of future societies retrieving waste should be considered even though they would have knowledge of the repository and be intentional intruders. During the operational phase of a repository for spent fuel, there will be a need to satisfy international requirements for nuclear material safeguards, and a continuation of such monitoring may be required after closure. Post-closure monitoring of the repository could, however, be regarded as a form of intentional intrusion

Guidance from the regulator concerning the treatment of intentional intrusion, and defining the extent to which retrievability, post-closure monitoring, and other "intentional" activities (e.g., future co-disposal of waste) must be considered in PAs, would be of value.

2.5 Selection of Exposed Groups

Assessments of the evolution of the repository may consider a number of performance measures, including average annual doses to individual members of a potentially exposed group. An exposed group is a reasonably homogeneous group of members of the public, and is defined on the basis of day-to-day behaviour that a reasonable person might adopt. Behaviour which such a person might find extreme, and which habit surveys have not revealed, need not be considered in defining such groups. Because of the uncertainties in determining future exposures, a single exposed group or critical group cannot be defined for post-closure assessments, and it is necessary to consider all exposed groups whose lifestyle and habits could potentially lead to high doses.

Regulatory criteria are commonly expressed in terms of individual doses, but care is required to ensure that undue emphasis is not placed on high doses received by a few individuals over a short period. These doses will be highly uncertain, and it is questionable whether they are appropriate for regulatory decision making. It may not be possible to compare the dose received by one or a few individuals from a specific short-term event with a regulatory criteria expressed as an average annual dose.

Potentially exposed groups that have the potential to receive longer-term doses, e.g. from groundwater releases, must be defined for undisturbed performance scenarios. Human intrusion assessments may need to consider additional doses received by these groups, as well as doses to different groups arising from the formation of new pathways. Guidance on the selection of potentially exposed groups for consideration in consequence calculations would be appropriate.

2.6 Summary

This Section has summarised a number of the issues associated with the treatment of human activities in assessments of waste repositories, and indicated topics on which regulatory guidance would be appropriate. The topics identified are:

- The period for which institutional controls can be assumed to be effective, and the treatment of passive controls in assessments, where considered necessary.

- The treatment of recent and ongoing human actions versus future human actions in assessments.

- The range of future human actions to be assessed, including the treatment of societal and technological development.

- The treatment of intentional intrusion, and the extent to which retrievability, post-closure monitoring, and other forms of intentional intrusion must be considered in assessments.

- The identification and selection of potentially exposed groups for intrusion assessments.

The following two Sections summarise guidance and criteria in countries outside Sweden, and the assumptions made in a number of assessment programmes, concerning the treatment of human actions in assessments. The purpose of these Sections is to provide background material for the discussion of a regulatory strategy in Sweden.

3 Regulatory Developments outside Sweden

In this Section we provide a summary of the status of regulatory developments concerning the treatment of human actions in assessments in six OECD countries outside Sweden. Further details of the regulations and their requirements with respect to the assessment of human actions are provided in Appendix A.

The following summaries are brief statements of the regulatory position in each of the countries included in the review. The national regulations are further summarised in Table 3.1.

- Canadian regulations (AECB, 1985; 1987a; 1987b) require inadvertent human intrusion to be addressed in the safety assessment via the identification of intrusion scenarios and estimation of probabilities of occurrence.

- Draft Finnish regulations (STUK, 1998) recommend that the effects of disruptive future human actions should be evaluated both qualitatively and quantitatively. However, disposal depths are required to be sufficient that intrusion should be rendered very unlikely and site selection should avoid areas with mineral resource potential.

- French regulations (DSIN, 1992) specify several specific scenarios involving human actions which must be addressed by proponents.

- Swiss regulations (HSK and KSA, 1993) acknowledge the impossibility of predicting future human actions, but do require events and processes that could disrupt a repository to be considered in developing scenarios. Intentional intrusion, events with a very low probability, and events with large non-radiological impacts are excluded.

- In the United Kingdom, recently published regulatory guidance explicitly mentions future human actions (Environment Agency et al., 1997). Inadvertent and intentional actions are defined and it is stated that intentional actions do not require a quantitative risk assessment. The guidance does not specify how inadvertent future human actions should be treated in a safety assessment. Some preliminary work has been initiated to examine the application of probabilistic models, including Markov models, of human intrusion.

- In the United States, several different environmental regulations address human actions at waste disposal sites:

  - Regulations for the Waste Isolation Pilot Plant (WIPP) (EPA, 1993; 1996) provide detailed criteria bearing on the evaluation of human activities, including differentiation between intentional and inadvertent actions, specification of timescales for active and passive institutional controls and their assessment, specification of the types of future intrusive activities to be considered (mining and deep drilling), and guidance on the probability and consequence assessment of these activities.

- Final regulations for Yucca Mountain are yet to be promulgated, but specific recommendations on the way in which future human actions should be assessed have been made by the NAS (National Academy of Sciences) (NAS, 1995). These recommendations include the use of a stylised intrusion scenario involving a borehole through a waste canister and into the underlying aquifer, and the specific exclusion of doses to drillers from estimates of long-term risk.

- RCRA (Resource Conservation and Recovery Act) and CERCLA (Comprehensive Environmental Response, Compensation and Liability Act) regulations (US Congress, 1976; 1980) allow substantial discretion regarding the assessment of future human actions, and proponents are allowed to specify particular types of institutional control on a case-specific basis.

The following summaries are brief statements of the different regulatory strategies adopted to address the issues highlighted at the end of Section 2.

Institutional controls

All of the regulations recognise the eventual loss of institutional control at a disposal site. In France and the US, the regulations define maximum timescales that can be considered for effective controls. None of the regulations define a cut-off for the consideration of disruptive human actions different to that used for assessments of natural events and processes.

Scenario development

Most regulators specifically advocate some type of scenario development methodology to be adopted by the proponent in the consideration of potential future human actions at radioactive waste repositories. Some of the US regulations and guidance in the US and France are explicit in describing the types of human actions that must be considered in assessments. In general, however, regulations provide only general guidance on the types of human actions to be considered. In France, Switzerland, and the US, there is specific guidance on the use of current social structures and technological capabilities for defining potential future human actions.

Inadvertent and intentional human actions

The distinction between intentional and inadvertent intrusion is made in most recent regulations for radioactive waste disposal, with the provision that only inadvertent intrusion needs to be addressed. No distinction between intentional and inadvertent intrusion is made for the US RCRA and CERCLA regulations for non-radioactive hazardous substances. None of the regulations specifically mention nuclear material safeguards. Most regulations highlight the assumption that disposal facilities should not require intervention by future generations to maintain safety, and therefore implicitly exclude retrieval of waste as a potentially disruptive future human activity.

Selection of exposed groups

The majority of regulations specify that the critical group or potentially exposed group concept should be used in assessments of doses or risks. Some US regulations specify the maximally exposed individual, but this is for undisturbed conditions (i.e., in the absence of disruptive human actions). Only in the US regulations is there any specific guidance on the selection of parameter values (e.g., drilling rates and borehole diameters) for use in probability and consequence calculations.

Table 3.1 Summary of the Treatment of Human Actions in Regulations for Radioactive Waste Disposal

This table summarises the treatment of human actions in the regulations reviewed in this report (see Appendix A for further details). The categories used are based on issues identified in Section 2 of the report, and have the following scope:

Institutional controls and timescale for assessments: Are time limits defined which constrain the period for which future human actions must be considered?

Classification of human actions: Is a distinction made between recent and ongoing human actions and future human actions? Is a distinction made between global human actions (over which the proponent has no control) and local human actions that might be mitigated by institutional controls?

Intentional and inadvertent future human actions (FHA): Should deliberate actions taken with knowledge of the location and hazardous nature of the disposal facility be considered in assessments?

Potentially exposed groups: For which population groups are dose or risk calculations required?

All of the regulations reviewed exclude an explicit evaluation of the possible evolution of society.

Country: Regulator	Duration of institutional controls and timescale for assessments	Classification of human actions	Intentional and inadvertent FHA	Potentially exposed groups
Canada: AECB [1]	10,000-year limit for overall demonstration of compliance	No distinction made	Not necessary to consider intentional FHA	Must consider exposure of those located where the risk is greatest
Finland: STUK [2]	No time frame for quantitative assessments specified	No distinction made	Not necessary to consider intentional FHA	Not specified
France: DSIN [3]	Lower time limit of 500 years; no upper time limit	Explicit distinction of local and global human actions	Not necessary to consider intentional FHA	Drilling and mining scenarios imply exposure of drillers and miners to waste. Well and unsealed borehole scenarios imply contamination of aquifers and exposure through drinking water
Switzerland: HSK/KSA [4]	No time frame for quantitative assessments specified	No distinction made	Not necessary to consider intentional FHA	Not specified
United Kingdom: EA [5]	No time frame for quantitative assessments specified	No distinction made	Intentional FHA defined but not necessary to consider it	Impact on potentially exposed groups should be based on past and present human behaviour
United States (WIPP): EPA [6]	Maximum limit of 100 years for active institutional controls. Additional period of up to 600 years for passive controls. 10,000 year limit for overall demonstration of compliance	Recent and ongoing human actions to be considered for undisturbed performance	Not necessary to consider intentional FHA	All releases to accessible environment to be evaluated. Dose calculation for maximally exposed individual required for undisturbed performance (includes recent and ongoing FHA)

Table 3.1 (contd.) Summary of the Treatment of Human Actions in Regulations for Radioactive Waste Disposal

Country: Regulator	Duration of institutional controls and timescale for assessments	Classification of human actions	Intentional and inadvertent FHA	Potentially exposed groups
United States (Yucca Mountain): EPA/NRC [7]	Regulations under development. NAS recommends future human actions to be considered within the context of an illustrative intrusion scenario, which should be evaluated separately from the assessment of undisturbed repository performance			
United States (other environmental regulations) [8]	Not specified	No distinction made	No distinction made	Not specified. In CERCLA, distinction made between trespassers and intruders. Regulations only apply to trespassing

References:

[1] AECB, 1985; 1987a; 1987b
[2] STUK, 1998
[3] DSIN, 1992
[4] HSK and KSA, 1993
[5] Environment Agency et al., 1997.
[6] EPA, 1993; 1996; NRC, 1983
[7] EPA, 1993; NRC, 1983
[8] US Congress 1976; 1980

Table 3.1 (contd.) Summary of the Treatment of Human Actions in Regulations for Radioactive Waste Disposal

4 Treatment of Human Actions in Recent Assessments

In this Section we provide a summary of the treatment of human actions in recent performance assessments and supporting studies for deep geological repositories for radioactive waste in nine OECD countries. Further details of these assessments and studies are provided in Appendix B. Summaries are also provided of the different strategies adopted to address the issues highlighted at the end of Section 2. Table 4.1 provides an overview of the treatment of human actions in recent assessments.

Our review of recent performance assessments and supporting studies for deep geological repositories for radioactive waste has revealed a wide range of approaches to the treatment of human actions:

- In Belgium, SCK/CEN's assessment of the Mol site (Marivoet, 1994) included ongoing human activities, such as groundwater extraction and quarrying, in the normal evolution scenario. Greenhouse-gas-induced climate change was included in an altered evolution scenario, but no consequence calculations were undertaken. Other altered evolution scenarios considered disruptive future human actions such as drilling.

- In Canada, AECL's Environmental Impact Statement (EIS) PA (AECL, 1994a; 1994b) involved probabilistic consequence analysis of human actions in analyses that were separate from the undisturbed performance PA calculations (SYVAC scenarios). Probabilities of future activities, such as drilling, were defined by expert judgement using an event-tree approach.

- In Finland, the TVO-92 and TILA-96 assessments (Vieno et al., 1992; Vieno and Nordman, 1996) did not define or analyse scenarios involving human actions because such scenarios were considered impossible to assess quantitatively. It was also argued that the various countermeasures that would be taken at the disposal site would render human intrusion very unlikely. However, an earlier Finnish assessment (Vieno et al., 1985) analysed a drilling scenario (TVO-85).

- In the Netherlands, ECN's PROSA PA (Prij et al., 1993) involved a probabilistic consequence analysis of several future drilling, mining and archaeological investigation scenarios involving future human actions. However, the probabilities of occurrence of these scenarios were not estimated because they were considered to be too uncertain to quantify.

- In Spain, the PA for a generic granite site (ENRESA, 1997) identified an alternative scenario involving construction of a well and modification of hydrological conditions in the vicinity of the repository. Intrusion directly into the repository was not considered.

- In Sweden, SKB made a detailed analysis and classification of possible human activities that could adversely affect a repository (SR 95; SKB, 1995). As an example, probabilities were assigned in order to make an assessment of a borehole intrusion scenario. SKB have yet to implement this type of analysis within a full PA. In SITE-94, SKI (1996) undertook scenario development, but did not perform consequence calculations for the supplementary scenarios that included future human actions. The future human actions used to define supplementary scenarios included drilling and mining, surface activities, liquid waste injection, and the effects of mining on hydrochemistry.

- In Switzerland, for the Kristallin-I PA, NAGRA (1994) screened out most FEPs related to future human actions because it was assumed that the deep disposal environment would isolate the repository from most future human activities. The only alternative scenario involving future human actions was one in which a deep groundwater well is drilled in the vicinity of the repository.

- In the UK, UK Nirex Limited has not yet considered future human actions within a full PA but has provided a description of how a quantitative analysis of future human actions would be made (Nirex, 1995; 1997). The analysis relies heavily on using the frequency of past drilling and mining to predict the probability of future drilling and mining.

- For the US WIPP Compliance Certification Application (CCA) (DOE, 1996), regulatory requirements dictated much of the approach to treating human actions in PA. A detailed probabilistic treatment of the disturbed performance of the repository was made to account for relevant future human actions. The scenarios evaluated involved mining, deep drilling, and mining and drilling combined. In addition, a large number of recent and ongoing human actions were evaluated in detail to determine their possible impact on undisturbed performance (including mining, drilling, water flooding, resource extraction, etc.). The detailed analysis of human actions reflects the WIPP's location in a resource-rich area.

- Little effort has yet been invested in developing or modelling scenarios for human actions at the Yucca Mountain site in the US. Wilson et al. (1994) analysed the effects of drilling through a waste container or surrounding rock and transporting contaminated material to the surface. More recent assessments (TRW, 1995; EPRI, 1996) have not considered future human actions.

The following summaries are brief statements of the different approaches adopted in assessments to address the issues highlighted at the end of Section 2.

Institutional controls

The maximum period assumed for effective institutional controls is 500 years. In the assessment of the WIPP site, passive controls were assumed to reduce but not eliminate intrusion for a period of 600 years after the end of effective active institutional controls (100 years after closure). In assessments that calculated potential doses, intrusion was assumed to take place as soon as controls fail. Assessments that calculated risks generally used a probability of intrusion (based on drilling frequencies) to determine the time of intrusion: each simulation or set of calculations was based on a different time of intrusion.

Scenario development

Many assessments have used a systematic approach to scenario development for future human actions, involving the generation of a comprehensive list of potentially relevant FEPs, screening of this list according to defined criteria, and assignment of the FEPs surviving screening to one or more scenarios. A common approach has been to define an undisturbed performance scenario that includes all FEPs having a probability of one of occurring. Recent and ongoing human actions, if they are considered, are generally included in the undisturbed scenario. Alternative scenarios are defined by adding lower probability FEPs to this scenario. Future human actions are normally classified as low-probability FEPs and, therefore, if screened in, are included in alternative scenarios rather than the undisturbed performance scenario. The most common future human action scenarios considered in the PAs reviewed involve drilling (e.g., sinking water wells), and mining. However, several assessment programmes are still at an early stage in the identification of scenarios. All of the assessments use present-day social structures and technological capabilities as the basis for developing scenarios and analysing consequences of future human actions.

Three assessments (SITE-94, SR 95 and WIPP) distinguished between human activities that have a direct effect on the repository and those that have an indirect effect. In the WIPP assessment, recent, current and ongoing human activities were included in the assessment of undisturbed performance (i.e., without disruption of the repository) as well as being combined with potential future human actions in calculations of disturbed performance. SITE-94 included a supplementary scenario characterised by a warmer, wetter climate (greenhouse effect) than the central scenario. SR 95 discussed indirect effects such as greenhouse gas warming but did not include them in any of the illustrative calculations actually undertaken. SCK/CEN identified the potential for greenhouse gas effects to affect the groundwater system, and hence performance, but did not carry out any calculations. No assessments have yet been published in France, but the regulation requires that the effects of greenhouse-gas-induced climate change be considered.

Inadvertent and intentional human actions

All previous assessments have excluded intentional intrusion from the analyses of future human actions. Only the WIPP assessment has discussed the issue of retrievability (DOE, 1996; Appendix WRAC). However, this discussion is in the context of repository design rather than post-closure performance. None of the assessments surveyed discuss post-closure monitoring for nuclear materials safeguards, although it is considered for other aspects of a safety case (e.g., DOE, 1996, Appendix MON).

Selection of exposed groups

All of the assessments defined critical groups or potentially exposed groups for calculating doses and risks. Several assessments, including those by AECL, TVO, SKB, SCK/CEN and Nirex, have also calculated (or proposed to calculate) doses to members of a drilling crew. AECL, Nirex, and the Yucca Mountain project have all considered the dispersal of contaminated material from intrusion events and subsequent uptake through the food chain. AECL, Nirex, NAGRA and the WIPP project all account for the formation of new pathways that by-pass some of the engineered and natural barriers.

Table 4.1 Summary of the Treatment of Human Actions in Assessments for Radioactive Waste Disposal

This table summarises the treatment of future human actions in the assessments reviewed in this report (see Appendix B for further details). The categories used are based on the issues identified in Section 2 of the report, and have the following scope:

Institutional controls and timescale for assessments: What period is used for consideration of human actions?

Classification of human actions: Is a distinction made between recent and ongoing human actions and future human actions? Is a distinction made between global human actions (over which the proponent has no control) and local human actions that might be mitigated by institutional controls?

Potentially exposed groups: For which population groups have dose or risk calculations been made?

None of the assessments reviewed consider intentional human intrusions or make an attempt to evaluate the possible evolution of society.

Country: Organisation: Assessment	Duration of institutional controls and timescale for assessments	Classification of human actions	Potentially exposed groups
Regulatory Assessments			
Sweden: SKI: SITE-94 [1]	No limits specified for FHA. Overall assessment to 1,000,000 years	Ongoing use of groundwater (well) in "Central Scenario". Scenario with warmer, wetter climate than Central Scenario (global). Other scenarios include drilling, mining, pumping groundwater, liquid waste injection into shaft or fracture, human activities on the surface (all local)	Consumption of groundwater in Central Scenario. No exposed groups defined for other scenarios
Proponent Assessments			
Belgium: SCK/CEN: Mol [2]	No limits specified for FHA. Overall assessment to 150,000 years	Ongoing activities include groundwater extraction and quarrying. Other scenarios include greenhouse gas warming (no calculations) and drilling	Consumption of water from aquifer. Examination of radioactive drill core
Canada: AECL: EIS [3]	No limits specified for FHA. Overall quantitative assessment to 10,000 years	Ongoing use of groundwater (well) included in undisturbed performance scenario. Future human actions include drilling into vault	Consumption of groundwater. Exposure of drillers, lab technician (drilling) and building worker, resident (house construction on excavated waste)
Finland: TVO/POSIVA: TVO-85, TVO-92, TILA-96 [4]	No limits specified for FHA, but inadvertent human intrusion considered very unlikely due to siting repository in region of low economic potential. Overall assessment to 1,000,000 years	Ongoing use of groundwater. Future drilling in TVO-85	Consumption of groundwater. TVO-85 considered exposure of drillers
The Netherlands: ECN: VEOS, PROSA [5]	Assumed no FHA before 250 years after closure. Overall assessment to 20,000,000 years	Ongoing use of groundwater. Future drilling and mining	Consumption of groundwater. Various exposed groups associated with drilling and mining

Country: Organisation: Assessment	Duration of institutional controls and timescale for assessments	Classification of human actions	Potentially exposed groups
Spain: ENRESA: ENRESA, 1997 [6]	No limits specified for FHA. Overall assessment to 1,000,000 years	Ongoing use of groundwater. Future construction of well that affects hydrological conditions around repository	Consumption of groundwater
Sweden: SKB: SR-95 [7]	No limits specified for FHA. Overall assessment to 10,000,000 years	Ongoing use of groundwater. Global warming could affect geosphere / biosphere conditions. Future drilling.	Consumption of groundwater. Exposure of drillers
Switzerland: NAGRA: Kristallin-1 [8]	No limits specified for FHA. Overall assessment to 10,000,000 years	Ongoing use of groundwater. Future construction of deep well	Consumption of groundwater
United Kingdom: Nirex: Sellafield [9]	No limits specified for FHA. Overall assessment to 100,000,000 years	Ongoing use of groundwater. Drilling and well construction discussed in supporting literature	Consumption of groundwater. Exposure to drillers proposed
United States: DOE: WIPP CCA [10]	Maximum limit of 100 years for active institutional controls. Range of 100-700 years for passive controls. Overall assessment to 10,000 years	Recent and ongoing human actions, including drilling and mining outside controlled area, considered in undisturbed performance. Mining and deep drilling inside controlled area considered in disturbed performance	No releases to surface during undisturbed performance; illustrative dose calculations for drinking water pathway. Cumulative releases to the accessible environment calculated for combined effects of mining and drilling
United States: DOE: Yucca Mountain [11]	No limits specified for FHA. Overall assessment to 10,000 years	Ongoing use of groundwater. Future drilling with repository penetration in Wilson et al. (1994). FHA scenarios not considered in TRW (1995)	Consumption of groundwater. Exposure of residents to material brought to surface by drilling

Table 4.1 (contd.) Summary of the Treatment of Human Actions in Assessments for Radioactive Waste Disposal

Country: Organisation: Assessment	Duration of institutional controls and timescale for assessments	Classification of human actions	Potentially exposed groups
United States: EPRI: Yucca Mountain [12]	No limits specified for FHA. Overall assessment to 10,000 years	Ongoing use of groundwater	Consumption of groundwater

References:

[1] SKI, 1996
[2] Marivoet, 1994
[3] AECL, 1994a; 1994b
[4] Vieno et al., 1985; Vieno et al., 1992; Vieno and Nordman, 1996
[5] Prij et al., 1987; Prij et al., 1993
[6] ENRESA, 1997
[7] SKB, 1995
[8] NAGRA, 1994
[9] Nirex, 1995; 1997
[10] DOE, 1996
[11] Wilson et al., 1994; TRW, 1995
[12] EPRI, 1996

5 International Views and Issues

In this Section, we provide brief summaries of a number of international activities relevant to the treatment of future human actions in safety assessments. In Section 5.1, we summarise the activities of two Working Groups on future human actions established by the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD). In Section 5.2, we summarise an NEA Workshop and collective opinion on the "Environmental and Ethical Basis of Geological Disposal". In Section 5.3, we discuss three initiatives by the IAEA relevant to the treatment of future human actions in assessments.

5.1 NEA Working Groups

5.1.1 Working Group on Assessment of Future Human Actions

In 1991, the NEA's Performance Assessment Advisory Group (PAAG) established a Working Group on the "Assessment of Future Human Actions at Radioactive Waste Disposal Sites". SKI participated in this Working Group, which completed its activities in late 1993, the final report being published by the NEA in 1995 (NEA, 1995a).

The principal conclusions of the Working Group were:

- The most effective countermeasure to inadvertent disruptive actions is active institutional control of the surface above and for some distance around the disposal site. However, institutional control cannot be relied upon over the timescales for which wastes present a potential hazard.

- The analysis of human actions can only be illustrative and never complete, and scenarios of future human actions have to be viewed as representations of potential realities based on sets of assumptions.

- Site-specific scenarios for future human actions could be based on the premise that the practices of future societies correspond to current practices at the repository location.

- Intentional disruptive human actions should not be considered in safety assessments.

The Working Group also identified a number of international efforts that could be undertaken to build confidence in safety assessments. These recommendations, and the activities that have been undertaken as a result, included:

- Further discussion should be promoted between interested countries concerning regulatory policies for judging the risks associated with future human actions. The NEA subsequently established a second working group on regulatory aspects (see Section 5.1.2).

- An internationally reviewed database of features, events and processes that could be considered in safety assessments would help build confidence in the comprehensiveness of national site-specific assessment programmes. The NEA subsequently established a FEP Working Group, which developed an international list of FEPs and a database for comparing this with lists developed by national projects (NEA, 1998).

- An international archive of radioactive waste repositories could be developed to conserve information at different societal levels and locations and help ensure that administrative knowledge of the repository is not lost. An initiative by the IAEA to provide guidance on a records management system is described in Section 5.3.3.

- Development of marker systems. A consistent approach towards marker systems would help society to retain awareness of their meaning, and ensure that once the meaning of markers had been understood in one part of the world, the meaning of any similar markers discovered elsewhere may be more apparent.

- Development and trial application of a set of methodological principles for the construction of human action scenarios. Scenarios could be developed using site-specific information, based on an internationally agreed approach.

The latter two recommendations have yet to be acted upon.

5.1.2 Working Group on Regulatory Aspects of Future Human Actions

As a follow-up to the work of the first Working Group, the NEA established a new Working Group in 1994 on the "Regulatory Aspects of Future Human Actions at Radioactive Waste Disposal Sites," which was active through 1995. The main conclusions of this Working Group were:

- Future human actions should be considered in licensing.

- Their consideration should be clearly separate from that for undisturbed performance ('normal evolution').

- The consequences of future human actions should be assessed.

- The probabilities of future human actions should be discussed essentially in qualitative terms.

- Sites should not be disqualified during licensing on the basis of assessments of future human actions alone, as long as it could be demonstrated that future human actions had been adequately considered in the siting and design of repositories.

The Working Group considered that no further consensus beyond that expressed at the two meetings of the Working Group was achievable, and there was no wish to ensure international consensus at a regulatory level on such issues as effectiveness of institutional controls in PA. The Working Group considered that additional work, for example on a reference methodology for developing scenarios of future human actions, or determining consequences and probabilities of these scenarios, would be better considered within the wider remit of the PAAG. The Working Group was therefore disbanded after two meetings, but no follow-up activities have yet been initiated by the NEA.

5.2 Environmental and Ethical Basis of Geological Disposal

As part of its continuing review of the general situation in the field of radioactive waste management, the NEA organised a Workshop in 1994 on the Environmental and Ethical Aspects of Long-lived Radioactive Waste Disposal (NEA, 1995c). Based on the material presented and discussed at the Workshop, the NEA published a collective opinion on the same topic (NEA, 1995b).

The collective opinion focused on two considerations:

- Intergenerational equity, concerning the responsibilities of current generations who might be leaving potential risks and burdens to future generations.

- Intragenerational equity, concerning the balance of resource allocation and the involvement of various sections of contemporary society in a fair and open decision-making process.

The collective opinion concluded that principles of intergenerational and intragenerational equity must be taken into account in assessing the acceptability of strategies for the long-term management of radioactive wastes.

With regard to intergenerational equity, two principles have relevance for consideration of future human actions in safety assessments:

- Wastes should be managed in a way that secures an acceptable level of protection for human health and the environment, and affords to future generations at least the level of safety that is acceptable today.

- A waste management strategy should not be based on a presumption of a stable societal structure for the indefinite future, nor of technological advance; rather, it should aim at bequeathing a passively safe situation which places no reliance on active institutional controls.

5.3 IAEA Initiatives

Three recent publications of the IAEA have considered issues relevant to the treatment of future human actions in safety assessment. Two of these publications have been prepared by a group considering the "Principles and Criteria for Radioactive Waste Disposal", established under the International Radioactive Waste Management Advisory Committee (INWAC). Topics relevant to the treatment of future human actions include the use of different safety indicators (Section 5.3.1) and the establishment of safeguards for spent fuel (Section 5.3.2). The third publication, which is still in draft form, discusses work undertaken on the maintenance of records (Section 5.3.3).

5.3.1 Safety Indicators in Different Time Frames

The first report of the "Principles and Criteria for Radioactive Waste Disposal" subgroup (IAEA, 1994) deals with the problem of establishing appropriate indicators of safety for underground radioactive waste repositories in the presence of increasing uncertainty of the results of safety assessments with time. The report divides post-closure safety assessment into three time frames: from facility closure until 10,000 years, from 10,000 to 1,000,000 years, and beyond 1,000,000 years.

For the first period, from facility closure until 10,000 years, the report recommends that, for the purposes of assessing future human actions, the future level of technology should be assumed to be at least equivalent to that existing at present. This assumption was viewed as a balance between the assumption of a lower level of technology (which would make it less likely that intrusion could be technically achievable), and an improved technology (which would make it more likely that records would be retained and that an awareness of the risks posed by radioactive waste repositories would still exist). The report also concludes that it is reasonable to consider changes in climatic conditions, but with the use of reference biospheres as a means of reducing speculation about the exact nature of future environments. It was acknowledged that unintentional intrusion of a repository may take place, and that its likelihood should be reduced as much as possible by selecting appropriate sites and repository designs.

For the second period, from 10,000 to 1,000,000 years, the report recommended that assessment calculations relating to the near-surface zone and human activity should be simplified by assuming present-day communities under present conditions. The calculations should be viewed as illustrative and the doses as indicative. The use of reference biospheres was again recommended.

The report concluded that quantitative, and even qualitative, assessments for the period beyond 1,000,000 years would contribute little to the decision-making process.

5.3.2 Issues in Radioactive Waste Disposal

The second report of the "Principles and Criteria for Radioactive Waste Disposal" subgroup (IAEA, 1996b) addresses three topics, all related to the long timescales requiring consideration in safety assessment of radioactive waste repositories. The three topics are post-closure controls and public reassurance, optimisation, and nuclear material safeguards. The issues surrounding material safeguards are of particular relevance to the assessment of future human actions at repositories. Nuclear materials are safeguarded throughout most stages of the nuclear fuel cycle in order to prevent their diversion for the purpose of creating nuclear weapons. The report concludes that it may be necessary to continue safeguarding spent fuel, even after it has been emplaced in a deep geological repository. The report examines possible safeguards requirements and discusses whether they could improve or compromise safety at disposal sites. No specific timescale for the continuation of safeguards is specified, but the IAEA will allow termination of safeguards after the nuclear material has become “practicably irrecoverable”. This term has yet to be clearly defined for regulatory purposes.

The report identified two important questions concerning the possible conflict between safeguards requirements and repository performance:

- How can an effective safeguards procedure be developed that has no negative impact on the safety of the repository?

- How long should safeguards last, bearing in mind that spent fuel will remain a potential source of nuclear material for weapons production for thousands of years?

The report considers that repositories should be safeguarded by non-intrusive surveillance mechanisms, such as satellite observation, that would allow the repository site to be checked periodically. Such surveillance should reduce the likelihood of possible future human intrusion because likely intrusion practices (drilling, mining) would be easily observable. The duration of such safeguards should be decided by future generations and will depend upon the future development of society. It is possible that safeguarding of nuclear materials may continue to be a high priority for hundreds of years or millennia. The report notes that the requirement for open-ended surveillance contradicts ethical considerations of radioactive waste disposal by imposing a burden on future generations, and would also involve costs which cannot be reliably estimated.

5.3.3 Maintenance of Records for Radioactive Waste Disposal

The IAEA is in the process of finalising a report on the maintenance of records for radioactive waste disposal (IAEA, 1999). The objective of the report is to provide technical guidance on the establishment of a records management system to ensure the availability and retention of information concerning radioactive waste repositories after closure. The following major observations have been made:

- Maintenance of information for geological repositories is to enable future societies to make informed decisions about intentional actions.

- Information may become less understandable over time as societies evolve. Therefore, the information preserved in archives should be in condensed form and only essential information should be preserved.

- Preservation of information beyond the duration of active institutional control requires the establishment and maintenance of a records management system. Records generated during the active institutional control phase, such as monitoring and facility maintenance data, should be added to the records management system.

6 Key Elements of a Regulatory Strategy

A regulatory strategy for the treatment of human actions in safety cases for radioactive waste repositories requires consideration of issues beyond simply scientific and technical issues. In particular, consideration must be paid to societal concerns, public perceptions, the scope of regulations for other activities, cost-benefit evaluations and international practice. Because of this wide scope, it is appropriate that any regulatory strategy should take account of the views of a wide range of stakeholders, including, ***inter alia***, licensees, local communities and environmental groups (Hoegberg, 1998). These views could be obtained through the conduct of a broad-based consultation exercise, for example, via the conduct of meetings and/or the provision of a period for public review and comment on a draft regulatory strategy. In the following subsections we return to the issues highlighted in Section 2, and provide interim suggestions for key elements of a regulatory strategy based on the possible outcomes of such a consultation exercise.

6.1 Institutional Controls

6.1.1 Types of controls

Institutional controls are likely to be a key element in assessments for near-surface repositories, and these controls will be most effective in the period immediately after closure, when the waste poses the greatest hazard. In the case of deep repositories, radionuclides are extremely unlikely to reach the biosphere until well beyond the period when institutional controls could be treated as effective.

The most significant assumption about institutional controls is the choice of a period for which controls are treated as preventing ***any*** disruptive human actions. It is generally assumed that the only type of controls that could be totally effective in this respect are “active” controls involving a continued presence at the site, either through continuous monitoring with guards, or through periodic monitoring and maintenance of fences. Other controls, often referred to as “passive”, which involve either the understanding of a message or marker, or a search for information regarding ownership and responsibilities, cannot be regarded as totally effective although they may reduce the probability of disruption or extend the period before disruption occurs.

The maintenance of fences, notices, guards, periodic surveillance and monitoring all require continual funding by the site owner or by another organisation that assumes responsibility for the site. In contrast, markers and archives, once established, may require significantly less additional funding.

The period for which active markers are effective is dependent upon the longevity of individual organisations and on the stability of the society within which such organisations operate. An assumption of a stable society is also implicit in any assumption regarding searches for information about site ownership. Markers and archives may be assumed to retain some effectiveness even if there have been changes to society. Under these circumstances, however, markers and archives may also encourage disruption by highlighting the existence of a feature with a forgotten and uncertain purpose.

6.1.2 Effectiveness of controls

The effectiveness of institutional controls is dependent upon societal factors which could be assumed to be broadly similar in all of the developed countries that have nuclear power and waste disposal programmes. An international consensus amongst such countries concerning the effectiveness of controls would be desirable, but is perhaps unlikely given that different countries have already established markedly different allowable periods of effectiveness in their applicable regulations (see Section 3).

Because of the societal factors involved and the lack of an international consensus, it is recommended that the regulator consult widely within society on the likely effectiveness of controls. This should be a broad debate that considers, ***inter alia***:

- The ability of local communities and society as a whole to maintain interest in and control over a closed disposal facility.
- The possible roles of national, regional and local government in maintaining planning controls, and the role of international agencies.
- The type of markers appropriate to the possible disposal sites.
- Existing planning regulations and any requirements for after-use controls of other hazardous facilities, including nuclear power plants and hazardous waste disposal facilities.

One possible conclusion of the debate, based on the assumption that society as a whole is more stable than individual organisations, is that responsibility for maintaining control over disposal sites should pass from the proponent to a governmental organisation at some time after closure in order to prolong knowledge of the site. Different periods of effectiveness may be recommended depending on the extent and complexity of the controls established and the organisation that assumes responsibility. The longest period of effective institutional control is likely to require the greatest investment in terms of site maintenance, markers and archives. Regulatory guidance derived from the consultation exercise could eliminate the requirement for the proponent to justify the effectiveness of these controls. However, the proponent will remain responsible for providing details in the safety case of the controls to be used and the funding arrangements for implementing these controls.

If public debate concludes that no controls will be effective in preventing disruption, we suggest that the regulators should nevertheless encourage implementation of a minimum set of institutional controls, in particular an extended period of site maintenance and surveillance. Further debate is required on the effectiveness of markers, especially whether they might encourage disruption by individuals or societies unable to decipher their meaning, before they can be recommended as a regulatory requirement. Similar concerns regarding the potential for encouraging exploration can be levelled at recording the location of disposal facilities on maps and in archives. However, because the location will be widely known and recorded during the operational and active management phases, it is unreasonable to assume that information on the whereabouts of an interesting feature will necessarily be lost if knowledge of radioactive waste is lost. It is therefore sensible for the regulator to provide guidance on the form and content of archival material, to increase the potential for future generations to understand the hazardous nature of the site. The basis for such guidance has already been established in the study on the conservation and retrieval of information concerning nuclear waste repositories undertaken by the Nordic Committee for Nuclear Safety Research (Jensen, 1993) and by the IAEA (see Section 5.3.3).

Regulations in the US (EPA, 1993) allow for a period following effective active institutional control when passive controls can be assumed to reduce but not to eliminate the possibility of disruptive human actions. The difficulties of defining the duration of this period and the extent of the effect are even greater than those of defining the period of effective active control. Pending the results of public consultation on this issue, or proposals put forward by the proponent, the regulator should consider a simple, two-stage approach of a period when disruption is prevented by a combination of active and passive controls followed by an extensive period when there is no control over activities at the site.

The regulator should also require any assessment that considers future human actions (see below) to make the assumption of no mitigation by passive controls as a bounding analysis for comparison purposes. The proponent should nevertheless be allowed to argue for an additional period of partial control, and any regulatory guidance should not unduly constrain the assessment to conservative assumptions. This approach will help to motivate the proponent to develop controls to their best potential whilst ensuring that the safety case does not rely solely on optimistic assumptions regarding the effectiveness of controls.

6.2 Scope of the Safety Case

Whatever period is assumed for the effectiveness of controls, it must be assumed that disruptive human actions could occur at the site at some (unknown) time in the future, with an uncertain probability. Any public consultation that considers the effectiveness of controls should also consider the way in which potentially disruptive human actions should be considered in a safety case.

There are several reasons that could be considered to militate against a detailed consideration of potential disruptive future human actions in a safety case for radioactive waste disposal, beyond a demonstration that reasonable controls will be put in place to discourage such activities. These include:

- Regulations governing other hazardous activities, especially disposal of hazardous wastes, may not require assessment of potential disruptive human actions.

- The inherently uncertain nature of human activities, and the way in which society might evolve, means that only a few arbitrarily selected activities can be analysed, and that the overall evolution of the repository including human actions cannot be assessed other than in an illustrative fashion.

- The costs involved in assessing the effects of human actions at radioactive waste disposal sites should not be disproportionate to the benefits associated with such an analysis. For example, given the KBS-3 repository design in Sweden, the scope for design optimisation may be relatively small with respect to intrusion activities.

Nuclear power and radioactive waste disposal are, however, activities about which the public often expresses concerns in respect of control, familiarity, dread and equity (Covello et al., 1983). These factors all lead to a relatively low tolerability to the risks assessed for these activities, and different regulatory approaches for different industries may be warranted.

Scientific and technical approaches to assessments commonly conclude that knowledge of the physical processes affecting repository performance is adequate to extrapolate over long periods, in contrast to the conclusion that the evolution of human society cannot be meaningfully extrapolated beyond the present day. It is, however, possible that some stakeholders would not reach the same conclusion and may consider the uncertainties regarding future human activities as not significantly greater than the uncertainties associated with the physical processes affecting repository performance. Finally, cost-benefit concerns by the proponent are likely to have a low priority in the public's attitude towards the content of a safety case.

Together, these factors suggest that the consultation with stakeholders is likely to conclude that human actions should be considered in the safety case. We consider that the regulator should consult widely on the overall issue. A suggested approach that could form the basis for any such consultation is outlined in the following subsections.

6.3 Human Action Scenarios

6.3.1 Recent and ongoing human actions versus future human actions

The regulators could explicitly distinguish between recent and ongoing human activities that may have an effect on the characteristics of the engineered or natural systems, but which are not under the direct control or influence of the proponent (such as current groundwater abstraction, and greenhouse gas effects on climate change), and potentially disruptive future human actions (such as future drilling, mining and subsequent resource extraction):

- Recent and ongoing human activities should be included in any FEP list developed as the basis for FEP screening and scenario development. Any such FEPs that cannot be eliminated on the basis of low consequence should be accounted for in assessments of the undisturbed performance of the repository.

- Potentially disruptive future human actions should be used to define one or more additional sets of calculations to illustrate potential risks to defined critical groups.

We suggest that the proponent remains responsible for determining the detailed approach to scenario development in accordance with such regulatory guidance, and also for the methods used to account for uncertainty in all types of natural, repository-related and human action FEPs.

6.3.2 Future states assumption

The purpose of PA calculations is to provide information on the behaviour of the repository under various conditions and not to provide a prediction of the actual evolution of the system. The assumptions that underlie a PA are key elements in understanding the context of the results and it is important that these assumptions are clearly identified. PAs also provide means of accounting for the uncertainties inherent in site characterisation data and process understanding. In this context, PAs that account for future human actions provide an illustration of the potential risks associated with these activities and not a prediction of actual human behaviour.

Accounting for all possible disruptive human actions in a single set of assessment calculations would necessarily involve accounting for very large uncertainties, and it is doubtful whether the results of such a calculation would provide meaningful insights into system performance. One method of reducing the scope of the calculations, and thereby reducing the uncertainties that need to be addressed, is to base the PA on recent and current human activities in the region of the disposal site. This ensures that the maximum amount of characterisation data is used and eliminates the need for speculation regarding future societies.

The assumption that future societies are essentially the same as those in the vicinity of the site and at similar sites has been termed the "future states assumption." It can be applied to demographic patterns, human characteristics, water and land use patterns, technical and intellectual ability, medical knowledge and resources, and social structures and values. The regulators could adopt this assumption in independent assessments, and also require this assumption to form the basis of assessments that form part of a proponent's safety case.

Within the next 35,000 to 70,000 years, disposal sites in northern latitudes, including Scandinavia, are expected to be covered by a continental-scale ice-sheet. Prior to the arrival of this ice at a particular site, it is likely that permafrost will develop and that demographic patterns in the region will change. The resources available in the region, which provide the underlying reason for any potentially disruptive future human actions, will not change with the cooling climate. Activities that are a function of population density are likely to decrease during cooler climate periods, and activities that are a function of resource availability are likely to continue at a similar rate. For such climate change, the assumption of present-day demography would probably provide a bounding analysis for the extent of future human actions.

During the period that the waste remains a potential hazard, the climate will cycle several times between present-day climatic conditions and continental-scale glaciation. Assessments that consider climate change may need to consider all of these cycles in order to determine when groundwater passing through the repository reaches the biosphere. However, assessments that consider potentially disruptive human actions that by-pass the natural and engineered barriers around the repository need only focus on the first cycle of climate change. Radionuclide decay means that the waste will be less hazardous during the second and subsequent cycles, and these types of disruptive human actions are likely to result in lower releases in subsequent glacial cycles. Similarly, human activities that do not by-pass the engineered barriers, but which intersect radionuclides that have migrated into the geosphere, are likely to lead to lower doses during all glacial cycles.

6.3.3 Defining disruptive activities

The future states assumption is based on recent and ongoing human activities in the region of the disposal site. The size of the region considered, and the length of the period considered, will both affect the range of activities considered in the scenario development process. There are conflicting influences affecting the choice of region and period considered. Use of a small region and limited period could exclude potentially significant human activities, whereas a larger area or period could include unreasonable activities or activities that are no longer relevant. It is not, however, possible for the regulator to define ***a priori*** the size of the region or the period to be considered. We suggest that the proponent remain responsible for defining and justifying the region and time used to define the activities considered in scenario development.

If the rates or frequencies of activities are considered as well as their occurrence, then determining the appropriate region and period is further complicated. Restricting the region to include only areas with similar geological characteristics, or restricting the period considered to exclude different practices, may reduce the number of events to such an extent that derived rates or frequencies are not statistically significant. A number of assessment programmes have concluded that the derivation of intrusion rates based on extrapolation of rates from a defined period is not justifiable, and have therefore restricted assessments to conditional consequence calculations. We suggest that the proponent remain responsible for defining and justifying the region and time used to determine any rates or frequencies of disruptive events used in assessment calculations.

6.4 Intentional Intrusion

The regulators could restrict the consideration of future human actions to those that are inadvertent, and provide a definition of "inadvertent" in regulatory guidance. A definition similar to that used by the NEA (1995a) for inadvertent actions would be appropriate:

> *Those in which either the repository or its barrier system are accidentally penetrated or their performance impaired, because the repository location is unknown, its purpose is forgotten, or the consequences of the actions are unknown.*

It is generally accepted that radioactive waste repositories should be regulated in a manner that ensures that future societies have the same level of radiological protection as the current society (NEA, 1995b). The current society cannot, however, protect future societies from their own actions if the latter understand the potential consequences of their activities. Future societies may attempt to retrieve the waste from the repository. The effects of any engineered features intended to ease retrieval should be considered during the design and optimisation stage, but retrieval should be regarded as an intentional act and should not need to be included in assessments. Recommendations concerning the extent to which retrievability should be considered in repository design are outside the scope of this report. The regulators could provide separate guidance to proponents on the requirements for design and optimisation studies, and exclude retrieval as a topic to be considered in post-closure assessments.

Guidance from the IAEA identifies the need for safeguards, including long-term inspection and monitoring, for repositories containing spent fuel (see Section 5.3.2). These safeguards can be provided during the operational phase of the repository but may conflict with long-term safety requirements following closure. Any monitoring of the repository after emplacement of shaft seals may compromise the performance of the seals. Maintenance of site controls (fences, ownership, etc.) will provide some safeguards during the period following closure of the repository. Recommendations concerning the provision of safeguards and post-closure monitoring are outside the scope of this report. The regulators could provide separate guidance to proponents on the requirements for safeguards and post-closure monitoring, and on the extent to which safeguards and post-closure monitoring should be considered in assessments of post-closure safety.

6.5 Selection of Exposed Groups

Section 6.3 above provides suggestions for an approach to determining which human actions should be considered in assessment calculations. In this Section we provide suggestions on the selection of exposed groups to be considered in calculating the consequences of these actions.

Individual members of a drilling crew who intrude into a HLW repository may receive high doses from handling core material. A drilling crew cannot be considered, however, to fulfil the criteria of a critical group or a potentially exposed group for the purposes of assessing the performance of a repository. For example, currently proposed regulatory criteria in Sweden would require the determination of average annual doses for members of a critical group (SSI, 1997). Short-term doses (i.e. received over a few hours or less) to one or a few individuals cannot be compared to these criteria without meaningless averaging. Furthermore, there are many assumptions that would have to be made about an individual's actions and behaviour (e.g., how closely they examined the core, or how quickly they recognised the material as hazardous) in order to define a dose calculation of this type. It is questionable whether regulatory decisions concerning long-term safety can be made on the basis of potential doses to a single individual at some unknown time in the future. The regulators could specifically exclude drillers and other direct intruders from consideration in assessments of post-closure safety.

Future human actions may affect the performance of the repository other than through doses to drillers. Such actions may lead to the creation of new pathways or to the modification of properties of existing pathways between the repository and the biosphere. These new or modified pathways could then lead to increased doses to a wider community through ingestion of contaminated drinking water or foodstuffs. Intrusion could also result in the dispersal of radioactive material in the biosphere where it may subsequently enter the food chain or lead to doses through inhalation. The potentially exposed groups relevant to these types of human actions are the same as those considered in assessments of releases through natural pathways. The regulators could provide guidance on the selection of potentially exposed groups, but the proponent should remain responsible for selecting, documenting and justifying the dose calculations presented in a safety case.

6.6 An International Approach to Assessing Human Actions

Calculations of biosphere performance face similar problems to the assessment of human actions concerning the definition of calculations, the processes to be considered, the exposed groups to be assessed, and the treatment of uncertainty. These issues have been the subject of extensive discussion within the BIOMOVS and BIOMASS international fora (BIOMOVS II Steering Committee, 1996a; IAEA, 1996a). A proposed approach that would help to define the scope of biosphere calculations, and provide a means for comparison between programmes and between sites or design options within a single programme, is the Reference Biosphere Methodology (BIOMOVS II Steering Committee, 1996b; IAEA, 1998). This approach includes the definition of a reference or generic biosphere (or suite of biospheres for use at different times or different locations) and reduces the extent of conjecture and site characterisation data required for a particular site.

An international project that developed generic scenarios of future human actions, derived distributions of parameter values for a range of assessment contexts, and provided a forum for the intercomparison of models and codes would be of benefit to most assessment programmes (see Section 5.1.1).

6.7 Conclusions

The study has led to the following major conclusions and recommendations.

- Consideration of future human actions requires a wider perspective than the solely technical/scientific issues that underpin assessments.

- Wide consultation within society is necessary to provide a consensus on the effectiveness of institutional controls, and the type of controls most likely to be effective.

- The regulator should define and require a minimum set of site controls, including post-closure site maintenance and archival material, and require proponents to identify funding arrangements for implementing these controls. The regulator should encourage proponents to implement additional controls, providing a consensus can be reached with stakeholders on the value of markers and other controls. Proponents must justify any assumptions regarding the effectiveness of controls beyond the minimum determined through consultation.

- A debate amongst stakeholders should consider the extent and scope of any treatment or analysis of future human actions after the failure of institutional controls and, in particular, whether regulatory decisions should be made on the basis of speculative analyses.

The following elements of a regulatory strategy on the treatment of future human actions are proposed as a basis for consultation:

- Assessments of future human actions should be based on present-day conditions in the region of the disposal site and at similar sites. Site-specific definitions of the region considered and the period examined for defining rates and frequencies of such actions should be provided by the proponent.

- Assessments must include calculations of repository performance without any disruptive future human actions. These calculations should include the effects of any recent and ongoing human activities that might affect the performance of the repository, such as local groundwater extraction or the influence of global greenhouse gas emissions on climate change. Any additional calculations should illustrate the potential effects of disruptive future human actions. The proponent should develop and justify the methods used for scenario development and uncertainty analysis for all assessment calculations.

- Assessments could be restricted to the analysis of inadvertent human actions that occur locally, and could exclude intentional intrusion, including retrieval of the waste, post-closure monitoring (including safeguards), and co-disposal of additional wastes in the future. Assessments could also exclude future global actions, and other future actions where the other effects of the actions lead to greater consequences than those resulting from disruption of the repository itself (e.g., war).

- Assessments of disruptive future human actions should consider doses to potentially exposed groups similar to those considered under undisturbed performance scenarios. Thus, assessments could be restricted to consideration of the long-term effects of disruption through the formation of new pathways and the dispersal of radioactive material in the biosphere. The proponent should develop and justify the scenarios analysed in an assessment, and should discuss the conceptual basis for consideration of their consequences.

In addition to developing guidance for the proponent on the scope and conduct of assessments, the regulator could undertake illustrative assessments in order to assure themselves that they understand the impacts of any proposed strategy, and to demonstrate the proposed strategy to the proponent.

This work could be supported by the development of an international reference human action approach, as recommended by the NEA (1995a). International cooperation has proved useful in tackling the treatment of other uncertainties concerning future evolution of the natural system, such as the reference biosphere approach currently under development within BIOMASS.

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Appendix A

Regulatory Developments outside Sweden

In this Appendix we review and document the status of regulatory developments concerning the treatment of future human actions in countries outside Sweden.

A.1 Canada

The Atomic Energy Control Board (AECB) is responsible for regulating all aspects of the development and application of nuclear energy in Canada. The AECB has issued three regulatory documents applicable to the long-term management of radioactive wastes (AECB, 1985; 1987a; 1987b). These documents contain guidance for the analysis of human intrusion scenarios in safety assessments, and siting criteria.

Regulatory Document R-71: This document concerns requirements for the Concept Assessment phase, and specifies that inadvertent human intrusion during the post-closure phase must be addressed, via identification of intrusion scenarios, and estimating probabilities of occurrence and consequences. The value of prominently marking the site with a durable monument should be investigated.

Regulatory Document R-104: This document concerns long-term requirements for waste disposal. It specifies that safety features to reduce the likelihood of inadvertent human intrusion must be developed, and provides a methodology and a criterion for assessing the combined risk of intrusion and other scenarios. A risk limit of 10^{-6} per year is specified, to be calculated without taking credit for long-term institutional controls, and to be applied to a group of people that is assumed to be located at a time and place where the risks are likely to be the greatest.

Regulatory Document R-72: This document deals with siting a repository and defines the characteristics of an acceptable site for radioactive waste disposal. Some of the characteristics are chosen to reduce the likelihood of human intrusion: R-72 includes requirements that the host rock is unlikely to be exploited as a natural resource, and that the repository is located deep underground.

A.2 Finland

STUK, the Finnish Radiation and Nuclear Safety Authority, has recently issued draft regulations concerning the disposal of spent nuclear fuel in crystalline rock (STUK, 1998). They include consideration of future human actions. Such actions are classified as "unlikely disruptive events", meaning low-probability events with the potential to adversely affect the performance of the repository barriers.

Relevant points in the draft regulations include:

- Unlikely disruptive events (including future human actions) should be discussed qualitatively, but where practicable the radiological consequences and probabilities of such events should also be assessed quantitatively.

- The safety analysis should include qualitative discussion of issues for which quantitative analyses are not feasible or too uncertain.

- The burden on future generations of managing the radioactive waste should be limited by implementing a disposal option that does not rely on long-term institutional control.

- The depth of disposal should be sufficient that surface events, including future human activities, will not have an adverse effect on the performance of the disposal system. The depth should also be sufficient that inadvertent human intrusion would be very difficult.

A.3 France

French regulations on deep geological disposal of radioactive waste are contained in Basic Safety Rule No. III.2.f and include specific mention of future human actions (DSIN, 1992). In Section 5, "Safety Demonstration of the Repository", guidance is given as to the scenarios that should be considered in any safety demonstration. These include a reference scenario, to include all highly probable features, events and processes (FEPs), and a series of scenarios corresponding to less probable FEPs but ones that would have potentially serious consequences. These less probable scenarios are divided into two categories: those associated with natural events, and those associated with human actions. Events associated with human activity include future activities such as direct and indirect human intrusion (drillings, mines, cavity-forming activities and surface and sub-surface construction), and climatic changes associated with human activity.

Appendix 2 of Basic Safety Rule No. III.2.f provides further details on the scenarios to be considered that involve future human actions. Human intrusion is not considered possible until 500 years after closure owing to the existence of records documenting the existence of the repository. Human intrusion scenarios are required to be based on the assumption that the existence of the repository and its location are forgotten, and that the level of technology used is the same as at present. The following alternative scenarios involving human actions are specified:

- Exploratory drilling through the repository and extraction of core samples.

- Operation of a mine. This scenario is excluded for sites hosted in granite and clay because it is considered that there is no incentive for mining at such sites in France at the proposed repository depths.

- Abandoned and improperly-sealed exploratory drilling passing through the repository.

- Drilling a well to obtain water for drinking or agricultural purposes from a deep aquifer.

- For a site hosted in salt, formation of a cavity intersecting the repository (solution mining).

- Climatic changes resulting in a change in sea level, to be studied as a part of the evaluation of the consequences of natural climatic changes.

A.4 Nordic Countries

In 1993, the Radiation Protection and Nuclear Safety Authorities in Denmark, Finland, Iceland, Norway and Sweden published a document that was intended to constitute the basis for the development of national regulatory activities on the subject of high-level radioactive waste (HLW) disposal (NKS, 1993). The document contains Nordic views on basic criteria for the disposal of HLW. Recommendations are made for deep disposal options, including guidelines for radiation protection, site selection and performance assessment. The document includes mention of future human actions in several contexts:

- The burden on future generations of managing the radioactive waste should be limited by implementing a disposal option that does not rely on long-term institutional control. In this way, future generations will not need to take any action to protect themselves against the effects of waste disposal.

- The estimation of probabilities and consequences of events such as human intrusion is very approximate and speculative. Quantitative assessment of human intrusion scenarios was considered impossible and the risks from such scenarios were termed “rest risks”. Rest risks should be limited as far as practicable, but their acceptability should not be judged against quantitative risk limits.

- Disposal sites should not be adjacent to any natural resources that are not readily available from other sources. Such resources include fossil fuels, metal ores, geothermal potential, major groundwater resources and unique mineral deposits (not necessarily economic). Two reasons were given to support this position:

    - Future generations should be able to exploit natural resources for their own benefit without having to incur undue radiological risk.

    - Knowledge of the location of the repository may become lost, and inadvertent intrusion into the repository may occur by individuals seeking to exploit natural resources.

- The depth of disposal should be sufficient such that future human activities on the surface, including excavations or explosions, will not have an adverse effect on the performance of the disposal system.

A.5 Switzerland

The Swiss Nuclear Safety Inspectorate (HSK) is responsible for regulation of radioactive waste disposal in Switzerland under regulation HSK R-21 "Protection Objectives for the Disposal of Radioactive Waste" (HSK and KSA, 1993).

In Section 7.4 of HSK R-21, it is stated that "it is impossible to predict accurately what will happen in the future, particularly in the distant future. However, by means of detailed analyses, the applicant has to show what processes and events could affect the repository system over the course of time and then derive potential evolution scenarios from these. Processes and events with extremely low probability of occurrence or with considerably more serious non-radiological consequences, as well as intentional human intrusions into the repository system are not required to be considered in the safety analysis."

In Section 7.2 of HSK R-21, it is stated that "...dose calculations for the distant future are not to be interpreted as effective predictions of radiation exposures of a defined population group. They are, in fact, much more in the nature of indicators for evaluating the impact of a potential release of radionuclides into the biosphere. In this latter sense, dose and risk calculations should be carried out for the distant future, at least for the maximum potential consequences from the repository, despite the uncertainties related to the condition of the biosphere and the existence of a population. For such calculations, reference biospheres and a potentially affected population group with realistic, from a current point of view, living habits should be assumed."

It is thus acknowledged that human behaviour cannot be predicted into the future, and that intentional human intrusion, together with low-probability events, need not be considered in safety analyses.

A.6 United Kingdom

A.6.1 Guidance on Requirements for Authorisation

In the United Kingdom, responsibility for granting an authorisation to dispose of radioactive waste rests in England and Wales with the Environment Agency. Future human actions have been explicitly considered in new regulatory guidance published last year in the UK (Environment Agency et al., 1997), the Guidance on Requirements for Authorisation (GRA).

The GRA contains four principles for the protection of the public from adverse radiological effects, and some of these have relevance for possible future human activities at disposal sites. For example, Principle Number 1 states that "following the disposal of radioactive waste, the closure of the disposal facility and withdrawal of controls, the continued isolation of waste from the accessible environment shall not depend on actions by future generations to maintain the integrity of the disposal system." For the period after withdrawal of control over the facility, the GRA considers that conformity with a radiation protection standard cannot be demonstrated or enforced. The standard is therefore expressed as a target in order to recognise the more limited assurance of conformity that can be achieved. The performance measure is expressed as risk, which is deemed more appropriate given the uncertainties inherent in the estimation of future performance.

Future human actions are explicitly mentioned in the GRA. Two points are made:

- The GRA distinguishes between two classes of future human action, intentional and inadvertent. Intentional actions are taken with knowledge of the location and hazardous nature of the disposal facility. Inadvertent actions occur because the location or purpose is unknown. The GRA states explicitly that it is not necessary to undertake assessments of intentional human actions. This is because it is assumed that "no such action would be taken without due regard to the safety implications and to the economic and environmental values of the time."

- The GRA states that in the longer term future, "institutional controls cannot be relied upon to safeguard the disposal facility, and the developer will be expected to assess the likelihood and consequences of possible future human actions." Reference is made to the report of the NEA Working Group (NEA, 1995a) for guidance and a framework for consideration of the effects of human actions on disposal facilities. The recommendations of the NEA report are summarised in Section 5 of this report.

A.6.2 Markov Models for Future Human Actions

In models for calculating doses and risks resulting from human actions, the radiological risk is normally considered to be directly proportional to the probability of future human actions disturbing the repository. The frequency of human activities such as drilling has sometimes been estimated by examining scientific records of deep drilling or mining practices in the vicinity of the site, or in similar geological environments (see, for example, the methodology described by Nirex (1995) described in Section B.2.9 of this report). It has then been assumed that the frequency of such actions in the future will be the same as their frequency in the past.

In order to consider alternative approaches, the Environment Agency for England and Wales has been engaging in research to develop a probabilistic model of future human actions based on Markovian information states. A Markov model can be used to represent processes of information retention and regulatory regime by assigning probabilities of human action that are state dependent (Woo, 1989; Sumerling et al, 1995).

A prototype model of possible sequences of future human actions was developed, based on the Markov model proposed by Woo (1989). The model consists of three elements:

- Physical models of different types of relevant human actions such as deep drilling, excavation, and water extraction.

- An information state model, representing the level of information available and the degree of site institutional control, within discrete states of varying duration.

- An event and consequence model to calculate the spatial and temporal occurrence of events and consequent doses to predefined critical groups.

An expert elicitation exercise was undertaken to investigate the feasibility of eliciting relevant information on this topic, and to derive a conceptual model and data for demonstration calculations. The exercise considered the probability of a future drilling intrusion into a repository at the Sellafield site. The group of experts included a nuclear regulator, an historian, an information scientist, a geophysicist, an archaeologist and a mining engineer. The group developed a model for describing the interaction of the various factors considered most relevant to estimating future human actions at a repository site. This "eight state model" is illustrated in Figure A.1.

The experts identified technology and motivation as the dominant parameter with information on repository location and/or content of secondary importance. The group then derived cumulative probability distribution functions (PDFs) of technology/motivation state durations for a general climate condition and a PDF of return times for drilling. Results using the model and data supplied by the experts lead to long-term calculated frequencies of drilling at Sellafield that are at least a factor of ten greater than would be obtained by extrapolating short-term historical UK hard rock drilling data.

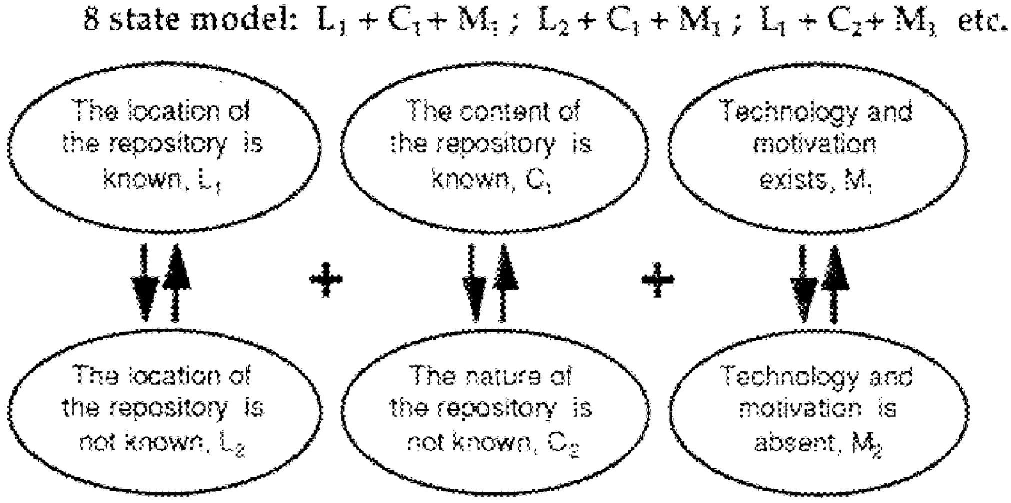


Figure A.1 Schematic illustration of an eight-state model for the interaction of the various factors considered most relevant to estimating future human actions at a repository site (after Sumerling et al., 1995).

The expert group came to the following conclusions:

- In the long-term, site markers are liable to cause an increase in interest in the site and a greater likelihood of disturbance, compared with a situation in which there are no site markers.

- Regulatory and planning controls alone cannot be considered to be effective in preventing human intrusion beyond a few tens of years.

- The timescales for the continuous retention of information in a relevant form are of the order of tens to hundreds of years.

- The most important factor affecting the likelihood of deep drilling or mining in crystalline rock is whether or not the relevant technology is retained or lost, and how strong a motivation exists to seek underground resources. Historical information on the gain and loss of human technologies provides an indication of the likely timescales.

- It is inappropriate to use short-term historical drilling data from a wide area, or from a different site, to estimate the future long-term drilling probability at a particular site. Historical evidence shows that human actions are influenced by site characteristics and do not occur randomly.

The final report on this project has yet to be published and, as a result, it is not known what final recommendations will be made regarding the use of a Markov model for considering future human actions in assessments.

A.7 United States

The issue of future human actions has been considered in a number of US regulations, including:

- Disposal programmes regulated by both the US Environmental Protection Agency (EPA) and the US Nuclear Regulatory Commission (NRC), such as those for high-level radioactive waste (HLW) including Yucca Mountain, low-level radioactive waste (LLW), uranium mill tailings, and decommissioning of nuclear facilities.

- Disposal programmes regulated by the EPA, such as the Waste Isolation Pilot Plant (WIPP), hazardous waste management and municipal solid waste management covered under the Resource Conservation and Recovery Act (RCRA), and sites covered under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), also known as the Superfund.

We briefly review approaches to the regulation of future human actions for the WIPP, Yucca Mountain, RCRA and CERCLA.

A.7.1 Waste Isolation Pilot Project (WIPP)

The EPA is responsible for developing and implementing regulations related to licensing of the WIPP repository in New Mexico. The WIPP has been developed by the United States Department of Energy (DOE) for the disposal of transuranic radioactive wastes in bedded salt about 650 metres below the land surface. The WIPP is sited in the Delaware Basin, a resource-rich area containing economically valuable deposits, primarily of hydrocarbons and potash, and future human activities at this site are therefore a particular concern.

General regulatory standards governing post-closure safety are given in 40 CFR Part 191 (EPA, 1993), and site-specific criteria are provided in 40 CFR Part 194 (EPA, 1996). 40 CFR Part 194 requires that performance assessments include consideration of all human-initiated FEPs relating to activities that have taken place in the vicinity of the disposal system and are reasonably expected to continue to take place in the near future. The scope of consideration of future human actions in performance assessments is limited to mining and drilling.

The EPA has provided additional guidance and criteria concerning the determination of both likelihood and consequences of future human actions:

- For example, with regard to the likelihood of future drilling, the EPA "…reasoned that while the resources drilled for today may not be the same as those drilled for in the future, the present rates at which these boreholes are drilled can nonetheless provide an estimate of the future rate at which boreholes will be drilled." Thus, in calculating the frequency of future drilling, the DOE is required to identify drilling that has occurred for each resource in the Delaware Basin over the 100 years prior to the time at which a compliance application is prepared. Historical drilling for purposes other than resource exploration and recovery (such as WIPP site investigation) need not be considered in determining future drilling rates. Furthermore, the DOE may limit the rate of future drilling based on a determination of the potential resources in the site area.

- With regard to the consequences of human intrusion scenarios, the EPA require that performance assessments "…shall assume that the characteristics of the future remain what they are at the time the compliance application is prepared." Furthermore, the EPA specifies that performance assessments need not consider the effects of techniques used for resource recovery subsequent to the drilling of a borehole. The EPA also states that "…inadvertent and intermittent intrusion by drilling for resources (other than those resources provided by the waste in the disposal system or engineered barriers designed to isolate such waste) is the most severe human intrusion scenario." Thus, human intrusion scenarios involving intentional intrusion need not be considered in performance assessments.

A.7.2 Yucca Mountain Regulations

The Energy Policy Act of 1992 (EnPA) mandated a separate process for setting a standard specifically for the proposed repository at Yucca Mountain. Under Section 801 of EnPA, the US Congress required the EPA to arrange for an analysis by the US National Academy of Sciences (NAS) of the scientific basis for a standard to be applied at the Yucca Mountain site, and required the EPA to issue health-based standards for Yucca Mountain based upon and consistent with NAS findings.

As part of its evaluation under EnPA, the NAS concluded that it is not possible to make scientifically supportable predictions of the probability that a repository's engineered or geological barriers will be breached as a result of human intrusion over a period of 10,000 years (NAS, 1995). The NAS considered that it is not possible to predict the probability that a future intrusion will occur within a certain period, nor the probability that a future intrusion would be detected and remediated. The NAS considered that although there is no scientific basis for judging whether active or passive institutional controls can prevent an unreasonable risk of human intrusion, such measures might be helpful in reducing the risk of intrusion for some period of time after the repository is closed.

The NAS suggested that it is not scientifically justified to incorporate alternative scenarios for human intrusion into a risk-based assessment. The NAS considered that it would be possible to carry out a consequence analysis for particular types of intrusion events, and that such an analysis, done separately from calculation of doses and risks for other events and processes, would be worthwhile. The NAS specified a stylised intrusion scenario in which the consequences of a borehole drilled from the surface through a waste canister to the underlying aquifer should be assessed. The analysis should exclude exposures to drillers and others due to fragments of radioactive material brought to the surface by drilling because such radiological impacts are impossible to quantify with adequate precision. The NAS recommended that the performance of the repository after having been intruded should be assessed using the same analytical methods and assumptions, including those about the biosphere and critical groups, used in the assessment of performance for the undisturbed case. The NAS recommended that the risk calculated from the assumed intrusion scenario be no greater than the risk limit adopted for the undisturbed repository case, because a repository that is suitable for safe long-term disposal should be able to continue to provide acceptable waste isolation after some type of intrusion.

At the time of writing, the EPA has yet to publish a proposal for new Yucca Mountain standards in response to the NAS recommendations, and the NRC has yet to modify its technical requirements and criteria (10 CFR Part 60). The current NRC strategy for development of Yucca Mountain regulations (10 CFR Part 63) is described by Kotra et al. (1998). The NRC expects that it will follow NAS recommendations by requiring future human actions to be considered within the context of a distinct, illustrative intrusion scenario to be evaluated separately from the assessment of undisturbed repository performance.

A.7.3 Other US Environmental Regulations

The EPA is responsible for implementing many environmental statutes that take a variety of approaches to protecting human health and the environment. EPA regulations established to limit human health risks from non-radioactive hazardous chemicals also contain requirements to consider future human actions at disposal sites. However, the requirements are rather different to those for radioactive waste repositories.

Two particular pieces of legislation and associated regulations are considered here:

- Regulation of the management and disposal of hazardous wastes under the Resource Conservation and Recovery Act (RCRA) (US Congress, 1976), codified in 40 CFR Part 264, Subparts G to X.

- Regulation under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) (US Congress, 1980), also known as Superfund, which was designed to address existing chemical waste sites where releases have already occurred and for which active monitoring and maintenance do not exist.

Resource Conservation and Recovery Act (RCRA)

The EPA's requirements for the closure of RCRA hazardous waste management facilities do not specifically address intrusion. However, intrusion protection is considered when reviewing closure and post-closure permits. At final closure of landfills, the owner/operator is required to install a cover designed to protect against long-term migration of groundwaters through the landfill, minimise erosion, and accommodate settling and subsidence. The owner/operator of the site is required to control access to the site and to restrict disturbance during the 30-year post-closure period, a period which may be shortened or lengthened at the EPA's discretion. For the duration of this period, the owner/operator is obligated to maintain and operate all monitoring systems at the facility and to protect the markers used to delineate the waste cells. Passive institutional controls are also required and are primarily land-use restrictions and the maintenance and archiving of records prepared by the owner/operator recording all relevant information about the site. Eventually, RCRA sites could become subject to regulation under CERCLA.

Comprehensive Environmental Response, Compensation and Liability Act (CERCLA)

Under CERCLA, a site baseline risk assessment must be made in order to determine whether site remediation is warranted, and risk assessments are made for a number of future site-use scenarios, assuming current site conditions. When making a risk assessment, under most circumstances, nearby residents are the receptors of primary concern. However, human intrusion is also considered, with a distinction drawn between trespassers (i.e. individuals who trespass on the ground surface immediately above the buried waste) and intruders (i.e. individuals who actively enter and disturb a waste facility). The following distinction is usually made:

- Risks to occasional trespassers are usually calculated based on a recreational scenario, with exposure related to soil contact and to on-site hunting and fishing. No consideration is given to a scenario in which the trespasser interferes with the isolation of the wastes on site.

- Risks to intruders are not typically addressed as part of a CERCLA risk assessment of a chemical waste facility. This is probably due to an assumption (in the case of chemical waste facilities) that institutional controls will typically prevent such intrusion from occurring for as long as the site presents a potential health risk.

CERCLA allows the use of a wide variety of institutional controls on a site-specific basis. Active controls such as site security measures may be required for 30 years or longer. Passive controls include deed restrictions, Government ownership of the site, and perpetual oversight by responsible parties.

In general, the requirements on institutional controls, monitoring, future site uses and human intrusion are more prescriptive for radioactive waste repositories than for chemically hazardous sites. RCRA and CERCLA both rely on institutional controls to control unacceptable future risks. It is assumed that permits will continue to be required to operate facilities, restrictions on future land use will continue to be enforced, and that monitoring, if required, will continue for the foreseeable future. For many CERCLA sites, particularly those in industrial areas, it is common for the EPA and the parties responsible for the site to agree to restrictions to prevent future residential use of the site. This is because the future on-site resident scenario, which includes an assumed private water well and vegetable garden, is usually the scenario calculated to have the highest risk.

Appendix B

Treatment of Human Actions in Recent Performance Assessments

In this Appendix we summarise the treatment of human actions in recent performance assessments and supporting studies for conceptual deep geological repositories for radioactive waste in nine different OECD countries. We have focused on performance assessments conducted by proponents because regulatory assessments, in general, have not given much consideration to human actions. Supporting studies conducted by some regulators are discussed in Appendix A. We have excluded recent international initiatives, for example the EC-sponsored EVEREST project (Evaluation of Elements Responsible for the Effective Engaged Dose Rates Associated with the Final Storage of Radioactive Waste, Marivoet et al., 1997), because these do not add significant additional thinking on the treatment of future human actions.

B.1 Regulatory Performance Assessments

B.1.1 Sweden

SITE-94 (SKI, 1996) was a performance assessment conducted by SKI of a hypothetical repository at a real site (Äspö). The main objectives were to determine how site-specific data should be assimilated into the performance assessment process, and to develop a sound methodology for scenario development and analysis including systematic FEP screening. Several scenarios involving future human actions were defined.

A Central Scenario was developed, based on:

- A deterministic description of the possible changes in climate at the site over the next 100,000 years.
- A description of the possible changes in the surface environment of the site over the same period.
- Quantitative information on how these changes might affect the disposal system.

Supplementary scenarios were developed by screening the 81 FEPs not included in the Central Scenario, and adding "screened-in" FEPs to the Central Scenario. Several FEPs related to human intrusion were screened out at this stage. For example, direct human intrusion into the repository was excluded on the basis of unpredictability and difficulty in establishing any quantitative model. After lumping the screened-in FEPs, four categories of human action FEP remained:

- mining, geothermal or water well drilling;
- poor seal;

- human impacts on the surface;
- groundwater flow and liquid waste disposal.

Two further human action scenarios were identified by considering combinations of these four remaining FEP categories. Consideration of naturally occurring FEPs led to the identification of two other supplementary scenarios, resulting in a total of eight supplementary scenarios:

Supplementary scenario 1:	Development of a warmer, wetter climate to that considered in the Central Scenario;
Supplementary scenario 2:	Large-scale tectonically induced seismicity;
Supplementary scenario 3:	Future operation of a large mine or well near the repository;
Supplementary scenario 4:	Inadequate shaft seal;
Supplementary scenario 5:	Future liquid waste injection into a fracture zone near the repository;
Supplementary scenario 6:	Future waste injection into a poorly sealed shaft combined with local groundwater pumping in a mine or well;
Supplementary scenario 7:	Future human impacts on surface water or groundwater;
Supplementary scenario 8:	Future mining impacts on surface water chemistry or groundwater chemistry.

The supplementary scenarios are purely descriptive and none were subjected to any quantitative modelling or consequence analysis in SITE-94, although in some cases specific suggestions were made as to how they could be modelled in future.

B.2 Proponent Performance Assessments

B.2.1 Belgium

Belgian performance assessments have been concerned with the possible disposal of radioactive waste in the Boom clay layer at Mol in northern Belgium. The first phase of performance assessment at Mol was completed in 1991 and consisted of the PAGIS (Marivoet and Bonne, 1988), PACOMA (Marivoet and Zeevaert, 1991), and UPDATING 1990 (Marivoet, 1990) studies. A second phase of performance assessment at the Mol site has adopted a more systematic approach to scenario selection (Marivoet, 1994).

The second phase followed the recommendations of the NEA Scenario Working Group (NEA, 1992) in adopting a systematic approach consisting of the identification, classification and screening of all possible FEPs prior to scenario formulation. The initial list of FEPs was based on those prepared by the IAEA (IAEA, 1985) and the NEA (NEA, 1992). After screening, a normal evolution scenario was defined to include all FEPs that are certain or highly probable to occur. Eight altered evolution scenarios were then defined by adding additional FEPs to the normal evolution scenario that have the potential to adversely affect the performance of one or more components of the disposal system.

Screened-in FEPs that involve future human activities included (Marivoet, 1994):

- Exploratory drilling.
- Exploitation drilling.
- Archaeological investigation.
- Groundwater abstraction.
- Loss of records.
- Anthropogenic climate change.
- Quarrying and/or peat extraction.

Groundwater extraction, and quarrying and/or peat extraction were both included in the normal evolution scenario. Loss of records was implicitly considered in all scenarios involving human actions. The remaining four FEPs were used to formulate three altered evolution scenarios.

Normal evolution scenario: This scenario considered most of the 60 screened-in FEPs, discussed in four time spans. From 0 to 500 years after closure, considerable heat and radiation are expected to be generated by the waste, but groundwater and the waste forms will remain separated by the waste canisters. From 500 to 10,000 years, corrosion of the canisters starts and radionuclides are dissolved in groundwater and start to migrate. From 10,000 to 150,000 years, the effects of expected climatic changes, particularly on the aquifer system, need to be taken into account. After 150,000 years, the changes caused by successions of glacial and interglacial episodes and neo-tectonic movements become increasingly difficult to predict, and only qualitative analysis of their effects can be made.

Exploitation drilling: This scenario considered the sinking of a water well into the underlying aquifer, thereby by-passing the aquifer barrier. This scenario was considered separately because the probability of occurrence of sinking a water well into the aquifer underlying the disposal site was expected to be significantly less than one. The essential modelling tools and data were already available to allow consequence analysis of this scenario. Results were similar to those of the normal evolution scenario.

Greenhouse effect: This scenario was formulated in response to studies which indicated that the consequences of the greenhouse effect on the earth's climate might last for several thousands of years. However, work on this scenario was suspended until more results from these studies become available.

Exploratory drilling / archaeological investigation: In this scenario, it was assumed that inadvertent intrusion by exploratory drilling or archaeological excavation brought a core or pieces of radioactive waste to the surface. The study considered that the probability of occurrence of this scenario should be carefully examined, because it could potentially lead to very serious consequences in terms of radiation exposure. If the probability was found to be lower than 10^{-8} per year, the scenario would not need to be analysed further.

B.2.2 Canada

A significant contribution to scenario development and performance assessment has been presented by Atomic Energy of Canada Limited as part of their Environmental Impact Statement (EIS) (AECL, 1994a; b). The primary objectives of the AECL assessment were:

- To develop and document a method for evaluating the long-term effects and safety of a facility for the disposal of Canada's nuclear fuel waste.
- To demonstrate the utility of the method by applying it to a reference disposal system.

AECL developed a probabilistic post-closure performance assessment methodology to evaluate the feasibility of deep disposal of spent nuclear fuel within crystalline rocks of the Canadian Shield. An expert group was convened to identify all factors that might conceivably influence the behaviour of the disposal system. Two groups of factors were identified, a group of ~150 factors which could contribute to risk within 10,000 years of closure, and a group of ~150 factors which could only contribute to risk on longer timescales.

The ~150 factors considered to be important over the first 10,000 years after closure were combined into three groups of scenarios:

- The first group contained all but two of the 150 factors, integrated into a system model. The expected release pathways involved normal groundwater-mediated processes in which radionuclides are released from the vault, migrate through the geosphere, enter the biosphere and cause radiation exposure. These pathways were also assumed to account for the use of a well constructed close to the repository. This central group of scenarios was modelled using the computer code SYVAC3-CC3 and are referred to as the SYVAC scenarios.

- The second group of scenarios (open-borehole scenarios) contained all the same factors as the SYVAC scenarios plus an unsealed borehole, which passed through or near the disposal vault, providing a direct pathway for contaminants to move from the disposal vault to the surface. Such a feature may significantly perturb groundwater flow fields. The scenario was evaluated by modifying the geosphere model in SYVAC to include this feature.

- The third group of scenarios (disruptive scenarios) encompassed other future human actions that could disrupt the disposal system, specifically inadvertent human intrusion into the vault by drilling or blasting. This group of scenarios is discussed further below.

Disruptive scenarios

The only disruptive event identified as being of relevance within a 10,000-year timeframe was inadvertent human intrusion. Its probability of occurrence was estimated at less than 5×10^{-6} per year for all times up to 10,000 years, and was taken to include activities such as drilling, mining and blasting near the vault. Intentional human intrusion and deliberate by-passing of the natural and/or engineered barriers were excluded from consideration.

Inadvertent human intrusion was classified according to five categories:

(1) exposure to undispersed waste;

(2) exposure to waste dispersed by previous intrusions;

(3) human-induced alteration of the expected evolution of the disposal system;

(4) contact with a contaminated groundwater plume;

(5) contact with materials contaminated by the groundwater plume.

Categories (4) and (5) were considered to have been included within the central SYVAC analysis of transport by groundwaters. Category (3) was considered to have been covered by the sensitivity analysis of transport by groundwater, through evaluation of the effects of enhanced transport. The first two categories were retained for separate consequence analysis and used an alternative form of analysis (Wuschke, 1991; 1992).

Four representative scenarios within the first two categories were analysed. All four scenarios involved drilling operations that penetrate the waste and bring it to the surface. Scenarios involving mining were also considered but were not selected for consequence analysis because the probability of mining was considered to be less than that of drilling. The four human intrusion scenarios analysed were:

- Drilling scenario: exposure of a member of the drilling crew.
- Core examination scenario: exposure of a laboratory technician.
- Construction scenario: exposure of a worker constructing a house on excavated waste.
- Resident scenario: exposure of the occupant of a house built on excavated waste.

Three alternative methods were considered for estimating probability of the scenarios:

- Extrapolation based on the historical frequency of drilling.
- An extremely conservative assumption that the consequences of intrusion were experienced once each year following closure.
- An event-tree methodology in which, for each scenario, a sequence of events leading to the exposure of the intruder was defined, and probabilities assigned to each of these events.

Wuschke (1991; 1992) considered that it was not justified to extrapolate historical information on the incidence of drilling into the future over timescales of thousands of years. An assumption of an annual intrusion rate was regarded as being implausible. Therefore, an event-tree methodology was used in which time-dependent probabilities were defined for each event, based on the judgements of experts from relevant fields. The overall probabilities of the scenarios were estimated from the event probabilities, and combined with estimates of consequences to produce time-dependent estimates of the risks from intrusion scenarios.

The calculated risks from these intrusion scenarios were over 1,000 times lower than the regulatory limit. Wuschke (1991; 1992) concluded that although it is easy to envisage highly unlikely situations in which human intrusion by-passes all natural and engineered barriers, the risk is negligibly small. The event-tree methodology was considered to have the advantages of explicitly displaying the assumptions made in the analysis, of permitting easy testing of the sensitivity of the risk estimates to assumptions, and of combining technological and sociological information.

B.2.3 Finland

Based on a decision made by the Finnish government in 1983, Teollisuuden Voima Oy (TVO) was required to propose suitable areas for detailed site investigations for construction of a repository for spent nuclear fuel. The repository is to be constructed 500 metres below the surface in crystalline bedrock of the Fennoscandian Shield. The spent fuel will be placed within composite copper/steel canisters surrounded by compacted bentonite. A preliminary safety analysis, TVO-85 (Vieno et al., 1985), considered a specific human intrusion scenario. In the TVO-92 safety analysis (Vieno et al., 1992), the long-term safety of a hypothetical repository was studied in order to demonstrate whether the five sites that had undergone preliminary investigation were potentially suitable disposal sites. The TILA-96 study was an update of TVO-92 (Vieno and Nordman, 1996) and focused on these short-listed sites.

TVO-85

A scenario involving future human intrusion into the repository was considered in the TVO-85 safety analysis. The scenario considered the possible dose to the members of a drilling crew who accidentally drilled through a canister. In TVO-85 the probability of accidental drilling through a canister was estimated to be 2×10^{-8} per year. If the drilling occurred at 100 or 1,000 years after sealing of the repository, the corresponding doses would be 4×10^{-2} Sv/year or 1×10^{-4} Sv/year, respectively. The expectation value of the dose in this analysis is very small, reaching a maximum of 2×10^{-11} Sv/year at 500 years when all knowledge of the location of the repository is assumed to have been lost.

TVO-92

In TVO-92, no detailed consequence analysis was made of any human intrusion scenario. Any attempt to estimate the probabilities or consequences of human intrusion into the repository was considered “very approximate and speculative”, following the conclusions of the working group of Nordic safety authorities (NKS, 1993). Accidental intrusion into the repository was considered to be very unlikely, provided that the repository was sited in an area of low ore and mineral potential, that the repository was adequately sealed, and that adequate countermeasures against intrusion were taken, such as construction of site markers and archiving of site information. TVO-92 considered that intentional intruders should bear responsibility for their own actions.

TILA-96

The set of scenarios analysed in TILA-96 was similar to that considered in TVO-92, and the conclusions regarding human intrusion are also similar. The three candidate sites all have similar geology and are located in regions where the local country rock has a low economic potential. Therefore, inadvertent human intrusion was regarded as very unlikely and was not considered as a scenario within the safety assessment.

B.2.4 The Netherlands

The Dutch OPLA (OPberging te LAnd) programme has been concerned with the evaluation of salt formations in the Netherlands as host rocks for a radioactive waste repository, and has consisted mainly of desk studies and laboratory research. However, scenario development methodologies are relatively well advanced, and probabilistic consequence analyses of scenarios involving future human actions have been made (e.g. Prij et al., 1993).

PROSA (PRObabilistic Safety Assessment of geologically disposed radioactive waste) adopted a systematic top-down procedure to scenario development to ensure that the most relevant processes were accounted for in the consequence analysis (Prij et al., 1993). The scenario development procedure resulted in the definition of 22 scenarios which were grouped into three families, each containing one scenario that could be considered as a base case.

One of the three scenario families contained all scenarios related to human intrusion. The base case scenario in this family was the migration of contaminated brine from the repository into a nearby storage cavern, followed by creep closure of the cavern and expulsion of the brine. Other FEPs that could result in the release of brine from the storage cavern were combined to form additional scenarios, as follows:

- Leaky storage cavern.
- Leaky storage cavern and reconnaissance drilling.
- Leaky storage cavern and solution mining.
- Leaky storage cavern and conventional mining.
- Leaky storage cavern and archaeological investigation.

These scenarios assumed that any disruptive human action would not take place sooner than 250 years after disposal. Dose was calculated using models of the intrusion activity (e.g. solution mining or direct excavation) and of human exposure (e.g. inhalation or ingestion). Consequence analysis for most of the human intrusion scenarios in PROSA was based on the earlier VEOS assessment (Prij et al., 1987), the safety study performed under Phase 1 of OPLA. No attempt was made to estimate scenario probabilities because it was considered that the low calculated doses did not merit significant effort in this regard. However, doses were higher in the human intrusion scenarios than in any of the other scenarios for which a consequence analysis was made.

B.2.5 Spain

The most recently available information concerning the approach to future human actions within the Spanish radioactive waste disposal programme is found in an ENRESA report describing a performance assessment for a generic granite site (ENRESA, 1997). In this study, a systematic approach to the definition of scenarios was presented. The process began with the compilation of 277 FEPs (termed "factors"), which was reduced to 121 by removal of all biosphere FEPs (considered to be outside the scope of this assessment), and removal of duplicate or irrelevant FEPs. Further screening reduced the number of FEPs to 100, divided into a subset of 60 FEPs considered to have a probability of one, and a subset of 40 FEPs considered to have a probability of less than one. The 60 FEPs were considered to define a reference system, and the 40 FEPs were considered to be external to the reference system. Human intrusion was one of the 40 external FEPs.

The 40 external FEPs could be combined with the 60 reference system FEPs to define many alternative scenarios. However, in the ENRESA (1997) assessment, only three scenarios were analysed. One of these was the reference scenario including the 60 FEPs with probability one. Two other scenarios were selected for quantitative analysis: "Human intrusion scenario; water well" and "Repository with deficient seals". The human intrusion scenario involved the presence of a well that extracts water from a 200-metre borehole for domestic consumption. Note that this scenario does not involve penetration of the repository itself. The well modified hydrological conditions in the vicinity of the repository and influenced the rate at which groundwater flowed through the repository. No attempt was made to estimate the probability of this scenario, or to consider other forms of human activity such as exploration drilling.

B.2.6 Sweden: SKB - SR 95

We have provided a more extensive analysis of SKB's work on future human actions, both because SKB is the organisation that SKI will be regulating and because SKB has given particularly extensive consideration to the issue. SKB's scenario construction methodology includes the following stages (SKB, 1995):

- A systematic description of the FEPs that can influence repository performance, and their coupling to each other via the construction of several interaction matrices.

- A method for documenting the interaction matrices, including coupling to the FEP database.

- Description and justification of scenarios.

- Qualitative analysis with the aid of the interaction matrix. Documentation of how the interaction matrices change for different scenarios.

The interaction matrices were constructed in order to show that no FEPs had been overlooked, and to identify important interactions and interaction pathways. The matrices were also considered to lead to a better understanding of the system and to facilitate communication between experts. Scenario selection was not done directly from the interaction matrices, but was made judgmentally by a panel of experts, who used the matrices as checklists once scenarios had been selected. The chosen scenarios were classified according to whether they affected the performance of the repository by changing or influencing the initial conditions, the behaviour of the rock, or the behaviour of the groundwater.

The scenarios whose initiating events are a consequence of human activities were termed future human action (FHA) scenarios. The actual procedure for analysing FHA scenarios varied depending upon the type of initiating event. In analysis of FHA scenarios, four factors were considered:

(i) Impact, meaning how repository performance is influenced by human activities. Human activities were divided into the following two groups with respect to impact:

- Direct intrusion of the radioactive waste. In effect this means that one or more of the barriers has been completely by-passed. Analysis can be made in the form of a standard risk assessment, in which both probability and consequence are estimated. SKB considered that the assumptions needed to make such an analysis are always subjective and, therefore, that the results of such analyses should only be regarded as illustrative.

- Indirect impact on the performance of the barriers. Examples of human activities having indirect impact are global warming and intensive agriculture. The barriers may be affected by changed conditions in the rock or in the groundwater. Scenarios should be analysed by qualitative discussion supported by scoping calculations.

(ii) Purpose, meaning whether the impact is intentional or inadvertent. Purpose is closely associated with knowledge of the repository and the waste [see (iii) below]. Apart from sabotage [see (iv) below], SKB considers that there is no need to deal with intentional intrusion in safety assessment. If intrusion is inadvertent, it is assumed that the intruders have an incomplete knowledge of the repository or its contents. Inadvertent intrusion may have a direct or an indirect impact.

(iii) Knowledge on the part of those who impact the repository, both regarding the repository specifically and the general level of knowledge at the time. The probability of human impact and its consequences are linked to the knowledge that future generations have of the repository, its contents, and radioactive materials.

(iv) Intent, meaning whether those who impact the repository have good or bad intentions. The consequences of intrusion depend upon the intent of the intruder, and SKB considers that it is the responsibility of the designer of the repository to build a system that is not vulnerable to sabotage.

SKB considers that future human impacts on the repository cannot be predicted and that FHA scenarios should be regarded as illustrations of conceivable situations. The choice of scenarios must be based in part on the design and function of the repository, which will have taken account of the possibility of future human activities. Some examples of requirements where human activities have been considered in connection with repository design and siting are:

- Repository performance shall not depend on monitoring or institutional control.

- The waste shall be retrievable.
- The backfill shall be emplaced so that it cannot easily be penetrated or removed.
- Valuable or rare materials should not be used in the engineered barriers because their use might encourage human intrusion.
- The repository shall not be sited in host rock that contains valuable minerals.
- The repository depth shall be great enough to make human intrusion unlikely.

As an example, SKB (1995) presented the results of a risk assessment of a scenario in which a deep borehole intersects a canister and exposes the drillers to radioactive material. This analysis was intended to serve as an illustrative example of a conceivable FHA scenario and a possible analysis method. With regard to the four factors discussed above, this scenario corresponds to a situation in which the impact is direct (all the barriers are by-passed), the purpose is inadvertent, the level of knowledge is similar to the present level, and the intent is not malicious.

The probability of drilling through a canister was assessed by considering three independent factors:

- The probability that the drillers have no knowledge of the repository and its contents.
- The probability that the borehole happens to be drilled within the repository footprint.
- The probability of drilling through a canister if the borehole is within the repository footprint.

Estimated probabilities are given in Table B.1. The estimation of doses to drillers depends on several independent factors:

- The quantity of waste and its radionuclide concentration.
- How humans come into contact with the waste.
- Exposure time.
- Drilling method.
- Distance and position of exposed individuals with respect to the retrieved waste.

SKB considered that each of these factors could only be estimated on the basis of speculative assumptions, the importance of which must be evaluated and quantified. Figure B.1 illustrates some of the assumptions made in this example with regard to the position of an exposed human from the various sources of radiation (drill core, contaminated ground and contaminated clothing). Figure B.1 also shows the contributions of the different radiation sources to the total dose.

The maximum risk per drilled hole was found to be on the order of 10^{-12} and occurs 500 years after repository closure, at the time when knowledge about the existence of the repository is assumed to be lost. Conversion of this to an annual individual risk requires assumptions regarding the number of boreholes that a driller might drill in a year. SKB considered this to be too speculative, but did note that more than 100,000 boreholes would be required to exceed acceptable risk levels. Other conclusions drawn from the analysis were:

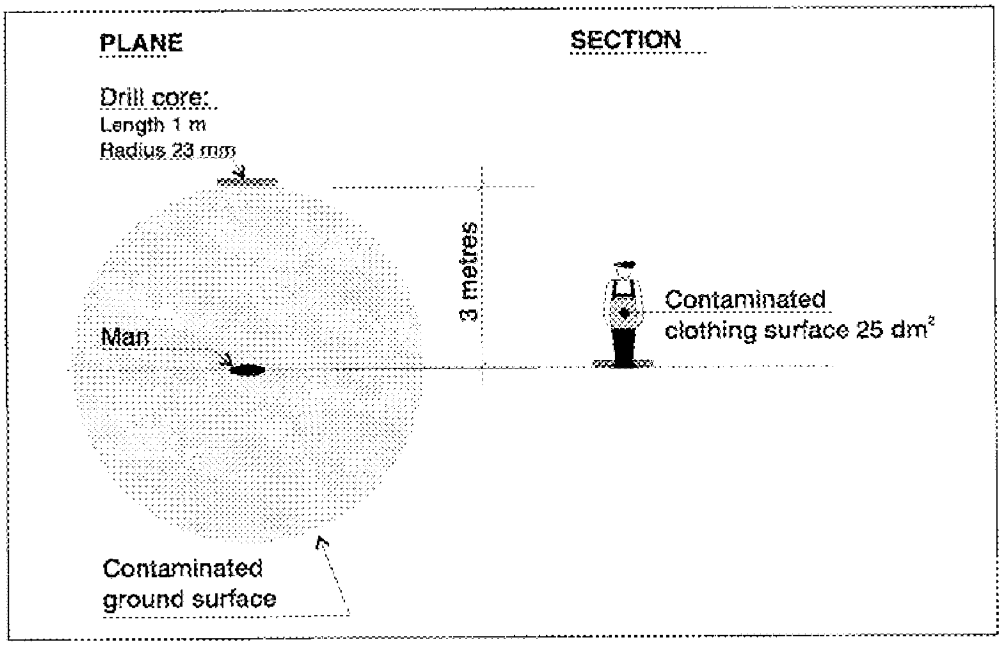
- Drilling through a canister is an event that cannot be neglected in terms of its estimated consequences.

- The probability that someone will drill through a canister is considered to be small, on the order of 10^{-7} per year.

The maximum risk is strongly influenced by the choice of the time at which knowledge of the repository is assumed to be lost. As an example, Figure B.2 illustrates the variation of risk with time for two cases, one in which all knowledge is lost after 500 years, and one in which all knowledge is lost at the time of repository closure. The maximum risk is approximately 10^4 times higher in the case in which knowledge of the repository is assumed to be lost at the time of repository closure. SKB concluded that it was worth attempting to ensure the preservation of knowledge of the repository for as long as possible in order to reduce the risk from this type of human intrusion scenario.

Event	Probability
The drillers have no knowledge of the repository and its contents	0 for first 200 years 1 after 500 years Linear increase from 0 to 1 during period between 200 and 500 years
The borehole lands within the repository area	10^{-5}
The borehole penetrates a canister	10^{-2}

Table B.1 Estimated probabilities of drilling through a waste canister in SKB's human intrusion scenario (SKB, 1995).



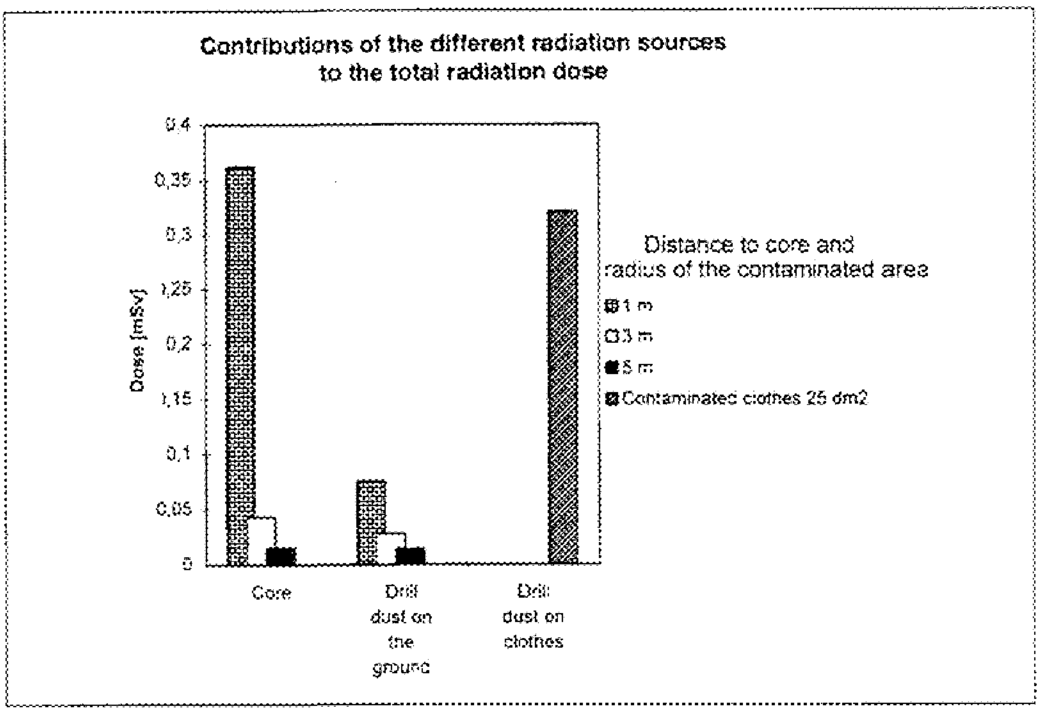
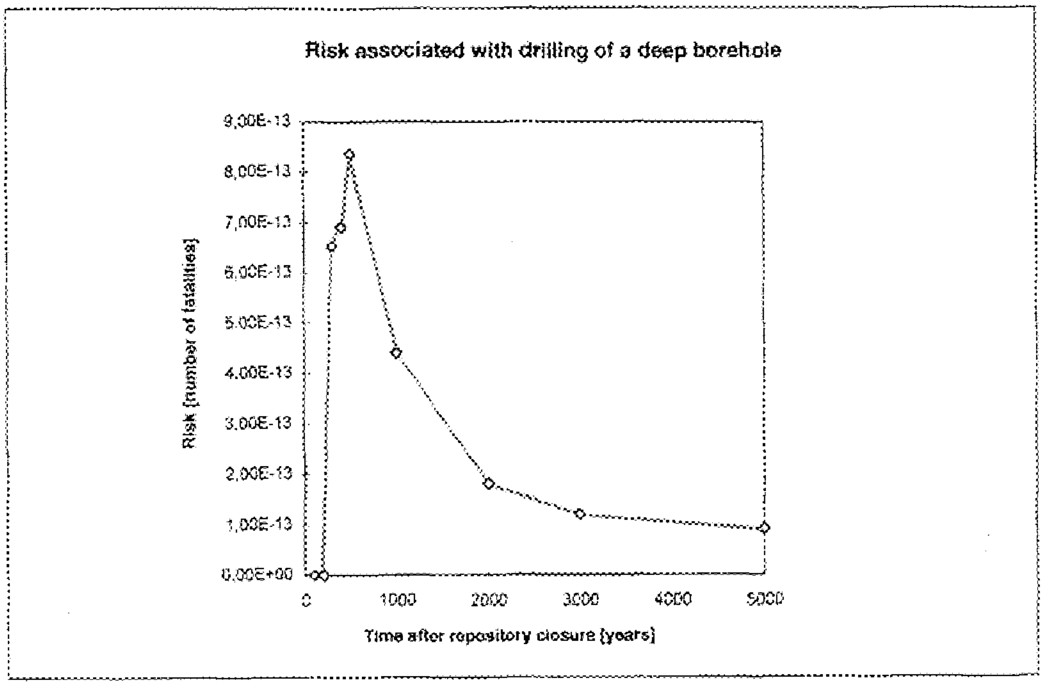


Figure B.1 Upper diagram: illustration of some of the assumptions made in SKB's example calculation with regard to the position of an exposed human from the various sources of radiation (drill core, contaminated ground and contaminated clothing). Lower diagram: the contributions of the different radiation sources to the total dose (after SKB, 1995).



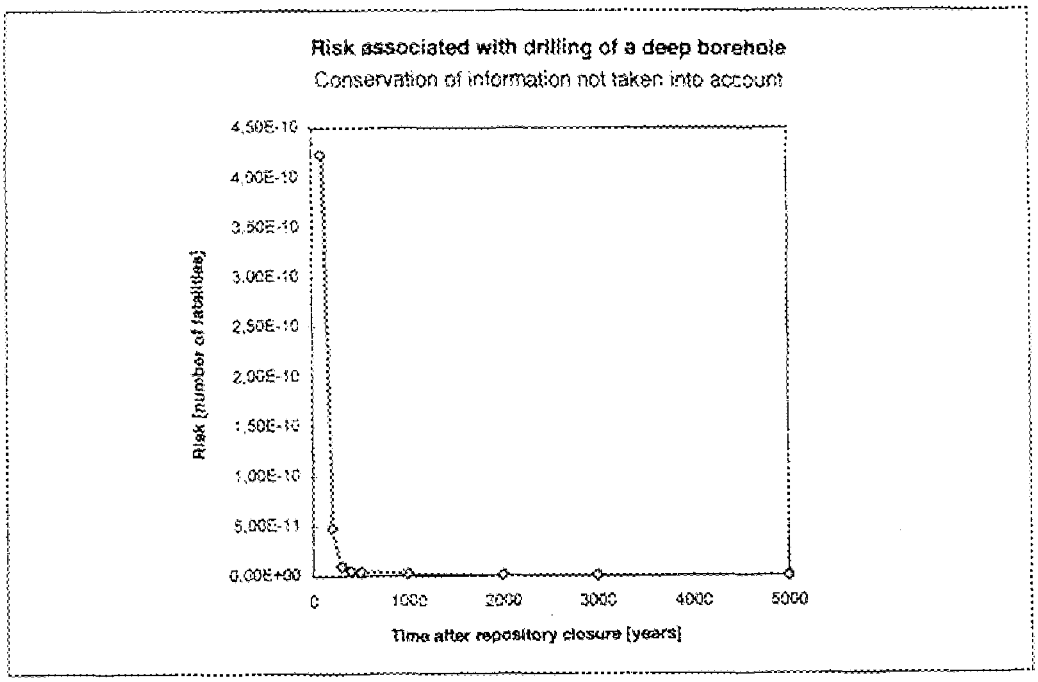


Figure B.2 Illustration of the variation of risk with time for two of SKB's example calculations, one in which all knowledge of the repository is lost after 500 years (upper diagram), and one in which all knowledge is lost at the time of repository closure (lower diagram) (after SKB, 1995).

B.2.7 Switzerland

NAGRA (the National Cooperative for the Disposal of Radioactive Waste) has completed an evaluation of the disposal of high-level radioactive waste in the crystalline basement of northern Switzerland (Kristallin-I), involving the systematic identification, classification and screening of FEPs, and definition of multiple scenarios, including those involving future human activities (NAGRA, 1994).

In Kristallin-I, a reference scenario was defined to provide the basis for a reference calculation set. Several alternative scenarios were also developed, arising from variation in the values of parameters associated with FEPs already included within the reference scenario, and/or from the addition of FEPs that were excluded from the reference scenario. The FEPs potentially giving rise to alternative scenarios were classified into three groups. One group included all FEPs related to future human activities, namely:

- groundwater, surface water and soil pollution;
- deep groundwater wells;
- water management schemes;
- mining and deep drilling;
- geothermal exploitation.

Each of these FEPs was critically evaluated. If the impact of varying or considering alternative states for each FEP was considered sufficiently important and relevant to Kristallin-I, the associated alternative scenario was further developed and described in more detail, and then subjected to a consequence analysis. The deep disposal environment in Kristallin-I was considered to insulate the repository from various types of surface environmental change, and this allowed several of the FEPs related to future climate change and to human activities to be screened out. As a result, only one FEP connected with future human actions (deep groundwater wells) remained to be developed into an alternative scenario for consequence analysis.

In the deep groundwater well scenario, radionuclides were assumed to enter the catchment area of a deep well in the high-permeability domain of the crystalline basement. It was conservatively assumed that all of the radionuclides were captured by the well. The pumping rate for the well was assumed to be 10^5 times greater than the flux through the repository region in the reference scenario. The biosphere model was modified slightly in order to calculate dose rates, which were all well below regulatory guidelines, the largest dose arising from ^{135}Cs.

B.2.8 United Kingdom

United Kingdom Nirex Limited (Nirex) has responsibility for the development of a deep geological repository for the disposal of solid intermediate-level and some low-level radioactive waste in the UK. In 1991, a potential site in fractured volcanic basement was chosen at Sellafield, West Cumbria. From 1991 until 1997, when permission for an underground rock characterisation facility (RCF) was refused, both site characterisation and safety assessment investigations focussed on this site. Nirex has published a series of PA documents related to Sellafield (e.g., Nirex, 1997), and one report specifically related to human intrusion (Nirex, 1995).

Nirex considers that a number of human intrusion scenarios require evaluation. For example, these could cover situations in which humans intrude directly into the repository, or where they intrude that part of the geosphere in which radionuclides are migrating. Nirex gave examples of two categories of scenarios covering these possibilities:

- Exploratory drilling scenarios, including the exposure of drillers, laboratory workers and local residents to radionuclides brought to the surface by drilling and coring operations.

- Regional well scenarios, involving abstraction of water from regions of the geosphere into which radionuclides have been transported. The water could subsequently be used for drinking water, irrigation of crops, and to augment river flow for industrial purposes.

Intrusion may also result in modification of other transport pathways for radionuclides, and such additional impacts should be documented and evaluated in the context of a systematic scenario analysis. Intentional intrusion was not considered by Nirex (1995) because it was considered that responsibility for intentional intrusion should rest with the intruder.

Nirex (1995) estimated the frequency of future human intrusions on the basis of current technology and demography. Drilling frequencies were based on recent or historical data for the site itself, or for an analogue area with similar geological features to the site. Drilling frequencies were estimated as a function of borehole depth. The probability of a well intersecting the contaminated region was estimated taking into account population density.

Nirex also evaluated the potential for the repository host rock, the Borrowdale Volcanic Group (BVG), to be explored for natural resource recovery, and concluded that there are few reasons today for drilling into the BVG. Given current societal and economic conditions, drilling might be attempted for the following reasons:

- For research purposes.

- For exploration for gold or other precious metals.

- For investigation of the geophysical anomaly caused by the repository, the investigators being ignorant of the nature and purpose of the repository.

Intrusion of the geological strata above the BVG was considered more likely, for reasons such as the exploitation of water resources, quarrying for sandstone, sand and gravel, and exploration for oil, gas and iron ore.

Nirex considered that institutional controls will be effective in preventing human intrusion at times soon after repository closure. Control will be achieved by maintaining local archives, planning controls, continued ownership of the site by an appropriate authority, conditions attached to the site's nuclear licence, and maintenance of suitable site markers. However, the effectiveness of institutional controls cannot be guaranteed. Persistence of knowledge about the repository and its contents may be achieved by storing information in libraries, marking the repository on relevant maps, storing information in relevant archives, and creating an on-site archive that is designed to persist for a long period of time.

No consequence calculations of human intrusion scenarios have yet been made by Nirex. However, by way of example, Nirex has illustrated the methodology that would be used to calculate doses and risks for the exploratory drilling scenarios and regional well scenarios.

Exploratory drilling scenarios:

Nirex (1995) assumed that the dose incurred will be proportional to the volume of material extracted from the borehole, and that it is possible to express the annual probability of exposure in terms of a depth-dependent frequency of boreholes drilled per unit area. On the basis of these two assumptions, the total annual risk from a particular radionuclide at a particular time can be determined by dividing the contaminated region into layers within which the drilling frequency is constant and calculating the risk associated with each layer.

Regional well scenarios:

Well depth and abstraction rate must be specified, as well as the subsequent use of the water. The probability of a well intersecting a region into which radionuclides have been transported can be estimated, and simple biosphere models used to estimate dose as a function of the concentration of radionuclides in abstracted water, or as a function of the radionuclide flux into a well with a specified abstraction rate.

B.2.9 United States

Waste Isolation Pilot Project (WIPP)

Several studies of human intrusion scenarios have been performed in the United States, for both HLW and L/ILW repositories located in salt formations. The most detailed and recent of these have been associated with the development of a safety case for the WIPP in New Mexico. The DOE has developed the WIPP for the disposal of transuranic radioactive wastes in bedded salt about 650 metres below the land surface. In October 1996, the WIPP CCA (DOE, 1996) was submitted to the EPA. In May 1998, the EPA certified the WIPP's compliance with the disposal standards of 40 CFR Part 191, Subparts B and C, and 40 CFR Part 194 (EPA, 1998). DOE's performance assessment used a probabilistic approach, and this and the scenario development procedures that accompanied it are described in the CCA (DOE, 1996).

Scenario development for the WIPP was based on the systematic identification, screening and combination of FEPs to form an undisturbed performance scenario and several disturbed performance scenarios. Undisturbed performance is defined as "...the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events." Undisturbed performance must account for the effects of recent and ongoing human actions in the vicinity of the disposal system. Systematic analysis of human actions led to the elimination from performance assessment calculations of all recent and ongoing human actions, with the exception of mining outside the controlled area, which was included within the undisturbed performance scenario.

The only disruptive events that were considered to require additional assessment outside the undisturbed performance scenario were future human actions. For evaluation of the consequences of disturbed performance, the DOE defined a mining scenario, M, a deep drilling scenario, E, and a mining and drilling scenario, ME.

The disturbed performance mining scenario (M)

The disturbed performance mining scenario, M, involves future mining within the controlled area at the WIPP site. Consistent with the criteria provided by the EPA, the effects of potential future mining within the controlled area are limited to subsidence-induced changes in hydraulic conductivity of the Culebra, which overlies the repository and is the most conductive stratigraphic unit in the region. Radionuclide transport may be affected in the M scenario if a head gradient between the waste-disposal panels and the Culebra causes brine contaminated with radionuclides to move from the waste-disposal panels to the base of the shafts and up the shafts to the Culebra. The changes in the Culebra transmissivity field may affect the rate and direction of radionuclide transport within the Culebra. The modelling system used for the M scenario is similar to that developed for the undisturbed performance scenario, but with a modified Culebra transmissivity field within the controlled area to account for the effects of mining.

The disturbed performance deep drilling scenario (E)

The disturbed performance deep drilling scenario, E, involves at least one deep drilling event that intersects the waste disposal region. If a borehole intersects the waste in the disposal rooms, releases to the accessible environment may occur as material entrained in the circulating drilling fluid is brought to the surface. Particulate waste brought to the surface may include cuttings, cavings, and spallings. Cuttings are the materials cut by the drill bit as it passes through waste. Cavings are the materials eroded by the drilling fluid in the annulus around the drill bit. Spallings are the materials that may be forced into the circulating drilling fluid if there is sufficient pressure in the waste disposal panels. During drilling, contaminated brine may flow up the borehole and reach the surface, depending on fluid pressure within the waste disposal panels.

When abandoned, the borehole is assumed to be plugged in a manner consistent with current practice in the Delaware Basin. An abandoned intrusion borehole with degraded casing and/or plugs may provide a pathway for fluid flow and contaminant transport from the intersected waste panel to the ground surface if the fluid pressure within the panel is sufficiently greater than hydrostatic. Additionally, if brine flows through the borehole to overlying units, such as the Culebra, it may carry dissolved and colloidal actinides that can then be transported laterally to the accessible environment by natural groundwater flow in the overlying units.

The units intersected by an intrusion borehole may provide sources for brine flow to a waste panel during or after drilling. For example, some stratigraphic units in the northern Delaware Basin contain isolated volumes of brine at fluid pressures greater than hydrostatic. In particular, pressurised brine reservoirs are found in the Castile Formation, which underlies the repository horizon. If an intrusion borehole intersected such a brine reservoir in the Castile, it could provide a connection for brine flow to the waste panel, thus increasing fluid pressure and brine volume in the waste panel.

The DOE has distinguished two types of deep drilling events according to whether or not the borehole intersects a Castile brine reservoir. A borehole that intersects a waste disposal panel and penetrates a Castile brine reservoir has been designated an E1 event. A borehole that intersects a waste panel but does not penetrate a Castile brine reservoir has been designated an E2 event. In order to evaluate the consequences of future deep drilling, the DOE has divided the E scenario into three drilling subscenarios, E1, E2 and E1E2, distinguished according to the number of E1 and E2 drilling events that are assumed to occur in the regulatory time frame:

- *The E2 Scenario*: The E2 scenario is the simplest scenario for inadvertent human intrusion into a waste disposal panel. A panel is penetrated by a drill bit, and cuttings, cavings, spallings, and brine flow releases may occur. Brine flow may occur in the borehole after it is plugged and abandoned. A modelling system has been developed to evaluate the consequences of an E2 scenario during which single or multiple E2 events occur.

C *The E1 Scenario*: Any scenario with a single inadvertent penetration of a waste panel that also penetrates a brine reservoir is called E1. The brine reservoir is the dominant source of brine in this scenario. The model configuration developed for the E1 scenario is used to evaluate the consequences of futures that have only one E1 event per panel. A future during which more than one E1 event occurs in a single panel is described as an E1E2 scenario.

C *The E1E2 Scenario*: The E1E2 scenario is defined as all futures that have multiple penetrations of a waste panel of which at least one intrusion is an E1 type. The E1E2 scenario can include many possible combinations of intrusion times, locations, and types of event (E1 or E2). The sources of brine in this scenario are those listed for the E1 scenario, and multiple E1-type sources may be present. The E1E2 scenario potentially has a flow path not present in the E1 or E2 scenarios: flow from an E1 borehole through the waste to another borehole. This flow path has the potential to (i) bring large quantities of brine into direct contact with waste and (ii) provide a less restrictive path for this brine to flow to upper stratigraphic units compared to either the E1 or E2 scenarios. Both the presence of brine reservoirs and the potential for flow through the waste to other boreholes make this scenario different in terms of potential consequences from combinations of E2 boreholes. The extent to which flow occurs between boreholes, as estimated by modelling, determines whether combinations of E1 and E2 boreholes at specific locations in the repository should be treated as E1E2 scenarios or as independent E1 and E2 scenarios in the consequence analysis. Because of the number of possible combinations of drilling events, the modelling configuration for the E1E2 scenario differs in significant ways from the model configuration used for evaluating E1 and E2 scenarios.

The disturbed performance mining and deep drilling scenario (ME)

Mining in the WIPP site (the M scenario) and deep drilling (the E scenario) may both occur in the future. The DOE calls a future in which both of these events occur the ME scenario. The occurrence of both mining and deep drilling does not create processes in addition to those already described separately for the M and E scenarios. The ME scenario is distinct in that the combination of borehole transport to the Culebra (E) and a transmissivity field impacted by mining (M) may result in more rapid transport of radionuclides to the accessible environment. For example, because the M scenario does not include drilling, the only pathway for radionuclides to reach the Culebra is up the sealed shafts. For clarity in describing computational results, the ME scenario was subdivided in the WIPP CCA according to the types of deep drilling subscenarios. Thus, the ME1 scenario (M and E1), the ME2 scenario (M and E2), and the ME1E2 scenario (M and E1E2) were defined.

The system used for modelling flow and transport in the Culebra for the ME scenario is similar to that used for the E scenario. However, in the ME scenario, the Culebra transmissivity field is modified to account for the effects of mining within the controlled area.

Yucca Mountain

Yucca Mountain, Nevada is currently being investigated for its suitability as a site for disposal of HLW. The potential repository would be located within a tuff formation in the unsaturated zone. The construction of scenarios for the future evolution of the disposal system is described in several recent total system performance assessments (TSPAs) (e.g. Wilson et al., 1994; TRW, 1995; EPRI, 1996).

The development and modelling of scenarios for future human actions has not received as much attention within the Yucca Mountain programme as at the WIPP. For Yucca Mountain TSPA, one human intrusion scenario has been analysed, involving direct release of radionuclides to the surface as a result of drilling into a waste container or contaminated rock (Wilson et al., 1994). In both cases, the direct removal of contaminants to the surface was modelled and dose rates calculated. Four baseline analyses were made assuming that the amount of waste released from a breached waste package has a uniform distribution ranging from 0 to 100%. None of these calculations showed releases that exceeded the EPA cumulative release limit in 40 CFR Part 191.

Human intrusion was excluded from the most recent EPRI TSPA (EPRI, 1996) because of the difficulty in quantifying the relevant probabilities, such as the probability that drilling will occur. The EPRI TSPA incorporated a model for container failure that allowed for the possibility that one or two containers fail soon after repository closure. Although these early failures were assumed to be due to manufacturing flaws, EPRI considered that they could also be thought analogous to human intrusion events, and no further analysis of human intrusion scenarios was made.