Safety Assessment of
Radioactive Waste Repositories

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Future Human Actions at Disposal Sites

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A report of the NEA Working Group on Assessment of Future Human Actions
at Radioactive Waste Disposal Sites

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
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The primary objective of NEA is to promote co-operation among the governments of its participating countries in furthering the development of nuclear power as a safe, environmentally acceptable and economic energy source.

This is achieved by:

- *encouraging harmonization of national regulatory policies and practices, with particular reference to the safety of nuclear installations, protection of man against ionising radiation and preservation of the environment, radioactive waste management, and nuclear third party liability and insurance;*
- *assessing the contribution of nuclear power to the overall energy supply by keeping under review the technical and economic aspects of nuclear power growth and forecasting demand and supply for the different phases of the nuclear fuel cycle;*
- *developing exchanges of scientific and technical information particularly through participation in common services;*
- *setting up international research and development programmes and joint undertakings.*

In these and related tasks, NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has concluded a Co-operation Agreement, as well as with other international organisations in the nuclear field.

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SUR LES SITES D'ÉVACUATION

Foreword

The management of radioactive wastes and, in particular, the safety assessment of radioactive waste disposal systems, are areas of high priority in the programme of the OECD Nuclear Energy Agency. Although a general consensus has been reached in OECD Member countries on the use of geological repositories for radioactive waste disposal, analysis of the long-term safety of these repositories, using quantitative performance assessment, is required prior to implementation. Such assessments involve detailed analysis of the potential for release of radionuclides from the disposed wastes to the groundwater and subsequent transport to the human environment. The effects of events and processes that could promote the release and transport of radionuclides – such as gas generation, neotectonic movements and glaciation – are also analyzed. One particular category of disruptive events is human intrusion into a repository or, more generally, future human actions that could affect the long-term safety of a disposal system. In some cases, potential future human actions may be the dominating factor contributing to the overall risk associated with the disposed waste.

The NEA Performance Assessment Advisory Group (PAAG) was established in 1986 with the mandate to advise the Radioactive Waste Management Committee on technical aspects of the performance assessment of radioactive waste disposal systems and to help co-ordinate NEA activities in this area. PAAG provides an international forum for discussion and information exchange between OECD Member countries on performance assessment matters. The overall aims of PAAG are to assist in the development of methods and tools of high quality for the assessment of the safety of radioactive waste disposal systems, and to promote a balanced and coherent use of these methodologies within national radioactive waste disposal programmes.

In 1990 the PAAG established a Working Group on Assessment of Future Human Actions at Radioactive Waste Disposal Sites. This followed an initial workshop held in 1989, proceedings of which are available from the OECD. The Working Group, whose members are listed in Appendix A, has extensively reviewed approaches to and experience of incorporating the effects of future human actions into long-term performance assessments. This report by the Working Group is based on the literature available and the work of national programmes currently underway. In addition, material prepared by Working Group members and their colleagues for presentation and discussion at the meetings of the Group has provided an invaluable input to the preparation of this report. The report reviews the main issues concerning the treatment of future human actions, presents a general framework for the quantitative consideration of future human actions in radioactive waste disposal programmes, and discusses means to reduce the risks associated with future human actions.

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Executive Summary

This report is concerned with the treatment in postclosure safety assessments of future human actions that have the potential to disrupt or impair significantly the ability of radioactive waste disposal systems to contain the wastes. For some deep geological disposal systems, the greatest risks associated with waste disposal may arise from the possibility of future human actions breaching the natural and/or engineered barrier systems.

Background

The OECD Nuclear Energy Agency (NEA) organised in 1989 a Workshop on Risks Associated with Future Human Intrusion at Radioactive Waste Disposal Sites. This Workshop provided the first opportunity at international level for representatives from the various national programmes to discuss the problem. The discussion and recommendations from this Workshop were reported to the relevant NEA groups, in particular the Radioactive Waste Management Committee (RWMC) and its Performance Assessment Advisory Group (PAAG). It was subsequently decided to establish an NEA Working Group to explore in more depth the issues associated with future human actions.

On the basis of a proposal by PAAG, the RWMC directed the Working Group to:

- *Review* relevant work that has been done in OECD Member countries and internationally.
- *Exchange* information and experience on approaches and results in the area.
- *Identify* issues that need special attention and discussion at an international level.
- *Discuss* these issues in depth.
- *Consider* whether generic methods and approaches could be formulated and agreed upon.
- *Prepare* a report reflecting the discussions and conclusions of the Working Group.

This report conveys the findings of the Working Group.

This report is not meant to be an exhaustive treatment of the topic. Rather, the intent is to focus on a set of key technical issues faced by all national waste disposal programmes. The report covers:

- The importance and role of future human actions in postclosure safety assessments of deep geologic disposal systems for long-lived radioactive wastes. The focus here is on a logical means for addressing future human actions in safety assessments.

The approaches and methods taken to assessing the risks associated with future human actions.

Administrative and practical countermeasures to reduce the consequences and likelihood of future disruptive human actions.

The Working Group did not consider in detail the non-technical regulatory policy aspects of future human actions, and no attempt has been made to anticipate conclusions on acceptability of the risks associated with future human actions. Evaluations of such risks will require policy judgements that must be made by each national regulatory organisation.

Furthermore, the Working Group did not deal explicitly with the near-surface disposal of low-level radioactive wastes.

Finally, the Working Group did not consider in detail the long-term consequences of human actions taken (or not taken) during the preclosure period, that is, prior to final sealing of the repository.

The principal conclusions and recommendations arising from discussions within the Working Group are outlined below.

Framework for Consideration of Future Human Actions

Future human actions can adversely impact radioactive waste disposal systems; these actions must, therefore, be considered both in the siting and design of waste disposal systems, and in assessments of their safety.

Disruptive human actions can be divided into those in which the barrier system is intentionally disrupted and those in which it is inadvertently disrupted. Inadvertent actions are defined here as those in which either the repository or its barrier system are accidently penetrated or their performance impaired, because the repository location is unknown or its purpose is forgotten. Human actions leading to the release of radioactivity and committed intentionally, rather than inadvertently, can be considered the responsibility of the society that takes these actions. Intentional disruptive actions should not be considered in safety assessments. In contrast, actions in which the disposal system is inadvertently disrupted should be considered.

Considerations Bearing on Quantitative Analysis

Both disruptive human actions and disruptive natural events can result in the same types of consequences and both are potentially important to safety. Thus, the general quantitative framework developed for safety assessments involving naturally occurring events and processes is also appropriate for the analysis of future human actions. Extensive human judgement is required for the development and modelling of scenarios of both future human actions and natural events and processes.

The analysis of human actions can only be illustrative and never complete. At best, scenario techniques as applied to future human actions could lead to the development of a representative set of scenarios describing what can be reasonably contemplated – rather than what will be. Probabilities of scenarios of future human actions are bound to be subjective and these probabilities should be termed "degrees of belief", to distinguish them from empirically determined frequencies. Using a range of scenarios and probabilities describing their relative likelihoods through degrees of belief is preferable to using a single scenario as a point estimate. It is important in risk and uncertainty analyses to portray, as well as possible, the range of possibilities. Considering a range of possibilities is also important in repository siting and design, and in the consideration of countermeasures.

Scenarios of future human actions have to be viewed as representations of potential realities based on sets of assumptions. Consequence analyses must therefore be considered as illustrations of potential impacts based on these sets of assumptions. These illustrations are for the benefit of decision makers (among others), in order that they have a broad knowledge of the disposal system and the risks associated with waste disposal.

An approach to quantitative assessment was sought that would avoid speculations about the future and that could be applied uniformly for various sites and systems. The Working Group considered that site- and system-specific scenarios could be based on the premise that the practices of future societies correspond to current practices at the repository location and at similar locations elsewhere. This premise could be adopted for drilling characteristics and frequencies, resource use, technological development, medical practice, demographics, and human lifestyles and nutritional requirements.

This premise is not meant to convey any information about the possible future evolution of society, but represents a practical choice on the treatment of societal development that allows illustrations of potential risks associated with future human actions to be made. This premise concerning societal development has been accepted de facto in most recent assessments. However, there is a need for further discussion of assessment principles – for example, concerning the effectiveness of passive institutional controls.

Countermeasures

The Working Group discussed methods to reduce the likelihood and to mitigate the consequences of future inadvertent human actions that might impair the effectiveness of the disposal system. The most effective countermeasure to inadvertent disruptive actions is active institutional control of the surface above and for some distance around the disposal site. This countermeasure forms one basis for the licensing of near-surface disposal facilities for low-level radioactive wastes. It could also be used for deep disposal facilities for as long as practicable to guard against inadvertent intrusion or other potentially disruptive human actions in the vicinity of the disposal site.

However, active institutional control cannot be relied upon over the timescales for which the waste presents a potential hazard (e.g., 10 half-lives of Pu-239 or other relevant radionuclide). Some national regulations allow credit for 100-500 years of active control subsequent to closure and decommissioning of the repository. Other possible countermeasures discussed by the Working Group included:

- Siting of repositories away from areas of currently recognised subsurface resource potential.
- Isolation of the waste from the human environment. For deep geologic repositories, the very depth of burial is an important feature mitigating against potentially disruptive human actions.
- Other criteria on the design of waste repositories (e.g., backfilling materials) and on the waste form itself (e.g., low tendency to form dust if exposed in open air) to mitigate the consequences of disruptive human activities.
- Conservation and communication of information about the location, contents and hazards of the repository can help reduce the likelihood of disruptive human actions.
- Durable physical marker systems placed at or near the site to help conserve information about the repository and warn potential intruders of the hazard.

- Physical barriers to deter attempted intrusion (e.g., a thick concrete cover above the disposed waste or a strong canister) may lower the probability of inadvertent intrusion.

Further discussion within each national programme is required of the means of determining an appropriate level of resource expenditure for the various possible countermeasures.

Further International Co-operation

The Working Group discussed international efforts that could contribute to building confidence in the assessments of the long-term safety of radioactive waste disposal systems. In particular, there are a number of actions that could be taken concerning assessments of future human actions that go beyond the scope of the Working Group's activities:

- *Further discussion between interested countries concerning regulatory policies for judging the risks associated with future human actions.* The treatment of future human actions has not yet been clearly defined in most national regulations. The Working Group considers that, on the basis of its report, a discussion could be promoted between interested countries as to how this issue could best be tackled. One possibility would be to judge the risks associated with future human actions in the same way as those associated with natural events and processes. At the other end of the spectrum, it might be considered that risks associated with future human actions should not play a role in the licensing of waste repositories. The issue is not purely technical, and any regulatory policy would need to be defended by means of philosophical and ethical argument.

- *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. One approach to developing scenarios discussed by the Working Group would base them on the use of current societal capabilities and practices in the vicinity of the disposal site and at similar locations elsewhere, in order to avoid speculations about future human endeavour.

- *Development of an internationally reviewed database of features, events and processes that could be considered in safety assessments.* This database would build upon the substantial work already accomplished at international level, and would help build confidence in the comprehensiveness of national site-specific assessment programmes. Human actions could form part of this database. An initial list has been compiled by the Working Group in Appendix B. Further compilation work at international level has already begun under the auspices of the NEA/PAAG.

- *Development of an international archive of radioactive waste repositories.* Conservation of information at different societal levels and locations can help ensure that administrative knowledge of the repository is not lost. One possibility would be to develop an archive at international level.

- *Development of marker systems.* A consistent approach toward marker systems would help society to retain awareness of their meaning, and to 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. This thinking underlies the use of marking for many hazardous artifacts in use today – for example those for radioactive materials and other toxic chemicals.

Chapter 1

Introduction

1.1 The Disposal of Radioactive Wastes

The use of radioactive materials for electricity generation, or for medical, industrial or research purposes, inevitably gives rise to radioactive waste, which must be managed safely both now and in the future. Basic options for wastes already produced include:

i) Concentration and confinement of the waste.

ii) Dilution and dispersion of the waste in the environment

iii) Recycling and reuse of the waste.

Other than for radioactive wastes containing relatively small quantities of radionuclides, the first approach is currently favoured by all OECD Member countries. In accepting concentration of the radioactivity in a confined space, risks associated with future human intrusion into the waste area or its surroundings must also be accepted. A balanced view on scenarios of future human actions and their significance in regulations and in performance assessments will be required in licensing procedures, particularly for high-level radioactive wastes.

While storage may be used in the short term, every OECD country with a nuclear power programme is now involved in studies to establish safe permanent disposal facilities. The aim of such disposal facilities is to isolate the waste from the human environment, while radioactivity in the waste decays to acceptable (e.g., normal background) levels. The methods being used, and planned, for this isolation vary according to the nature of the waste. Short-lived, low-level wastes can be safely disposed of by near-surface burial. Long-lived, high-level or intermediate-level wastes require more sophisticated treatment and disposal techniques. For such wastes, deep disposal in stable geological formations is considered the most appropriate solution [49].

Most deep disposal concepts provide for confinement and isolation of the radioactive materials by a combination of both natural and engineered barriers. These may include the solidity and inherent insolubility of the waste form; encapsulation in durable containers; backfilling of excavations with materials selected for their mechanical, chemical and/or hydrological properties; and the overlying rocks and soils, which will inhibit groundwater movement and further retard movement of radionuclides by sorption.

It is however possible to conceive of situations in which – subsequent to closure and decommissioning of the repository – this barrier system would be disrupted or bypassed by the actions of future societies. How should such human interaction with the disposal system be viewed? What role should assessments of the risk associated with future human actions play in developing radioactive waste repositories?

Questions such as these are faced by all national waste disposal programmes. For some disposal systems, the greatest risks associated with waste disposal may arise from the possibility of future human actions breaching the natural and/or engineered barrier systems. Such actions could be either inadvertent or intentional.

For these reasons, the OECD Nuclear Energy Agency (NEA) organised in 1989 a Workshop on Risks Associated with Future Human Intrusion at Radioactive Waste Disposal Sites [1]. This Workshop provided the first opportunity at international level for representatives from the various national programmes to discuss the problem. The discussion and recommendations from this Workshop were reported to the relevant NEA groups, in particular the Radioactive Waste Management Committee (RWMC) and its Performance Assessment Advisory Group (PAAG). It was subsequently decided to establish an NEA Working Group to explore in more depth the issues associated with future human actions.

1.2 Purpose of the Working Group

On the basis of a proposal by PAAG, the RWMC directed the Working Group to:

- *Review* relevant work that has been done in OECD Member countries and internationally.
- *Exchange* information and experience on approaches and results in the area.
- *Identify* issues that need special attention and discussion at an international level.
- *Discuss* these issues in depth.
- *Consider* whether generic methods and approaches could be formulated and agreed upon.
- *Prepare* a report reflecting the discussions and conclusions of the Working Group.

This report conveys the findings of the Working Group. During the discussions, many issues were identified, alternative approaches suggested to analyzing future human activities and, in some cases, resolution or agreement reached.

The treatment of future human activities remains, however, a difficult aspect of radioactive waste disposal performance assessment. The inherent difficulty in predicting human actions and our own inability to delve into the far future will always limit the ability to make definitive statements about the risks to future societies from the disposal of long-lived wastes. Of course, there is nothing special about radioactive wastes in this regard; there are many other human activities that may have significant consequences for the future that are difficult or impossible to predict.

A reasoned approach to assessing possible future human actions can, however, facilitate the design and siting of disposal systems, promote the comparison of alternative systems, enhance the optimisation of a disposal system, and assist in the comparison of projected performance to standards and regulations. One purpose of the Working Group was to suggest a general structure for such a reasoned approach, and to identify aspects of the suggested approach that may be common to a number of potential host rocks under investigation in the Member countries.

1.3 Conduct of the Study

The Working Group's discussions covered a broad range of issues, and a number of key questions concerning the general framework for consideration of future human actions received particular attention at its four meetings:

- Should human activities be evaluated in the same manner as natural events and processes? Is it possible to provide a similar level of justification or comprehensiveness in assessments of future human actions as in other areas?
- Should a distinction be made between inadvertent and intentionally disruptive human activities?
- What is the time frame for evaluation of human actions? How is this time frame related to the exercise of government control and the persistence of information and warnings within society?
- Is there a general basis for creating scenarios of human actions that can be used to compare and evaluate potential repository concepts and sites?
- What measures can be considered to reduce the risk associated with future human actions?

In addition to this discussion, at two of the Working Group meetings, participants were provided the opportunity to observe and interact with national efforts in the area of human intrusion assessment. The second meeting of the Group was held in conjunction with a workshop of the Marker's Panel established by Sandia National Laboratories (SNL) to assist with the development of a strategy for marking the Waste Isolation Pilot Plant (WIPP) – a proposed deep geologic repository for radioactive wastes in southeastern New Mexico (USA). The third meeting of the Group was held in conjunction with a Seminar on Long-Term Record Keeping organised by the Nordic Nuclear Safety Commission (NKS).

Finally, the Working Group developed a catalogue of national human action assessment activities. This catalogue has been compiled as an informal NEA document [2].

1.4 Scope of the Report

In this report, the following definition of future human actions is used:

> *Future human actions of concern are those occurring after repository closure that have the potential to disrupt or impair significantly the ability of the natural or engineered barriers to contain the radioactive wastes.*

This report is not meant to be an exhaustive treatment of the topic. Rather, the intent is to focus on a set of key issues faced by all national waste disposal programmes. The report covers:

- The importance and role of future human actions in postclosure safety assessments of deep geologic disposal systems for long-lived radioactive wastes. The focus here is on a logical means of addressing future human actions in safety assessments, including the relevant questions outlined in the previous Section.

- The approaches taken and methods used to assess the risks associated with future human actions.
- Administrative and practical countermeasures to reduce the consequences and likelihood of future disruptive human actions.

The Working Group did not consider in detail the non-technical regulatory policy aspects of future human actions, and no attempt has been made to anticipate conclusions on acceptability of the risks associated with future human actions. Evaluations of such risks will require policy judgements that must be made by each national regulatory organisation. This is one area that would benefit from further discussion at international level.

In addition, the Working Group did not consider in detail the long-term consequences of human actions taken (or not taken) during the preclosure period, that is, prior to final sealing of the repository.

Near-Surface Disposal of Low-Level Radioactive Wastes

This report does not deal explicitly with the near-surface disposal of low-level radioactive wastes. It is however recognised that human action assessments play an extremely important role in the design and waste acceptance criteria for such disposal systems. The safety of these disposal systems relies in part on a prescribed active institutional control period of definite duration. This period is generally in the range 100 years to several hundreds of years, with different countries having established different periods of control. After this period, it is assumed that the land surface passes over to uncontrolled use by society.

Assessments of future human actions are therefore required to provide estimates of how much intermediate half-life activity (e.g., Sr-90, Cs-137) can be permitted, to be commensurate with decay to acceptable levels by the end of the prescribed active institutional control period. Similarly, such assessments are required to provide bounding upper values for quantities of long-lived radionuclides that may be accepted for near-surface disposal. The activity of these radionuclides would persist beyond the period of assured institutional control and, in practice, these assessments may need to extend over timescales of many hundreds of years.

Many of the considerations discussed in this report for deep geological repositories should apply equally well to the long-lived activity component of low-level waste disposed of in near-surface repositories, or for any other long-lived radioactive wastes disposed of at or near the surface.

Uranium Mill Tailings

Issues associated with the disposal of uranium mill tailings are considered to be beyond the scope of this report. These wastes are not currently considered to require disposal in deep repositories, with in situ stabilisation and capping of tailings piles being the preferred waste management option.

1.5 Organisation of the Report

The report has been divided into four main Chapters, corresponding to the topics identified in Section 1.3. Chapter 2 is concerned with safety assessment in general and the importance of future human actions in safety assessment. Chapter 3 provides a more detailed review of quantitative approaches to incorporation of future human actions in system assessments, and discusses principles for the development and modelling of scenarios of future human actions. Chapter 4 outlines various administrative and practical countermeasures that can be used to reduce the consequences and likelihood of future disruptive human actions. Finally, Chapter 5 summarises the main views of the Working Group on how human actions could be considered in safety assessments from a practical point of view, and provides recommendations for further work at international level.

Chapter 2

Evaluating the Risk from Future Human Actions

2.1 Introduction

The long-term safety of any radioactive waste disposal system must be convincingly shown prior to its implementation. Future human actions have the potential to degrade the performance of deep geologic repositories for radioactive wastes. How should threats from these activities be appraised? This Chapter addresses some fundamental issues regarding assumptions in the analysis of future human actions. These issues include:

- The scope of safety assessments.
- The differences between inadvertent and intentional human actions.
- The time frame for evaluation of human actions.
- Criteria for evaluation of risks from human actions.
- The roles of qualitative requirements and quantitative evaluation.

2.2 Safety Assessment and Future Human Actions

Safety assessment is concerned with evaluating the overall performance of a waste disposal system, followed by comparison of the results with a regulatory limit. Equally important to the illustration of radiological impact is a demonstration that possible sources of uncertainty have been systematically identified and evaluated.

All national regulations for radioactive waste disposal share the same underlying basis – the requirement to ensure safety. Future human actions can affect the integrity of the disposal system – most obviously by short circuiting the safety barriers – and can thereby adversely impact radiological exposures. Most programmes have therefore taken steps to evaluate quantitatively the possible risks associated with future human actions.

Safety assessments of radioactive waste repositories are often made under several different sets of assumptions. A primary set of assumptions, sometimes referred to as a "base case" or the "central scenario", considers the repository as functioning without disturbance from unlikely human actions or natural events. Events involving human activity can be included in the central scenario if they are considered likely to occur. On the other hand, more complete analyses would require additional assumptions (or scenarios) concerning low-probability natural events and human activities that could elevate the risk.

A review of overall approaches to safety assessment can be found in several recently published NEA documents [e.g., 43, 48].

2.3 Uses of Safety Assessments

A safety assessment involving human activities has multiple uses, including:

- Illustration of the robustness of a repository system.
- Comparison of the response of alternative sites or disposal concepts to potentially damaging human actions.
- Optimisation of the system.
- Licensing of the system.

Illustrating robustness

Evaluation of the response of a repository system to inadvertent human actions is sometimes done to illustrate the robustness of the system (or, alternatively, its vulnerability). This is accomplished by using one or more scenarios that are thought to be important, either because they are considered to be likely or to have severe consequences.

Comparing concepts and sites

The repository siting criteria of many countries specify avoidance of areas of known subsurface resource potential (see Section 2.6). For these countries, safety assessments for siting purposes will include, implicitly or explicitly, consideration of future human actions. Differences between sites make comparison based on generic scenarios difficult. However, when an independent analysis is conducted for each system or site, assessments involving human actions may contribute to the decision basis for judging various options.

Optimising design

Decision-analysis techniques may be used to help optimise design of the repository system to reduce the risks associated with future human actions. If a specific scenario is given which could lead to impaired performance of the disposal system, the need for a revision in the system design and its costs can be discussed in terms of the possible reduction in risks. For example, a countermeasure useful against exploration for natural resources is the preservation of information about the repository, including its location, design, and radionuclide inventory. This countermeasure can be implemented through archives and markers – which have associated costs.

Moreover, *qualitative* cost-benefit considerations may form part of the basis in reaching decisions on sites whose use may lead to the loss of known resources. The most obvious case of this is for repositories located in salt formations. For example, balanced against the "cost" of being deprived of access to the salt (and any associated resources such as potash) must be the increased safety that such sites could provide in natural conditions.

Licensing

Quantitative performance assessment is required in licensing, because this is the principal means of demonstrating that system performance is likely to be satisfactory, or is capable of satisfying some standard to which it is compared. A quantitative performance analysis incorporating future human activities could never be complete, however, because these activities can neither be known with certainty nor can their full range be completely imagined. For this reason, the Working Group considers that it would be inappropriate for speculation about future human conditions to be a main focus of licensing assessments for deep geological repositories.

Should standards and regulations have different criteria for risks from human actions as opposed to risks from naturally occurring events and processes? As noted in Chapter 1, the Working Group did not consider in detail the non-technical regulatory policy aspects of future human actions; evaluation of the risks associated with future human actions will require policy judgements that must be made by each national regulatory organisation. This is discussed further in Section 2.6.

2.4 Inadvertent and Intentional Human Activities

Future human actions that degrade performance of the disposal system can be classified as inadvertent or intentional with respect to knowledge about the repository, its contents, and the potential harm. Inadvertent actions are defined here as:

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

In contrast, if future intruders are aware of the waste and the consequences of disturbing the repository or its barrier system, then their actions are intentional.

The Working Group agrees with the principle that the society that creates a radioactive hazard should bear responsibility for developing a safe disposal system that takes into account future societies to the extent possible. The current society cannot, however, protect future societies from their own actions if the latter are forewarned of the consequences.

Although in most cases the distinction between intentional and inadvertent human actions is straightforward to draw, for some situations the distinction is less clear. For example, consider the situation in which an inadvertent intrusion occurs, and the society later becomes aware of the hazard posed by the materials within the repository but fails to or is unable to exercise due prudence with regard to handling of the radioactive material or sealing of the repository. Should the risks to future societies from this situation be considered?

Two further issues are important in distinguishing between intentional and inadvertent intrusion. These concern the possible need for nuclear material safeguards requirements to be met for repositories containing spent fuel, and the desirability in some quarters of ensuring that waste disposed in deep geological repositories is retrievable by future societies.

Safeguards

The International Atomic Energy Agency (IAEA) is responsible for monitoring adherence to safeguards requirements for fissile material throughout the life-cycle of these materials [50]. The IAEA is currently considering the possible safeguards requirements to be imposed on radioactive waste repositories [46]. Possible safeguards issues were not discussed by the Working Group, pending the outcome of the IAEA study. However, it can be noted that these requirements may lead to additional active institutional controls and development of archival information within the IAEA on repositories for high-level radioactive wastes. This issue is referred to again in Section 4.2 of the report.

Retrievability

Public concern about the long-term safety of radioactive waste disposal systems has lead some OECD countries to consider repository designs that allow for long-term retrievability of the wastes.

In these countries, it is considered that the society disposing of the wastes should avoid foreclosing the options of future societies. For example, future societies should be able to access the waste if they decide that what we consider a waste actually has some resource potential, or if they decide that repair or corrective measures are required. With this concern in mind, Swedish workers have suggested an ethically based design principle for repositories [40]: "A repository should be constructed so that it makes controls and corrections unnecessary, while not making controls and corrective measures impossible". There is no time frame attached to this suggestion. Regulations in other countries, however, suggest that waste retrieval should be possible only for a period (to be specified) after closure and sealing of the repository (e.g., the United States). And yet other countries do not consider retrievability an issue at all, considering this type of requirement at odds with the need to ensure safety of future societies.

Long-term retrievability implies a wish to design a system that allows for future intentional access – the ability to gain access to the waste is seen as a desirable design characteristic. Safeguards requirements may also lead to suggestions for systems that provide for controlled access to the repository. Should safety assessments incorporate intentional intrusion if the capability to ease such intrusion is purposefully designed into the repository? This is essentially a policy question that national regulatory authorities will have to answer should retrievability be requested of the implementing agency.

2.5 The Time Frame for Assessments

Time is an important consideration in the analysis of potentially disruptive human actions. The time when government control of the repository can no longer be guaranteed and the time when human actions need no longer be incorporated in the safety assessment must both be considered.

Timescale of reliance on institutional controls

Analyses involving future human actions usually assume that there will be a period of active institutional control in which disruptive action could be prevented or detected by on-site security and surveillance. Monitoring might also be performed by an international agency. This period is important in safety assessment because the waste is most radioactive immediately after disposal and, assuming institutional controls are effective, the probability that inadvertent disruptive human actions will occur in this period can be taken as zero.

However, there is no consensus on the period for which active institutional controls can be relied on to prevent disruptive human actions. Some regulatory agencies (e.g., those in Canada and Switzerland) provide that, to the extent reasonably achievable, there should be no reliance on long-term institutional control as a necessary safety feature [3, 14]. Others limit the period of reliance for which credit can be taken in the performance assessment; for example, the US Environmental Protection Agency limits the period to 100 years after disposal [4]. In one study [5], a time-dependent probability of effectiveness of active institutional controls was assumed, in which the annual probability of failure increased from 0 at time 0, to 1.0 at 500 years after repository closure and decommissioning.

The likelihood of inadvertent human actions disrupting the disposal system may be reduced by providing potential intruders with warning of the presence of the waste and its potential hazard. Measures to reduce the risks associated with future human actions are discussed in more detail in Chapter 4. While there is general recognition that a variety of such measures should be taken, it is difficult to quantify their effectiveness. All assessment scenarios that include the occurrence of inadvertent human actions start with the assumption that these measures have failed.

Timescale for assessments

At the other end of the timescale is the period that future disruptive human actions should be considered in the assessment. The Working Group considers that assessments and decisions should be made using analyses with a timescale that accurately reflects the dangers inherent in the waste.

2.6 Existing Regulations

Existing international criteria for the radiological protection of individuals and populations form the basis of development of national long-term safety criteria for radioactive waste repositories in practically all countries. It is not obvious, however, how compliance with basic radiological protection criteria should be demonstrated for the long-term safety of repositories. The potential impact of a repository may happen far in the future and be dependent upon events that are not certain to occur. It is not possible to estimate the probability of many of these events with precision. This is particularly true for future human actions.

Table 1 summarises existing criteria for the evaluation of risks from the disposal of long-lived radioactive wastes. These criteria are based on limiting either individual doses, individual risks, collective doses, or radioactive releases. Existing international criteria can be used to distinguish between doses and risks to workers and those to the general public [7, 8], but these distinctions are unlikely to be of importance in assessing risks of future human actions in the far future.

The principle of individual protection is applied, in general, for radioactive waste disposal, but should different regulatory principles be applied to judgements concerning future human actions? In this regard, some regulatory authorities consider that in situations with a high degree of uncertainty in human behaviour, complementary approaches, such as the limitation of societal impact, should be given greater emphasis [e.g., 13].

A few countries, and the U.S. in particular, have explicitly cited human intrusion in laws and regulations governing radioactive waste (Table 1). U.S. regulations specifically deal with the treatment of inadvertent human intrusion. The purposes are two-fold: to ensure that human intrusion is dealt with in the siting, design and evaluation activities associated with a radioactive waste repository, and to provide guidance on how inadvertent human intrusion should be judged as a source of risk. For example, the U.S. Environmental Protection Agency regulation 40 CFR Part 191 [4] provides a range of guidance on assessing future inadvertent human intrusion – on drilling likelihood, borehole backfill properties, and the effectiveness of institutional controls. In addition, the U.S. Nuclear Regulatory Commission regulation 10 CFR Part 60 [16] contains extensive siting criteria, including a suggestion that sites with foreseeable adverse human activity should be avoided.

However, the basis for judging risks associated with future human actions in licensing assessments has not yet been clearly defined in most national regulations. One possibility – already embodied in U.S. regulations – would be to judge the risks associated with future human actions in the same way as those associated with natural events and processes. At the other end of the spectrum, it might be considered that risks associated with future human actions should not play a role in the licensing of waste repositories.

The issue is not purely technical, and any regulatory policy would need to be defended by means of philosophical and ethical argument. Further discussion concerning regulatory policies for judging the risks associated with future human actions is needed. The Working Group considers that, on the basis of its report, a discussion could be promoted between interested countries as to how this issue could best be tackled.

Table 1: **National and international criteria and objectives for the disposal of long-lived radioactive wastes.**

Organisation/ Country/ Reference	Main Objective/ Objective/Criteria	Other Main Features	Criteria for Judging HI Scenarios	Comments
NEA (1984) [7]	For HLW: max. indiv. risk < 10^{-5}/y (all sources)		Indiv. risk/dose - best criterion to judge long-term acceptability	No consensus on ALARA/ optimisation
ICRP (Pub. 46, 1985) [8]	For HLW, for individuals (all sources): 1 mSv/y (normal evolution scenarios); 10^{-5}/y (probabilistic scenarios)	Both probability and dose should be taken into account in ALARA	Future human activities should be treated probabilistically	ALARA useful, notably to compare alternatives, but may not be the most important siting factor
IAEA (Safety Series 99, 1989) [9]	Idem ICRP Publication 46		Future human activities are random disruptive events that usually are examined probabilistically	Also includes qualitative technical criteria on disposal system features and role of safety analysis and quality assurance
CANADA (Reg. Document R-104, 1987) [3]	For HLW: max indiv. risk objective: < 10^{-6}/y	Period of time for demonstrating compliance: 10^4 y No sudden and dramatic increase for times > 10^4 y	Main criteria applicable to all exposure scenarios; no criteria specific to HI scenarios	Additional qualitative, non-prescriptive requirements and guidelines in regulatory documents
FINLAND (Decision of the Council of State, 1991) [10]	For LLW and ILW: max. indiv. dose < 0.1 mSv/y, with max. indiv. dose < 5 mSv/y from accident conditions caused by possible natural events or human actions		Max. indiv. dose < 5 mSv/y from possible human actions	For spent fuel or HLW, proposed criterion for max. indiv. dose < 0.1 mSv/y
FRANCE (Basic Safety Rule, RFS III.2.f, 1991) [11]	For ILW and HLW: max. indiv. dose < 0.25 mSv/y for normal evolution scenarios; for altered evolution scenarios, risk may be considered (probability of scenario times effect of exposure)	Beyond 104 y, dose limit is considered as a "reference" level	Assumptions (French Basic Safety Rule, Appendix 2): Date of HI occurrence > 500 y; Existence of repository and location forgotten; Level of technology same as present day	Technical criteria for siting established in 1987
GERMANY (Section 45, para. 1 of Radiation Protection Ordinance, 1989) [12]	For all waste types: max. indiv. dose < 0.3 mSv/y for all reasonable scenarios	Calculation of individual doses limited to 10^4 y but isolation potential beyond 10^4 y may be assessed		Additional qualitative technical criteria in guidelines and regulatory document
NORDIC COUNTRIES (Basic Criteria Document, 1993) [13]	For all waste types: max. indiv. dose < 0.1 mSv/y (normal scenarios); max. indiv. risk < 10^{-6}/y (disruptive events)	For HLW, additional criterion on "total activity inflow" limiting releases to biosphere, based on inflow of natural alpha radionuclides		Includes other qualitative criteria

SWITZERLAND (Reg. Document R-21, 1993) [14]	For all waste types: max. indiv. dose < 0.1 mSv/y at any time for reasonably probable scenarios; max. indiv. risk $< 10^{-6}$/y for unlikely scenarios	Repository must be designed in such a way that it can at any time be sealed within a few years without the need for institutional control	No criteria for HI scenarios except that for high consequences, probabilities can be taken into account	
UNITED KINDOM [15]	For L/ILW: $< 10^{-6}$/y target for indiv. risk from a single facility For HLW: no specific criteria but likely application of principles similar to existing objectives for L/ILW	No time frame for quantitative assessments specified	Main criterion for HI scenarios currently indiv. risk	ALARA to be used to the extent practical and reasonable
UNITED STATES (EPA 40 CFR Part 191, 1985; 1993) [4,32]	For HLW, spent fuel, and TRU waste, limits on projected radionuclide releases to the accessible environment for 10^4 y, based on objective to limit serious health effects to less than 10 in the first 10^4 y after disposal for each 1000 MT of spent fuel or HLW disposed	Committed effective indiv. dose over 10^4 y < 0.15 mSv/y Other requirements on drinking water contamination	Main criteria applicable; additional guidance includes: active institutional controls should be relied upon for as long as practicable, but credit in the performance assessment limited to 100 y after repository closure; credit can be taken for passive institutional controls (records, markers), but these controls can not be assumed to eliminate the chance of inadvertent intrusion; max. number of inadvertent intrusions of 30 boreholes/km^2 per 10^4 y	1985 EPA standards were remanded, and have since been revised; in addition, the U.S. Congress recently mandated consideration of revisions to the standards specifically for the proposed Yucca Mountain Site in Nevada
(NRC 10 CFR Part 60, 1983) [16]	For HLW, minimum levels of performance specified for: Waste package ("substantially complete" containment for 300-1000 y) Engineered barrier system (releases $< 10^{-5}$ y^{-1} of the inventory at 1000 y after repository closure) Pre-waste- emplacement groundwater travel time between "disturbed zone" and "accessible environment" > 1000 y		Siting criteria for avoidance of foreseeable adverse human activity; separate consideration of anticipated processes and events (naturally occurring) and unanticipated processes and events (naturally occurring or human induced)	NRC subsystem requirements are intended to help achieve compliance with the EPA standards; revisions will be undertaken as required to conform to standards promulgated by the EPA for the Yucca Mountain site

2.7 Summary Remarks

Future human actions are potentially major contributors to the risks associated with the disposal of long-lived radioactive wastes deep underground. While safety analyses are sometimes performed without considering human actions, a more comprehensive analysis could include an evaluation of risks from future human actions. In this case, such actions should be limited to those that are considered to be inadvertent.

Safety assessments are most often quantitative evaluations. However, qualitative evaluation takes place as part of this quantitative evaluation – for example, in judgements about the selection of scenarios and in the design and siting of a repository.

Assessments of future human actions can be used in demonstrating the robustness of a site, in considering possible improvements to the repository design, in comparing alternative sites and designs, and in licensing of repositories. They are, however, inherently incomplete and, therefore, only illustrative of the total range of possibilities.

The period for assessment of future human activities is often bounded by two times:

- The time when institutional control of the disposal system can no longer be assumed to be effective.

- The time when the hazard presented by the waste is less than that arising from naturally occurring background hazards. This time may be several half-lives of the longest-lived radionuclides of importance for performance assessment.

Further discussion between interested countries concerning regulatory policies for judging the risks associated with future human actions is needed.

Chapter 3

Scenario Development, Consequence Analysis and Probability Estimation

3.1 Introduction

The Working Group considers that many of the issues that arise in considering the risks associated with future human actions could best be treated in the context of an internationally agreed set of principles for conducting illustrative calculations of disposal system performance. Given the central importance of defining what future human actions ought to be included in quantitative assessments of system performance, this Chapter begins with a brief review of past approaches to human action assessments, and a discussion of the principles needed to limit the scope of a quantitative assessment. Consequence analysis and probability estimation for future human actions are also dealt with in more detail in this Chapter.

3.2 Review of Existing Human Action Assessments

Appendix C includes a summary of past human action studies, classified according to the type of repository host-rock. It touches upon many of the principal studies that have been conducted to date, and considers all of the main rock types under investigation. The focus of the summary is on outlining the main scenarios that have been evaluated quantitatively, in an effort to provide an overview of the approaches to human action assessment taken. The purpose of this Section is to present the common points from these studies. It is concerned primarily with the overall framework in which the analyses were conducted, and with the main scenarios that were analyzed quantitatively (see Table 2).

Past Framework

In the studies reviewed, only inadvertent human activities were generally considered. The assumption was made that knowledge of the existence or location of the waste repository has been lost, so that there was no mechanism for deterring disruptive human actions.

Many previous analyses of future human actions have been characterised by an ad hoc approach to the selection of scenarios developed for quantitative analysis. This leads to difficulties in reaching a detailed understanding of the basis behind individual studies and the reason for differences between studies.

Generally, one or more scenarios have been constructed centred around a set of basic premises:

- Humans intrude directly into the repository at some future time, and bring contaminated material to the surface. Health effects are evaluated on the basis of direct exposure to contaminated material. Direct intrusion is usually assumed to occur in the process of searching for or extracting resources, such as hydrocarbons, minerals or thermal waters.

Table 2: **Human action scenarios analyzed in a representative selection of past studies.**

Country	Disposal Medium	Ref.	Human Intrusion Scenario Analyzed
BELGIUM (PAGIS)	clay	[22]m	Drilling a water well in a contaminated plume in the upper aquifer: -consumption of water, and animal and vegetable produce watered by the well.
CANADA	igneous rock	[23]	Drilling a water well into a fracture zone intersecting the repository: -consumption by humans and animals of water and field crops watered by the well.
CANADA	igneous rock	[5]	Exploratory drilling penetrating the waste: - exposure of member of the drilling crew. - core examination. - construction on land contaminated with extracted waste. - habitation of land contaminated with extracted waste.
CANADA	igneous rock	[24]	Using lake sediment overlying a contamination discharge zone as garden soil. Using peat overlying a contamination discharge zone as soil or heating fuel.
FINLAND	crystalline rock	[25]	Drilling a water well into the plume. Exploratory drilling penetrating the waste: - core examination.
FRANCE (CEC PAGIS Project)	granite	[26]	Construction of a 106-m^3 mine cavern 50 m from the repository: - altered groundwater flow causing enhanced radionuclide transport to the biosphere. - exposure of the public by consumption of milk from cattle watered with contaminated groundwater and consumption of vegetables in an area contaminated with mine spoil.
FRANCE	bedded salt	[27]	Solution mining intersecting a repository: -human consumption of salt.
GERMANY (PAGIS)	salt	[28]	Mining of a storage cavern, resulting in one-half the contents of a single borehole falling to the sump of the cavern. Subsequently the cavern is filled with water and sealed. Salt convergence slowly expels the contaminated cavern water to overlying drinking water aquifers.
GERMANY (Konrad Site)	former iron-ore mine	License report	Exploratory drilling into the repository: - exposure of the worker. - exposure of the public. Construction of a new mine down gradient from the site.
NETHERLANDS (OPLA)	salt	[29]	Exploratory drilling: - core examination. Leaking Storage cavern: - same as PAGIS study (above). Solution mining: - workers in a salt factory. -human consumption of salt. Conventional mining: - miners in an adjacent mine.

SWEDEN	crystalline rock	[30] [44]	Drilling a water well into the radionuclide plume.
SWITZERLAND	crystalline rock marl	[31]	Drilling a water well into overlying aquifers. Exploratory boreholes.
UK (NIREX)	crystalline rock	[20] [33]	Exploratory drilling penetrating the waste: - core examination. - habitation of land contaminated with extracted waste.
UK (DOE)	crystalline rock	[34]	Exploratory drilling penetrating the waste: - core examination.
US	salt	[35]	Solution mining: - consumption of salt.
US	bedded salt	[36]	Borehole drilling intersecting the repository and an overlying aquifer. Borehole drilling intersecting the repository and overlying and underlying aquifers.
US	edded salt	[37]	Borehole drilling intersecting the repository and an underlying pressurized brine pocket: - examination of waste chips. - habitation of land 500 m downwind from contaminated drilling fluid left on the site. - consumption of beef from cattle watered from a well in a nearby aquifer contaminated by brine flowing through a borehole intersecting the pressurized brine pocket, the repository and the aquifer. - cumulative release of radionuclides over 10,000 years to the accessible environment.
US	tuff	[47]	Borehole drilling intersecting a container or contaminated rock: -surface deposition of up to the content of one container or contaminated rock. -insertion of up to the content of one container into either of two underlying aquifers.
US	alluvium	[17]	Exploratory drilling penetrates a borehole containing waste: -waste brought to surface in circulating drilling fluid.

- After an intrusion, contaminated material may be left in the surface environment for some period, after which use is made of the contaminated land surface for human activities (e.g., farming). A range of exposure pathways may be considered.

- A water well is drilled into an aquifer or a fracture zone containing contaminated water. Health effects are assumed to arise from direct consumption of water and from use of water for irrigation and/or for watering stock which is later consumed.

Less attention has been given to the possibility of human activity adversely altering geosphere behaviour or the engineered barrier system, but without an immediate release of radionuclides to the surface. Most studies assume that future modes of intrusion will be identical to those that might occur today. Societal evolution may be considered in qualitative terms, but it has not specifically been taken into account in quantitative assessments. For example, current drilling technology is normally assumed to persist into the far future, and evaluation of drilling frequencies thousands of years from now may be based on those observed over the course of this century.

Using these assumptions, many studies have constructed scenarios and models in which inadvertent disruptive human actions lead to significant doses to hypothetical individuals living at some future time; in some cases, these doses may be higher than those from natural evolution scenarios. This is unsurprising given that one aim of geological disposal is the confinement of hazardous materials in a limited area. Probability arguments may be invoked in considering high individual doses, even if the approach to regulatory compliance is deterministic in nature.

Limited study has so far been made of the possible benefits to be derived from the adoption of passive institutional controls for radioactive waste repositories. Notable recent exceptions include work carried out on long-term marking by Sandia National Laboratories [45], and on archives and conservation of information by the Nordic Nuclear Safety Commission [39]. This work is discussed in the following Chapter of the report.

3.3 Principles for Quantitative Assessment of Future Human Actions

Scenario development

A state-of-the-art summary of approaches to scenario development has recently been published by a Nuclear Energy Agency (NEA) Working Group on the Identification and Selection of Scenarios for Performance Assessment of Radioactive Waste Disposal [18]. The NEA Group defined scenario development as "... the identification, broad description and selection of alternative futures relevant to a reliable assessment of the radioactive waste repository safety". A single scenario specifies "... one possible set of events and processes and provides a broad brush description of their characteristics and sequencing".

While examination of assumptions is important, speculation about the range of future human activities is bound to be controversial and incomplete. What is required for safety assessments is a reasonable set of assumptions that can be used for developing representative scenarios for illustrative calculations of risk. Each of these scenarios may be considered an artificial description of the future used as a basis for conducting illustrative calculations of disposal system performance.

Limiting the scope of an assessment

Uncertainties about the future involving conditions that are unknowable can only be dealt with by making assumptions and recognising that these conditions may not correspond to any actual future reality. The Working Group considers that speculation about future human conditions should not be the focus of a licensing assessment. An approach was therefore sought that would avoid speculations about the future and that could be applied uniformly for various sites and systems.

Required principles

One approach considered by the Working Group would be to assume that the future conditions of society are essentially the same as they are today in the vicinity of the disposal site and at similar sites elsewhere. This assumption is not meant to convey any information about the possible future evolution of society; rather, the assumption could be made because it provides a practical means of illustrating the potential risks associated with future human actions. Changes could be assessed with sensitivity studies and stochastic analyses covering varying deviations from the reference state(s).

In this approach, quantitative assessments would proceed based on the assumption that many future conditions related to humans or to interactions between humans and the environment will remain the same as those of today's world, in so far as they relate to the motivations and capabilities for activities that could impact the isolation capability of the disposal system. For example, the present demographic pattern could be retained. Human characteristics such as physiology and nutritional requirements, water and land use patterns, technical and intellectual ability (particularly involving direct intrusion capabilities), medical resources, social structure, and values could be defined as they are today in the vicinity of the waste disposal site. In some instances, consideration of these features may be specific to the region in which a disposal site is located (e.g., population distribution or patterns of water and land use).

There is one additional issue that would require further definition in developing and modelling scenarios involving future human actions: the length of time over which knowledge of the disposal site could be assumed to be retained. This period would allow for the effectiveness of maintaining archival records, and for the longevity and comprehensibility of site marker systems.

For example, the effectiveness of institutional controls is critically dependent on the stability of national governments. In establishing a period for effectiveness of controls, the Working Group notes that the historic stability of governments, the recurrence of war and secession, and the resulting shift of land and/or responsibility to a new government could be considered.

Application of scenario development methodologies

The methodologies documented in [18] have been applied to develop scenarios involving human activities, either alone or in combination with natural processes and events, and waste and repository effects [19]. Extensive lists of human actions have been developed as part of this work. The Group has compiled in Appendix B the various available lists, in order to assist national programmes with assembling the scenario-building elements required for their respective consequence assessments.

In defining and selecting scenarios involving future human actions, it is necessary to rely heavily on expert judgement. The Working Group suggests that experts from a range of scientific and social disciplines should be involved, and that confidence in the analysis can be improved through the use of formal elicitation techniques and extensive peer review. In addition, care should be taken to consider interactions of human activities with other site-specific features, events and processes.

As the summary of recent studies in Section 3.2 and Annex C bears out, there is already a de facto consensus that scenarios of future human actions could be based on the premise that the practices of future societies correspond to current practices at the repository location and at similar locations elsewhere. However, the Working Group considers that further discussion at an international level aimed at establishing a more formal consensus on a systematic methodology for developing scenarios for future human actions would be beneficial. It should be stressed that the actual scenario(s) of concern should be expected to vary from site to site, depending on local geological and societal conditions – as borne out by the past studies.

Summary Remark

The principles outlined above, used in conjunction with standard methodologies for scenario development [18], are seen as providing a practical limitation on the scope of the modelling exercise for future human actions. The compilation of scenario-building elements for human action assessments provided in Appendix B is relatively comprehensive. The list can be considered a valid starting point for the development of human action scenarios and for integrating human action considerations into safety assessments.

3.4 Consequence Analysis

The calculation of consequences requires the development of calculational models. These in turn are based on conceptual models derived for the various scenarios being analyzed. Consequence analyses need to be considered as illustrative measures of the conceivable, and should capture what can reasonably be expected.

Three types of consequences may need to be considered in assessing the risks associated with future human actions:

- Consequences arising from an impaired isolation system, including alteration to geosphere behaviour or to the engineered barriers.
- Consequences to intruders directly contacting contaminated material.
- Consequences due to wider dispersion of extracted material in the surface environment.

Such analyses may be either deterministic or probabilistic. In deterministic analyses, consequences are calculated for several sets of single parameter values, producing the consequences as single values for each of the sets. In probabilistic analyses, probability distributions of parameters are typically used as input to a Monte-Carlo simulation, and the result is expressed as a probability distribution of the consequences. In both cases, sensitivity and uncertainty analyses would need to be conducted.

Even in deterministic analyses, it will still be necessary to consider the *probability* of the scenario studied, e.g., the likelihood of drilling into the repository and consequent transfer of contaminated material to the surface. Such probability estimation is discussed in the next section of the report. In Monte-Carlo analyses, the probability distributions of the parameters used as input to the consequence determination also need to be considered, e.g., the time spent examining a contaminated sample. Regardless of whether deterministic or probabilistic techniques are used, expert judgement will be the main basis for deriving the input quantities required by calculational codes.

A system of coupled calculational models is required in order to illustrate potential consequences. Subsystems codes are normally developed for:

- The repository near field (the engineered barrier system and the immediately surrounding volume of rock).

- The geosphere (the natural barrier system – the entire volume of rock that lies between the repository and the biosphere).

- The biosphere, including consideration of all relevant exposure pathways.

Modelling the consequences of future human actions requires modifications in the ways these three subsystems are considered.

Near field

If there is no direct intrusion into the repository, the near field can be treated as in natural-evolution scenarios. If there is a direct intrusion, the normal near-field model should provide the capability to assess the radionuclide inventory available for immediate release. However, modification of the properties of components of the engineered barrier system may need to be considered.

Geosphere

There are many types of human actions that could change the properties of the geosphere, such as construction of dams, borehole drilling, deep excavations, etc. In most cases, however, it should be possible to use models developed for the undisturbed geosphere, modified to account for the relatively short timescale of these activities. For example, input parameter values, such as aquifer recharge rates may be modified. In addition, in the case of intrusion into the repository leading to a release directly to the biosphere, no geosphere model may be required.

Biosphere

In general, the human action scenarios that concern actions on and in the biosphere are covered under the analyses for natural evolution of the disposal system. Additional consideration may need to given to certain radionuclide transport and exposure pathways, such as direct external exposure to highly radioactive excavated material. For most of these exposure pathways, calculational tools can be used directly or slightly modified from those that have already been developed for evaluating the safety of disposal systems in the absence of disruptive human actions. In addition, codes are available from the field of operational radiological protection for calculating doses from small highly active sources of radioactivity.

Input data

Whereas the codes for consequence analyses can generally be derived from those that are already available, the input data to be used are not easily derivable. The situations treated are all hypothetical, and the parameter values assumed in the literature for apparently similar situations (scenarios) show large differences that are difficult to explain. In addition, there may be no way to argue convincingly that one set of parameter values or probability distributions is more or less reasonable than any other set. Direct validation of any model or choice of parameter values for future behaviour is impossible over the timescales of concern.

Caveats

Proof in an absolute sense is not possible for assessments of the long-term safety of radioactive waste disposal systems, and such assessments should always be presented with clear caveats. In presenting the results of consequence analyses, it should be pointed out that the quantification of human behaviour is not meant to be an accurate prediction. Rather, the results should be considered as an indication or illustration of the consequences of future human actions.

Summary remarks

In summary, the Working Group considers that:

- The range of present-day human actions is large, and society is changing rapidly.
- The prediction of future human actions is fraught with uncertainty.
- Differences in results produced by different groups are to be expected.
- It may be difficult to explain these differences.

These observations point to the need for a methodology for derivation of future human action scenarios and for performing calculations to address these scenarios. A fundamental purpose of this methodology would be to increase the transparency of the quantitative assessment effort. In addition, an acceptable methodology should allow two individuals, analyzing the same site and working to the same regulations, to arrive at consistent conclusions on the quantification of future human actions.

3.5 Probability Estimation and Expert Judgement

Physically verifiable probabilities do not exist for future human actions. It is not possible to design a repetitive experiment in which in some trials an event or action occurs and in other trials it does not occur. There will be only one future for the disposal system, and the event or action will either occur or it will not occur. Therefore, "probability" estimates will inevitably be speculative and subjective, even when historical data on drilling frequency are available. They should thus be considered "degrees-of-belief" rather than (verifiable) relative frequencies. Because of this subjectivity, these probabilities or degrees of belief can only be considered as illustrations required for the purpose of analyzing risks based on sets of assumptions.

The Working Group discussed similarities and differences in the predictability of naturally occurring disruptive events and processes and those relating to future human actions. For both types of event, estimates of the likelihood of occurrence have to be based to a large extent on expert judgement and are associated with significant uncertainties. However, the Working Group was unable to reach a consensus on the relative validity of the "expert" judgements required for evaluations of risks associated with the two types of potentially disruptive events. This is an area where further discussion at an international level could be useful.

Future inadvertent human actions can be decomposed to identify a series of events necessary for the action to occur. The probabilities of these events are aggregated to develop the probability of occurrence of the human action. Three methods have been identified for the development of these probabilities: (i) events trees used with scenario-based approaches, (ii) system simulation, and (iii) Markov models. These are discussed below. In addition, combinations of these methods could be used.

Scenarios and event trees

Event trees represent one approach to developing and illustrating the probability of human action scenarios. Event trees are graphs showing a sequence of events leading to several possible consequences. Each branching represents a question that resolves into two states. These states are assigned complementary probabilities that are conditional on the branchings at earlier nodes in the tree. The probability of reaching any end branch of the tree is the product of the branch probabilities leading to that end state.

For example, a scenario of intrusion into a deep geologic repository by exploratory drilling might include the following events:

(1) Exploration for a mineral is conducted in the repository region.

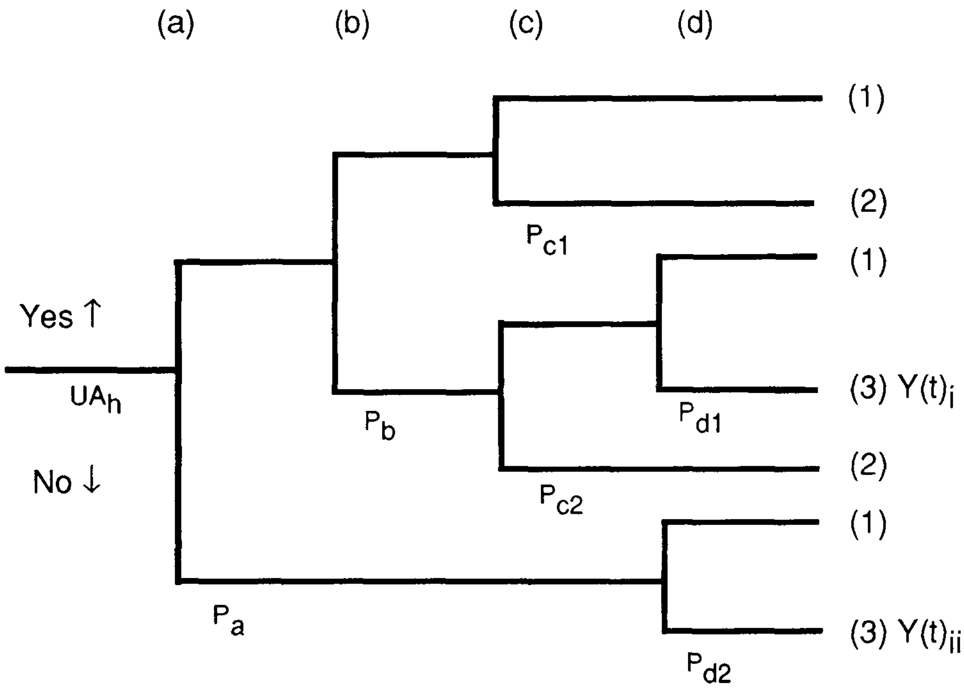
(2) Drilling is commenced above the waste.

(3) Drilling is sufficiently deep to intercept the repository.

(4) There is no detection of radioactive material during drilling, nor is there detection from the tailings.

Probabilities of each individual event could then be estimated directly, or frequencies could be estimated and probabilities derived from the frequencies. For example, consider Event 2 – drilling is commenced above the waste. One approach to quantification is to ask informed experts for probabilities of Event 2. The expert might provide either a single probability or a probability distribution for the drilling density. The drilling density would then be multiplied by the expected horizontal area of the repository or of the available waste canisters. The result would be either a single value or a probability distribution that describes the estimated frequency of drilling. The probability distribution is to be preferred because it better expresses the uncertainty in the event, but the methodology must be appropriate to the type of parameter and to the degree of knowledge about the parameter.

Figure 1 illustrates an event tree that can be used to provide the frequencies of both advertent and inadvertent intrusion from exploratory drilling [20]. The probabilities of the various outcomes are shown at the ends of the branches.



Nodal Questions

(a) Is a prior geological survey carried out?
(b) Does the survey detect an anomaly that is distinguished as characteristic of a radioactive waste repository?
(c) Does drilling go ahead?
(d) Does behind-the-bit gamma monitoring lead workers to an understanding of the potential hazards?

End Points

(1) Advertent intrusion
(2) No drilling occurs
(3) Inadvertent intrusion:

$$Y(t)_i = UA_h(1\text{-}P_a)P_b(1\text{-}P_{c2})P_{d1}$$

$$Y(t)_{ii} = UA_h P_a P_{d2}$$

Figure 1. **An event tree for human intrusion**

The annual frequency of inadvertent human intrusion at any time t is Y(t)i + y(t)ii, where U(t) is the annual areal frequency with which drilling is proposed, Ah is the horizontal area of the waste panels, and Pi are the probabilities of a No response to the nodal questions (a) - (d).

System simulation

In principle, future human activities could be incorporated into an overall probabilistic system assessment model, along with other nondisruptive natural events and processes [21]. In this approach, probability distributions for human activities would be incorporated into a computer code for stochastic analyses, and consequences explicitly modelled for each mode of intrusion.

For example, the simulation model could first sample the time that active institutional control fails. The type of intrusion could then be selected from a discrete distribution of intrusion types, and the time from failure of planning controls to intrusion sampled from another distribution. A complete sequence of intrusions could be simulated by repeated sampling.

Another value that could be sampled is whether active institutional control over use of the site would be reinstated after intrusion. Parameters defining the reinstatement of control could be single valued or assigned probability distributions, and could depend upon the type of intrusion and/or the consequence of the intrusion.

Markov models

Markov models could also be used to develop probabilities for future human actions [e.g., 51]. For example, in a first-order Markov model, the state of knowledge about radioactive waste in any period would depend only on the state of knowledge in the preceding period. From period to period knowledge of the repository would decay, unless the repository were rediscovered. Implementation of this first-order Markov model would require estimation of probabilities of moving from one state of knowledge to another, and probabilities that each type of intrusion would reinstate knowledge of radioactive waste.

Establishing Credibility

The analysis of human activities affecting deep geologic repositories must depend heavily on expert judgement. Even if experts are not used to establish directly probabilities of events and probability distributions for the frequency of various future activities, expert judgement will play a central role in choosing models, data sources, and assumptions for the analysis.

The foremost consideration in the assignment of probabilities to human intrusion events and processes is credibility. Some considerations that will enhance the credibility of probability estimates include:

- Careful interpretation of historical data when available.
- Careful explanation that human intrusion probabilities represent degrees of belief and not verifiable frequencies or, if historical frequencies are used, that the analysis is conditional on assumptions regarding the use of such data for projections of future human actions.
- Use of modelling approaches so as (i) to reduce the problem to a larger number of simpler, more reasonable assessments, and (ii) to represent clearly those factors that would serve to increase or reduce probabilities.

Given the large uncertainties involved, robust approaches that are easy to explain may be more convincing than complex analyses that are difficult to explain and to understand. In so far as probability assessments for future human actions are concerned, increased complexity is not indicative of increased realism, and is unlikely to lead to increased confidence in the results.

Establishing credibility is particularly important in the use of expert judgement. The keys here are to select experts carefully, to explain unambiguously the questions that they are asked to address, and to document fully the procedures, rationales, and findings of their efforts.

Chapter 4

Countermeasures

4.1 Introduction

Because of their long half-lives, some radionuclides present in radioactive wastes can constitute a hazard for future societies. The Working Group considers that the society disposing of these wastes has a responsibility to take measures to reduce the risks associated with future inadvertent human actions that might impair the effectiveness of the disposal system. Both the likelihood and the consequences of disruptive future human actions can be reduced by the selection of appropriate repository sites and designs and through the use of institutional measures. Institutional measures can in turn be either active or passive. Active measures include limitations on access to and use of the site. Passive measures include organised systems of information conservation and site marking.

The most effective countermeasure to inadvertent disruptive actions is active institutional control of the surface environment above and for some distance around the disposal site. This countermeasure forms a basis for the licensing of near-surface disposal facilities for any waste type. It may also be used for deep disposal facilities for as long as practicable to guard against inadvertent intrusion or other potentially disruptive human actions in the vicinity of the disposal site.

However, active institutional control cannot be relied upon forever. For example, some national regulations allow credit for up to several hundred years of active control subsequent to closure and decommissioning of the repository. Therefore, other countermeasures have also been considered, including:

- Siting of repositories away from areas of currently recognised subsurface resource potential. Although this might be considered the most powerful countermeasure and has been incorporated into both national and international guidance on siting, in practice other siting factors (e.g., geological formation, local acceptance of the repository) may emerge as being of greater importance.

- Isolation of waste from the human environment. For deep geologic repositories, the very depth of burial is an important mitigating feature against potentially disruptive human actions. Given that knowledge of the location of a waste repository is lost, the likelihood of direct intrusion is reduced as the depth of the repository is increased.

- Other criteria for the design of waste repositories (e.g., geometry of disposal, backfilling materials) and for the waste form itself (e.g., low tendency to form dust if exposed in open air) can help reduce the consequences associated with disruptive human actions.

- Conservation of information at different societal levels and locations can help to reduce the likelihood of disruptive human actions in the short term (first 500 years after disposal). Multiple systems should be used. The greatest longevity is currently associated with records maintained in paper form.

- At somewhat greater times, large-scale physical markers at or near the site may help reduce the likelihood of disruptive human actions. Recent work in the U.S. suggests that welldesigned markers have a high likelihood of maintaining their effectiveness for periods on the order of several thousands of years. On the other hand, some argue that far in the future the message concerning the hazard associated with the repository might not be properly understood, and that markers may serve primarily to increase interest in the repository (see below). In any case, surface-based marker systems located in areas prone to glaciation are unlikely to survive such glaciations when they next occur (on the order of 10,000 years from now).

- Physical barriers to intrusion (e.g., a thick concrete cover above the disposed waste or a strong canister) may lower the probability of inadvertent intrusion. However, this is probably the least effective countermeasure, and is not discussed further.

Both the siting of repositories and the depth of disposal could be considered as design features. They are discussed separately here because of their relative importance in mitigating the risk from inadvertent human actions.

Although a wide range of countermeasures is considered in more detail below, discussion within the Working Group benefitted greatly from the work done by Sandia National Laboratories on markers [45] and by the Nordic Nuclear Safety Commission on information conservation [39]. Much of the material on these topics has been drawn from the work sponsored by these two organisations.

4.2 Active Institutional Control

Active institutional control is likely to be highly effective in the short term in preventing future human actions from disturbing the disposal. Although such control cannot be relied upon forever, it could continue in principle for as long as the waste represents a potential hazard.

On the other hand, there is an ethical principle stating that the society that benefits from the use of a technology should bear the full burden for appropriate disposal of the ensuing waste products. The nuclear industry has been anxious to show that waste can be safely managed in a manner that puts negligible burden (e.g., for active institutional control) on future societies. This has been one of the main arguments for early disposal of long-lived wastes deep underground, as opposed to long-term storage of the wastes at the surface.

Active institutional control involves direct control of the site and/or ownership of the site by local or central government, with the aim of limiting access to and use of the site. Some interesting suggestions have been made concerning possible uses of the land surface near a deep repository, in order to help ensure that adverse human actions do not take place. These include construction of a museum dedicated to the use by humans of various forms of energy, and development of a nature reserve at the site.

In addition, countries that are signatories to the Treaty on the Non-Proliferation of Nuclear Weapons [50] agree to the application of safeguards measures to all peaceful nuclear facilities in their countries. Safeguards provide for monitoring of these facilities by the IAEA to detect any attempted diversion of nuclear (fissionable) material from peaceful nuclear activities. As already noted in Section 2.4, such measures have been studied but not yet specified by the IAEA for disposal facilities for spent fuel [46]. These measures would almost certainly have the capability of detecting drilling or other forms of intrusion at the disposal site in the postclosure phase. Furthermore, they would include submission to the IAEA of records and reports on the design and inventory of the disposal system, which would thus be included in an international database.

Thus, some existing national regulations allow credit in performance assessments for up to several hundreds of years of active institutional control subsequent to closure and decommissioning of the repository. However, reliance on this control may lapse with time. Beyond the regulatory exclusion period, it is necessary for performance assessors (and repository developers) to assume that active institutional controls cannot be relied upon to guarantee the absence of disruptive human actions.

4.3 Siting of Repositories

Both national and international guidance on siting suggest that areas of currently recognised subsurface resource potential should be avoided. The main principle behind this criterion is the thought that inadvertent intrusion will be more likely in areas containing known potential for natural resources. Furthermore, avoidance of such areas reduces the likelihood that these resources might become contaminated with radioactive material in the future, either through the groundwater pathway or through a human-initiated pathway – leading to loss of use (sometimes referred to as "sterilisation") of these resources.

It is sometimes argued that the disposal of radioactive wastes in salt, which in itself might be considered a resource, should be avoided. However, the abundance of salt reserves and the increased safety provided by the salt geology under natural conditions have been used to argue that the advantages of such sites for waste disposal outweigh the resulting loss of an exploitable resource.

Although siting criteria might be considered the most powerful countermeasure to be employed to reduce the likelihood of future inadvertent human intrusion, in practice other siting factors have usually been given greater importance, including:

- Safety-related criteria, such as the safety of the site in the absence of disruptive human actions. For example, this has led to the choice of salt host geology in several countries, such as the U.S. (WIPP) and Germany (Gorleben).

- The need for local populations to accept the repository. For example, negotiated siting of hazardous waste facilities – including those for radioactive waste disposal – is being used increasingly in OECD countries.

- Cost. For example, in some cases, consideration of relative transportation costs has contributed to the choice of repository sites near the main source of waste generation.

4.4 Isolation of Waste from the Human Environment

For deep geologic repositories, the very depth of burial is an important mitigating feature against potentially disruptive human actions. One of the arguments provided in favour of such disposal is that long-term monitored storage of waste at the surface actually leads to a higher risk from unintentional disruptive human actions, compared to disposal deep underground. Furthermore, given that knowledge of the location or hazard of a waste repository is lost, the risk from direct intrusion is reduced as the depth of the repository is increased to lie below the main potential targets for intrusive activity. These targets and their depths will differ from site to site. A prime concern for most sites, however, is to position the repository at depths below those likely to be used for groundwater abstraction.

The depth of potential intrusion targets forms only one basis for deciding on the depth of a repository. Most countries are considering disposing of long-lived radioactive wastes at depths of between 200 and 1000 m, the exact depth depending on the local geological and hydrological conditions.

4.5 Design Criteria

Criteria on the design of waste repositories and on the waste form itself can help reduce the consequences associated with disruptive human actions. Of course, mitigation of future human actions should not be the only or even the main guiding design principle. But design modifications that would not affect the intrinsic safety of the repository under normal operating conditions should be considered.

Design options that have been considered include:

- Vertical emplacement of waste canisters in drifts would tend to reduce the likelihood for a drilling intrusion directly into a canister. At one extreme, a series of very long boreholes in which canisters were vertically stacked would lead to the greatest reduction in intrusion probability. On the other hand, horizontal disposal in mined caverns at depth, while leading to a greater available surface area for a direct hit from drilling, might lead to lower consequences if a direct hit occurred.

- Both the permeability of the overall engineered environment and the solubility of radionuclides within that environment could be limited in order to reduce the transport of radionuclides towards a borehole that has penetrated the repository or its near vicinity. This might affect the choice of backfill material and its packing within the repository, the stacking pattern of waste canisters, and the design of the waste form itself.

- Waste forms could be engineered having limited tendency to form dust if inadvertently extracted from the repository and exposed to open air.

- Metal shields could be installed above containers to deflect drill bits and thereby reduce the likelihood of direct exhumation of waste.

- Materials could be used in the repository that would lead to a magnetic or other geophysical anomaly detectable at the surface. This might alert potential intruders of the presence of an unusual deposit at depth. However, whether this awareness of an unusual deposit would increase or decrease the likelihood of intrusion is an open question.

Site-specific optimisation of repository design will need to be done by each country on the basis of safety, technical, economical and ethical considerations. An in-depth discussion of these optimisation issues is beyond the scope of this report.

4.6 Conservation of Information

The likelihood of inadvertent human actions disrupting the disposal system may be reduced by providing potential intruders with warning of the presence of the waste and its potential hazard. This could be accomplished by onsite markers or monuments [45], national or international archives [39], and by a variety of other records and regulations such as mining databases, land-use controls, regulation of drilling, and government ownership of the site. It has been argued that 'societal memory", comprising all forms of verbal and written communication, has been effective in preserving knowledge over many centuries in the past and should be more effective in the future [41].

A main goal of an information conservation system for radioactive waste repositories is to prevent inadvertent and unauthorised intrusion. In addition, sufficient information for society to make informed decisions about intentional intrusion should be retained. The main questions that need to be addressed are:

- What type of information will be of most value and should be conserved?
- In what form should the information be kept in both the short-term and the long-term?
- What measures can be taken to ensure the safeguarding of information, and how long can information be retained?
- What can be done to ensure that the information will be communicated?

Information to be conserved

Primary information to be conserved could include:

- The geographical location of the repository.
- The design of the repository, its physical shape and barriers.
- The radionuclide and chemical inventory.

Secondary information to be retained might include:

- Laws governing waste disposal.
- Licensing documentation submitted for the repository, including the final safety assessment.
- Records from the operational phase of the repository, such as databases on locations of waste packages and design modifications.
- General information about the society disposing of the waste.

The Nordic study [39] estimated that the volume of the most important technical documents for a waste repository should be on the order of one to ten shelf-meters (one shelf metre is considered equivalent to about 7000 pages of paper).

Form of the information

The principal media for conserving information today include paper, microfilm, and magnetic and optical disks [39]. The durability of archive paper can be up to 1000 years if properly handled. The durability of microfilm is estimated to be about 200-400 years if the information is regenerated at least once. In contrast, magnetic and optical media must be copied every few years, as their current lifetime is less than 10 years. Therefore, for long-term record keeping, the choice is currently between paper and microfilm for storage of information.

Safeguarding of information

Experience in several European countries shows that institutional control of archival material is possible for periods of at least several hundreds of years. For example, the Office of Quarries in Paris was created by Louis XVI to prevent disturbances to buildings built above quarries. This Office still exists and continues to maintain control over components of the infrastructure of Paris. For radioactive waste disposal, it would seem reasonable to assume that it will be possible to maintain records for periods of up to 500 years. Human history suggests that institutional stability cannot be guaranteed for longer periods.

The threats to the integrity of a single archive are many. For example, in France, archival information on Paris was destroyed in a fire at the Tuileries Palace during the civil war of 1870, and many buildings where archives were kept were bombed during the Second World War. The best strategy to counter such threats is to maintain duplicate information at different places. For example, the Mormons chose to maintain duplicate records in special underground rooms in granite near Salt Lake City, Utah, to ensure that information about ancestry was properly conserved.

An archive on radioactive waste repositories should also be maintained at an international level. This is particularly important given that the states disposing of radioactive wastes today may disappear or change over the relevant timescale.

Communication of information

Not only must information be conserved, it must also be communicated effectively to potential intruders. This implies that archived information must be readily available, and that it must be consulted by the potential intruder. Regardless of how effective the system of conservation, if the necessary information is not communicated, or is not communicated properly, the system can be considered to have failed.

One means available for ensuring that information is both retained and communicated is the systematic inclusion of waste repositories on maps.

4.7 Use of Site Marker Systems

Site markers may be placed at the surface or in the subsurface. They may consist of solid constructions designed to last many thousands of years and be interpretable by future societies, or they may consist of simple fences and warning signs having a lifetime of only some decades. It is the use of long-term markers that is of interest here. This turns out to be a contentious subject. Some argue that they would serve to warn future societies about the location of the repository and the risk associated with it. On the other hand, as noted in the Introduction to this Chapter, some argue that far in the future the message concerning the hazard associated with the repository might not be properly understood, and that markers may serve primarily to increase interest in the repository. This concern has implications for the design of marker systems.

If markers are to be effective, they must last for long periods (ideally thousands of years or more), and the messages they convey must be interpretable by societies living in the far future. We have today examples of systems that have already survived 5000 years, and the task therefore appears daunting but feasible to the Working Group.

Surface markers

Such systems have been widely discussed in the U.S.. In addition, recent work in France, inspired by discussions within the Working Group, adds some new ideas bearing on the design of marker systems.

United States

Site markers are a legal requirement in the U.S. [4]. Substantial work on marker design was already undertaken more than a decade ago by the Department of Energy (DOE) for the high-level waste disposal programme. More recently, Sandia National Laboratories (on behalf of the DOE) has been sponsoring work on marker design for the Waste Isolation Pilot Plant (WIPP).

The more recent work has led to the development of a set of criteria for marker development [38]:

- Markers should be made from material with little intrinsic value, and with great resistance to surface erosional processes.
- Because the disposal site will be "indelibly imprinted by human activity" [38] – or intrinsically marked – markers should be constructed directly above the repository. The idea is that markers should complete the process of imprinting the site by explaining the nature of the repository.
- The marker should be on a scale to be visible from the air, as humans are likely to continue to use air transport.
- Redundant messages and different message levels should be employed on the markers. Four different message levels were proposed corresponding to four different levels of communication. These levels range from pictograms to succinct and unmistakable written warnings to increasingly more detailed and lengthy written messages and documentation concerning the repository. It was proposed that the highest level messages should be written in the six official languages of the United Nations and in Navajo, a regionally important written Indian language.

The study concluded that a deterrent probability of 50% was possible as far as 5000 years in the future [45].

France

A different type of marking system has been evaluated by the French National Agency for Radioactive Waste Management (ANDRA) [42]. This system is motivated by the concern that onsite messages may be misunderstood or not understood at all, and that the markers may arouse curiosity and actually increase the risk of human intrusion. An alternative set of criteria was proposed for marker development:

- Markers should not be located directly above the repository, but rather 10-20 km away. This distance should limit direct intrusion due to curiosity, and allow the markers to be located in the same political and geographical region as the repository itself.

- Markers should be sufficiently large to be known by any people living in the vicinity of the site.

- Markers should contain redundant messages indicating the exact position of the disposal site, but this information should be in a form recoverable only by a civilization knowing the basic elements about radioactivity; otherwise, the situation would be equivalent to that for a marker built directly above the repository. Thus, the messages and particularly the location of the disposal site should be encoded, for example using the symbols and quantities used in nuclear physics.

The principle here is that if a society has the capability to understand the warning message, it will probably also understand the exact hazards associated with the waste, and will realise that the message should not be ignored. A less advanced society motivated by curiosity may not understand the message or the nature of the waste but may still have the capability to drill. The off-site marker would help ensure that drilling carried out for the sake of curiosity directly above a repository would not have an increased likelihood of occurrence.

Underground markers

Another physical means of recording information about the repository would consist in using underground markers, for example many hundreds or thousands of very resistant disks containing different messages. This means has already been touched upon in discussing design criteria for repositories (see Section 4.5 above). Specific underground markers have been proposed as part of the SNL/WIPP work [38]:

- Acoustically obvious markers, perceivable by seismic techniques – for example, granite disks or spheres for repositories in sedimentary formations.

- Magnetic markers.

- Radioactive markers – for example, samples of the isotopes contained in the waste.

These markers all share the property of being detectable from a distance (e.g, at the surface) using the appropriate geophysical tools. The markers could be arranged at depth so as to indicate the position of the repository. Of course, as for surface markers, some consider that such underground markers would serve primarily to increase interest in the repository.

In summary, the Working Group considers that marker systems can form a useful part of a system of warnings to future societies about the location and contents of the repository. Although welldesigned markers may be durable and interpretable for long periods of time, the Working Group notes that it will be difficult to take credit for marker longevity for periods much beyond one thousand to several thousand years from repository closure and decommissioning.As for information conservation, the Working Group considers that further international cooperation would be useful. In particular, there is likely to be a benefit in further international cooperation on the principles behind marker systems. A consistent approach toward markers would help society to retain awareness of their meaning, and to 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.

4.8 Accounting for Passive Institutional Countermeasures in Quantitative Assessments

How should the passive institutional measures discussed in Sections 4.6 and 4.7 above be accounted for in long-term safety assessments? There are two reasons for giving these measures consideration. First, if a safety assessment is to provide a fair appraisal of risks and uncertainties in risk, assumptions should not be unduly conservative nor optimistic. Second, incorporating these measures in safety assessments can provide a motivation to implementing agencies to develop these measures to their best potential.

As discussed in Section 4.6, the work of the Nordic countries has identified archives as one method of preserving information over long periods [38]. Because archives tend to transcend governments and require little maintenance, it is thought that they can be effective for longer periods than direct government control. In addition, as discussed in Section 4.7, the results of a recently completed study in the United States indicate that large-scale permanent site marker systems may serve as a deterrent to inadvertent human intrusion relatively far into the future [45]. Because the marker systems are passive, they, like archives, are apt to be more persistent than direct government control.

Direct government control of the land above the repository is normally assumed for only relatively short periods, such as 100-500 years. This is due to the historically ephemeral nature of governments and the perception that governments often lose track of or disregard older commitments as time passes. Over the long-term, therefore, both archives and markers may prove more effective than active government control of the site. It therefore would not make sense to apply arbitrarily to these passive systems the time cut-off used for active government control. To do so in a quantitative assessment may be unduly conservative. Moreover, doing so may dampen interest in developing these passive countermeasures and may discourage implementing agencies from their use.

It is also important to note that markers and information conservation systems are likely to be most effective immediately after repository closure and their effectiveness will decay with time. But this decay is counterbalanced by the natural decay of the radioactivity contained within the disposal system so that the markers and information conservation systems are of most effect when the potential consequences of inadvertent human intrusion are the greatest [e.g., see 5].

4.9 Summary Remarks

The Working Group considers that an optimal system to reduce the likelihood and consequences of future disruptive human actions might include:

- Procedures during the siting and design of repositories that require consideration of site and repository design properties that could reduce the likelihood of potentially disruptive future human actions, and mitigate the consequences should they occur.

- Planning procedures that take into account the need for long-term conservation of information on nuclear waste repositories. The information could form part of both nationally and internationally maintained archives. Surface and subsurface site marker systems could be considered.

The obligation of our society to protect and warn future societies requires that each of these measures be considered.

- Additional needs exist for:

- An ongoing review of the state-of-the-art in media used for storing information.

- A legal framework for conserving information on repositories.

- International co-operation concerning archives, transfer and recovery of information, site markers, and standardisation of symbols and warnings pertaining to radioactive waste repositories.

Chapter 5

Summary and Recommendations

5.1 Framework for Consideration of Future Human Actions

Future human actions can adversely impact radioactive waste disposal systems; these actions must, therefore, be considered both in the siting and design of waste disposal systems, and in assessments of their safety.

Disruptive human actions can be divided into those in which the barrier system is intentionally disrupted and those in which it is inadvertently disrupted. Inadvertent actions are defined here as those in which either the repository or its barrier system are accidently penetrated or their performance impaired, because the repository location is unknown or its purpose is forgotten. Human actions leading to the release of radioactivity and committed intentionally, rather than inadvertently, can be considered the responsibility of the society that takes these actions. Intentional disruptive actions should not be considered in safety assessments. In contrast, actions in which the disposal system is inadvertently disrupted should be considered.

5.2 Considerations Bearing on Quantitative Analysis

Both disruptive human actions and disruptive natural events can result in the same types of consequences and both are potentially important to safety. Thus, the general quantitative framework developed for safety assessments involving naturally occurring events and processes is also appropriate for the analysis of future human actions. Extensive human judgement is required for the development and modelling of scenarios of both future human actions and natural events and processes.

The analysis of human actions can only be illustrative and never complete. At best, scenario techniques as applied to future human actions could lead to the development of a representative set of scenarios describing what can be reasonably contemplated – rather than what will be. Probabilities of scenarios of future human actions are bound to be subjective and these probabilities should be termed "degrees of belief", to distinguish them from empirically determined frequencies. Using a range of scenarios and probabilities describing their relative likelihoods through degrees of belief is preferable to using a single scenario as a point estimate. It is important in risk and uncertainty analyses to portray, as well as possible, the range of possibilities. Considering a range of possibilities is also important in repository siting and design, and in the consideration of countermeasures.

Scenarios of future human actions have to be viewed as representations of potential realities based on sets of assumptions. Consequence analyses must therefore be considered as illustrations of potential impacts based on these sets of assumptions. These illustrations are for the benefit of decision makers (among others), in order that they have a broad knowledge of the disposal system and the risks associated with waste disposal.

An approach to quantitative assessment was sought that would avoid speculations about the future and that could be applied uniformly for various sites and systems. The Working Group considered that site- and system-specific scenarios could be based on the premise that the practices of future societies correspond to current practices at the repository location and at similar locations elsewhere. This premise could be adopted for drilling characteristics and frequencies, resource use, technological development, medical practice, demographics, and human lifestyles and nutritional requirements.

This premise is not meant to convey any information about the possible future evolution of society, but represents a practical choice on the treatment of societal development that allows illustrations of potential risks associated with future human actions to be made. This premise concerning societal development has been accepted de facto in most recent assessments. However, there is a need for further discussion of assessment principles – for example, concerning the effectiveness of passive institutional controls.

5.3 Countermeasures

The Working Group discussed methods to reduce the likelihood and to mitigate the consequences of future inadvertent human actions that might impair the effectiveness of the disposal system. The most effective countermeasure to inadvertent disruptive actions is active institutional control of the surface above and for some distance around the disposal site. This countermeasure forms one basis for the licensing of near-surface disposal facilities for low-level radioactive wastes. It could also be used for deep disposal facilities for as long as practicable to guard against inadvertent intrusion or other potentially disruptive human actions in the vicinity of the disposal site.

However, active institutional control cannot be relied upon over the timescales for which the waste presents a potential hazard (e.g., 10 half-lives of Pu-239 or other relevant radionuclide). Some national regulations allow credit for 100-500 years of active control subsequent to closure and decommissioning of the repository. Other possible countermeasures discussed by the Working Group included:

- Siting of repositories away from areas of currently recognised subsurface resource potential.
- Isolation of the waste from the human environment. For deep geologic repositories, the very depth of burial is an important feature mitigating against potentially disruptive human actions.
- Other criteria on the design of waste repositories (e.g., backfilling materials) and on the waste form itself (e.g., low tendency to form dust if exposed in open air) to mitigate the consequences of disruptive human activities.
- Conservation and communication of information about the location, contents and hazards of the repository can help reduce the likelihood of disruptive human actions.
- Durable physical marker systems placed at or near the site to help conserve information about the repository and warn potential intruders of the hazard.

- Physical barriers to deter attempted intrusion (e.g., a thick concrete cover above the disposed waste or a strong canister) may lower the probability of inadvertent intrusion.

Further discussion within each national programme is required of the means of determining an appropriate level of resource expenditure for the various possible countermeasures.

5.4 Further International Co-operation

The Working Group discussed international efforts that could contribute to building confidence in the assessments of the long-term safety of radioactive waste disposal systems. In particular, there are a number of actions that could be taken concerning assessments of future human actions that go beyond the scope of the Working Group's activities:

- *Further discussion between interested countries concerning regulatory policies for judging the risks associated with future human actions.* The treatment of future human actions has not yet been clearly defined in most national regulations. The Working Group considers that, on the basis of its report, a discussion could be promoted between interested countries as to how this issue could best be tackled. One possibility would be to judge the risks associated with future human actions in the same way as those associated with natural events and processes. At the other end of the spectrum, it might be considered that risks associated with future human actions should not play a role in the licensing of waste repositories. The issue is not purely technical, and any regulatory policy would need to be defended by means of philosophical and ethical argument.

- *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. One approach to developing scenarios discussed by the Working Group would base them on the use of current societal capabilities and practices in the vicinity of the disposal site and at similar locations elsewhere, in order to avoid speculations about future human endeavour.

- *Development of an internationally reviewed database of features, events and processes that could be considered in safety assessments.* This database would build upon the substantial work already accomplished at international level, and would help build confidence in the comprehensiveness of national site-specific assessment programmes. Human actions could form part of this database. An initial list has been compiled by the Working Group in Appendix B. Further compilation work at international level has already begun under the auspices of the NEA/PAAG.

- *Development of an international archive of radioactive waste repositories.* Conservation of information at different societal levels and locations can help ensure that administrative knowledge of the repository is not lost. One possibility would be to develop an archive at international level.

- *Development of marker systems.* A consistent approach toward marker systems would help society to retain awareness of their meaning, and to 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. This thinking underlies the use of marking for many hazardous artifacts in use today – for example those for radioactive materials and other toxic chemicals.

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APPENDIX A

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APPENDIX B

Scenario-Building Elements for Development of Future Human Action Scenarios

B.1 Introduction

The list of scenario-building elements compiled here are for postclosure scenarios involving surface or subsurface activities. Several scenarios sometimes considered to be human action scenarios have been omitted from this compilation. These include any deliberate attempts to retrieve the waste, and scenarios resulting from actions or failures during the siting, design, operation and closure of a repository. The former are considered outside the scope of intrusion scenarios requiring analysis; the latter are generally included in preclosure performance assessment studies or groundwater transport scenarios, and have not been considered by the Working Group.

B.2 Subsurface Activities

Drilling Activities

	Activity	References
B2.1.1	Water well drilling	B1-B12
B2.1.2	Exploratory drilling for natural resources	B1-B9, B11-B13
B2.1.3	Exploitation drilling for natural resources (including water)	B1-B2, B5, B7-B9, B11-B12
B2.1.4	Drilling (purpose unspecified)	B10, B14-B15
B2.1.5	Withdrawal wells	B14, B16
B2.1.6	Drilling for research or site characterisation studies	B3, B17
B2.1.7	Drilling for storage	B5

Mining and Other Excavation Activities

	Activity	References
B2.2.1	Resource mining (including solution mining)	B1-B3, B5-B6, B8, B11-B14
B2.2.2	Shaft construction	B7
B2.2.3	Excavation for storage or disposal (including solution mining)	B3, B5-B7, B12, B18, B22
B2.2.4	Excavation for military purposes	B5-B6
B2.2.5	Excavation for industry	B5
B2.2.6	Recovery of repository materials	B1, B4, B8, B11
B2.2.7	Scientific or archaeological investigation	B1-B3, B7-B8, B11, B17
B2.2.8	Subsurface sampling	B7
B2.2.9	Tunnelling	B1, B3, B5, B7-B8, B11
B2.2.10	Underground construction	B1
B2.2.11	Underground nuclear testing	B1, B8, B11-B12
B2.2.12	Malicious intrusion, sabotage or war	B1, B4-B5, B7-B9, B11-B12
B2.2.13	Geothermal energy production	B1-B2, B5, B7-B8, B11-B12
B2.2.14	Injection of liquid wastes and other fluids	B1-B3, B5-B6, B8, B11-B12, B14

B.3 Surface Activities

Although physical activities at the surface will not penetrate a repository, they can lead to human exposure if the activities occur on a surface that has become contaminated by waste either during a previous intrusion into the repository or by the normal groundwater transport pathway. In addition, exposure could arise at some later time if the surface activity disrupts or impairs the performance of the natural and/or engineered barriers systems.

Physical Activities

	Activity	References
B3.1.1	Dam construction	B2-B3, B5, B8, B11-B12, B14
B3.1.2	Dam reservoir drainage	B1, B8, B11
B3.1.3	Quarrying	B1, B8, B11
B3.1.4	River rechannelled	B1, B8, B11
B3.1.5	Trenching	B7
B3.1.6	Altered soil or surface water chemistry	B1, B8, B11
B3.1.7	Site improvement	B1, B8
B3.1.8	Changes in groundwater conditions, water table change	B1-B2, B4-B6, B8, B21
B3.1.9	Surface sampling	B7
B3.1.10	Excavation for construction	B1, B3, B8, B11
B3.1.11	Pile driving	B7
B3.1.12	Residential construction	B1, B7, B11
B3.1.13	Industrial construction	B1, B7, B11
		continued.....

Physical Activities (Cont.)

	Activity	References
B3.1.14	Construction for transportation	B7
B3.1.15	Agriculture/irrigation	B1-B2, B5-B7, B11-B12, B14, B21
B3.1.16	Aircraft crash into repository site	B7, B10
B3.1.17	Explosions	B3, B14-B15
B3.1.18	Road construction	B17
B3.1.19	Child playing outdoors	B17
B3.1.20	Examination of drill core	B17, B19
B3.1.21	Site occupation	B17
B3.1.22	Operation of a drilling rig	B17
B3.1.23	Ingestion of salt	B20, B21
B3.1.24	Working in a salt factory	B21
B3.1.25	Use of contaminated lake sediment as soil or in a building system	B23
B3.1.26	Burning of contaminated peat or biomass	B23
B3.1.27	Using contaminated wood for building material	B23

Social and Institutional Activities

	Activity	References
B3.2.1	Demographic change, urban development	B1, B8
B3.2.2	Changes in agriculture and fisheries practices	B1, B5
B3.2.3	Land use changes	B1, B3, B8, B10
B3.2.4	Loss of records	B1, B8, B11, B17
B3.2.5	Site survey	B7
B3.2.6	Environmental audit	B17, B19
B3.2.7	Loss of on-site barriers, markers	B17
B3.2.8	Loss of archives, land use data bases	B17
B3.2.9	Geophysical survey	B19
B3.2.10	Detection and recognition of radioactive waste fragments or repository	B17, B19
B3.2.11	Behind-the-bit gamma monitoring	B19
B3.2.12	Loss of societal memory	B9
B3.2.13	Interest in mining	B9
B3.2.14	Disposal of drilling waste in a landfill site	B19

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APPENDIX C

Summary of Past Human Action Assessments

C.1 Introduction

It should be noted that the summary presented here is not comprehensive. It does, however, touch upon many of the principal studies that have been conducted to date, and considers the main rock types under investigation. Further studies are summarised in [C1].

In addition, the focus of the summary is on outlining the principal scenarios that have been evaluated quantitatively, in an effort to provide an overview of the approaches taken. Detailed calculational models are not discussed, nor are results in the form of doses, intrusion frequencies or risks presented. The interested reader is referred to the references for further information, as well as to the catalogue compiled by the NEA [C2].

C.2 Repositories in Crystalline Rock

OECD Member countries having actively investigated the suitability of crystalline rock formations for the deep disposal of radioactive wastes in specially engineered repositories include Canada, Finland, France, Japan, Spain, Sweden, Switzerland, the United Kingdom, and the United States. Both Finland and Sweden already have deep repositories in operation for the disposal of low- and intermediate-level wastes (L/ILW). There are not yet any licensed repositories for high-level radioactive wastes (HLW). Human action studies undertaken by investigators in these countries are described below.

Canada

Canadian HLW disposal work is focused on the concept of repository development at 500-1000-m depth in igneous rocks of the Canadian Shield. Atomic Energy of Canada Limited (AECL) has evaluated doses arising from the use of water obtained from a well drilled into a fracture zone assumed to extend from the repository near-field to the surface [C3]. It was assumed that water withdrawn from the well could be used to satisfy both domestic water and garden irrigation requirements for a small community.

In addition, AECL's system model includes a variety of other human actions that could adversely impact the radioactive waste disposal system: the use of contaminated lake sediment as soil or a building material, the burning of contaminated peat or biomass for heat or land clearing, and the use of contaminated wood as a building material.

More recently, Canadian HLW performance assessment studies have considered exploratory drilling scenarios [C4]. Risks have been calculated for a geotechnical worker who examines contaminated drill core, and for a driller who spends a significant amount of time close to the drilling fluid discharge pond. External irradiation and dust inhalation are reported to be the two most important pathways for these individuals.

Risks have also been calculated for two scenarios arising from the dispersal of waste from previous drilling operations [C4]. These scenarios involved the exposure of a worker who constructs a building on contaminated land, and the exposure of residents who obtain a portion of their food requirements from the contaminated land.

An interesting feature of the Canadian work was the use of an event tree to determine the frequency with which the scenario was assumed to arise. Unlike the UK Nirex work (described below), experts were consulted to derive time-dependent nodal probabilities explicitly.

Finland

Finland (after Sweden) is only the second country to have a crystalline-rock deep repository for L/ILW in operation. It has been constructed by the Finnish Industrial Power Company (TVO) at the Olkiluoto nuclear site at depths of 50-125 m. The only intrusion scenario examined was the drilling of a water well into the radionuclide plume [C5].

Finnish workers have also examined the risk to a driller who handles a core from the direct penetration of a HLW canister disposed of at depths of depths of more than 500 m in crystalline rock. Both dose and frequency were evaluated.

France

Auriat in France was chosen to be the reference granite site for an international project sponsored by the Commission of the European Communities (CEC), known as PAGIS – Performance Assessment of Geological Isolation Systems. The objective of PAGIS was to evaluate the ability of various geological formations to confine vitrified HLW. The repository design consisted of waste canisters stacked in vertical boreholes drilled from horizontal galleries that were excavated at depths of 500-1000 m.

The intrusion scenario examined involved the construction of a 106-m3 mine cavern, 50 m from the repository [C6]. A direct breach of the repository was not considered. The mine was assumed to be pumped for a 50-year period, causing an altered groundwater flow and enhanced radionuclide flux to the biosphere. Doses to mine workers from external irradiation and dust inhalation were calculated, as were doses to the public resulting from (i) consumption of milk from cattle watered with contaminated mine water, and (ii) consumption of vegetables grown in an area where 10% of the soil comes from mine spoil. The probability of mine construction was not considered.

Sweden

The Swedish Radioactive Waste Management Company (SKB) has been evaluating the performance of repositories for both high-level waste (HLW) and low- and intermediate-level wastes (L/ILW) since 1977 [C7]. The Swedish Final Repository (SFR) for L/ILW has been in operation since 1988. The SFR is located at 60-m depth in granite bedrock below the Baltic sea, and is accessed from a tunnel extending from the Forsmark nuclear site.

The drilling of a water well into the radionuclide plume has been considered in all of the Swedish studies. For the SFR, the consequences arising from the well penetrating various waste vaults was also studied [C8]. One reason for the choice of an offshore location for the SFR was to ensure that wells would not be drilled directly into the repository in the first thousand years.

Switzerland

The Gewähr Project, undertaken by the Swiss Co-operative for the Disposal of Radioactive Wastes (NAGRA), included a performance assessment for a generic HLW repository located at a depth of 500-1000 in the basement of northern Switzerland [C9]. Inadvertent drilling into the repository was considered implausible on the basis that the actual repository site would be selected to avoid areas of known resources. Deep drilling for water supplies was also excluded, in this case on the basis of the relatively low yield of water available at depth. The only scenario for which doses were calculated involved the drilling of a drinking water well into an aquifer overlying the repository horizon.

United Kingdom

Current work by the implementing agency, U.K. Nirex Limited, is focused on investigating the suitability of the deep geology below the Sellafield site in Cumbria for the disposal of L/ILW. Human intrusion studies were undertaken as part of the site-selection process. These studies centred on evaluating the risk to geotechnical workers who examine core material taken during exploratory drilling that directly penetrates the waste, as well as risk to inhabitants of land contaminated by the disposal of waste extracted during previous exploratory drilling [C10, C11]. In examining scenario probability, an event tree was used to represent the various factors which could mitigate the frequency with which the worst radiation exposures took place. The nodal "probabilities" proved difficult to derive, and so conservative upper-bound values were taken for many of the "probabilities'. Even when the upper-bound approach is taken, it was noted that a benefit occurs from deriving the event tree because it helps to illustrate the conservatism included in the analysis. Drilling frequency versus depth for a U.K. hard-rock area is presented in [C10].

As part of a study by the regulator, the U.K. Department of the Environment (DoE), of the best practicable options for disposal of L/ILW, doses and risks associated with exploratory drilling that penetrates a deep repository were calculated [C12]. The calculations were not aimed specifically at a repository located in crystalline rock, although drilling frequencies appropriate to such rock were used in the study. The scenario considered involved exposure of a geotechnical worker who examined contaminated core material. The doses received from external irradiation, dust inhalation and ingestion were evaluated.

C.3 Repositories in Salt Formations

OECD Member countries having actively investigated the suitability of bedded salt or domal salt formations for the deep disposal of radioactive wastes include France, Germany, the Netherlands, Spain, and the United States. Human action studies undertaken by investigators in these countries are described below.

It should be noted that salt repositories were also examined as part of the CEC's PAGIS Project. [C13]. Disposal in salt domes in Germany and bedded salt in France were considered. Subsequent CEC studies have considered the disposal of alpha-contaminated and ILW in German salt domes [C14] and the disposal of L/ILW in various types of salt deposit in the Netherlands [C15].

France

French studies have considered a scenario involving the consumption of contaminated salt extracted by solution mining that intersects a HLW or a cemented ILW (alpha-waste) repository located in a bedded salt formation [C16]. The doses resulting from the consumption of 6 g of salt per day were evaluated, assuming mining occurred either 500 or 2500 years after repository closure. The likelihood of the scenario was not discussed.

Germany

In the German studies [C14, C17], the main intrusion scenario involved solution mining of a storage cavern 1000 years after repository closure. The mining operation was assumed to expose one half of the contents of a single waste panel, which were assumed to fall into the cavern sump. After 50 years of use for storage purposes, the cavern was assumed to be filled with water and sealed. However, the process of salt convergence was expected to generate sufficient pressure to fail the cavern seal, leading to slow expulsion of the contaminated waters to overlying aquifers used for drinking water. Annual dose rates for a range of radionuclides were presented, but intrusion frequency was not discussed.

Netherlands

In the Netherlands, a research project known as OPLA has been reviewing a range of options for HLW disposal in salt, including bedded salt, salt domes and salt pillows. Four intrusion scenarios have been examined [C15, C18]:

- Exploratory drilling. Both the dose and risk to a laboratory worker who examines a 1-m-long section of contaminated core were evaluated.
- Solution mining. Doses received by salt factory workers who inhale salt dust generated during the evaporation process were evaluated, as were doses arising from salt consumption.
- Leaking storage cavern. This was the same as the intrusion scenario in the German study.
- Conventional mining. It was assumed that a conventional mine gallery was excavated immediately adjacent to the repository, with a thickness of only 0.5 m of salt concealing the presence of the repository. The external irradiation dose to mine workers who passed by this point was evaluated.

The likelihoods of the latter three scenarios were not discussed.

United States

A considerable number of studies involving the examination of intrusion scenarios have been performed in the U.S. for both HLW and L/ILW repositories located within salt formations. An early study considered doses received as a result of consuming salt obtained by solution mining through a HLW repository [C19]. The mine was assumed to consist of a series of 12 wells, with 3-4 pumping at any time. The mine was assumed to operate for 50 years, during which period 2-5% of the repository volume was considered to fall into the sump. A comprehensive set of dose results was presented, but frequency (and hence risk) was not discussed.

In the 1980's, the Salt Repository Project was established by the U.S. Department of Energy (DOE), with the aim of considering the feasibility of locating a HLW repository within a salt formation [C20]. Both bedded salt and domal salt formations were studied prior to termination of the Project in mid-1988. Intrusion scenarios examined involved the migration of radionuclides along a borehole that connected the repository to an overlying aquifer or to both an overlying and an underlying aquifer.

The Waste Isolation Pilot Plant (WIPP) is a research and development facility which may become the first mined geologic repository for transuranic (alpha-bearing ILW) waste for defense operations. The repository would be located at a depth of 650 m within a bedded salt formation. By 1989 Sandia National Laboratories (SNL), under contract to the DOE, had performed preliminary consequence calculations for a limited number of human action scenarios, all related to borehole drilling [C21]. All analyses were assumed to include one or more boreholes that passed into a waste panel or through a waste panel to intersect a pressurised brine pocket that underlies the repository. Calculations were made of the:

- External radiation dose received by a geologist who examines contaminated drill cuttings for one hour.
- Dose to a hypothetical farming family living 500-m downwind from the contaminated drilling fluid left at the end of the drilling operations.
- Dose received by an individual who consumes beef contaminated as a result of the stock being watered from a well drilled into a nearby aquifer. Contamination of the aquifer was considered to occur by flow of brine up the borehole that connected the pressurised brine pocket, the repository and the aquifer.
- Cumulative release of radionuclides over 10,000 years to an "accessible environment" defined by the U.S. Environmental Protection Agency

The preliminary performance assessment calculations indicated that human intrusion was likely to be the most significant mechanism for release of radionuclides to the accessible environment at the WIPP site. This finding has led to a major new programme of work centred on the use of expert elicitation to identify potential modes of intrusion, to derive estimates of the frequencies with which these modes might arise, and to develop criteria for the construction of barriers and markers to deter future intrusion [C21].

C.4 Repositories in Argillaceous Formations

There are several OECD Member countries actively investigating the suitability of argillaceous formations for the deep disposal of radioactive wastes. However, the Belgian programme has been leading the effort to produce quantitative evaluations of human action scenarios. Other countries having investigated argillaceous rock include Canada, France, Japan, Spain, Switzerland, and the United Kingdom.

Belgium

The Mol nuclear site in Belgium was chosen as the reference for the PAGIS clay disposal option. The repository was assumed to consist of horizontal galleries located at 200-m depth in a 100 m thick layer of clay. The clay layer is sandwiched between two aquifers, the upper of which is suitable for use as a drinking water supply. The intrusion scenario examined involved inadvertent drilling of a water-extraction well into a radionuclide plume located in the upper aquifer [C23]. Both direct intake of well water and the consumption of animal and vegetable produce watered by the well were considered in the analysis.

Since completion of the PAGIS work, a re-evaluation of the features, events and processes of potential importance for the deep disposal of radioactive wastes at the Mol site has been completed by the Belgian Nuclear Energy Research Foundation (SCK/CEN) [C24]. This work has lead to the identification of a range of human actions and effects which will be taken into account in future Belgian performance assessments.

United Kingdom

As a variant site for the PAGIS clay option, a repository located at 275-m depth in Oxford Clay below the Harwell site in the U.K. was examined [C23]. Again the only intrusion scenario considered was use of water from a well drilled into an overlying aquifer.

C.5 Repositories in Tuff Formations

United States

The United States is currently the only country considering a tuff host-rock disposal formation. The U.S. Department of Energy (DOE) is evaluating the suitability of an unsaturated tuff formation at Yucca Mountain (Nevada) for the disposal of HLW. An analysis of two drilling scenarios has been recently completed [C25]. The first scenario involved direct transfer of waste to the surface environment via contamination of drilling fluids. Both direct penetration of waste containers and "near-misses", in which the contaminated area around a waste container is intersected by the borehole, were considered. The second scenario involved the transfer of waste downwards through the borehole to the saturated zone, and the subsequent transport of radionuclides by groundwater in this zone. The probability of human intrusion at the site during the next 10,000 years was assigned a probability of one.

A companion study addressed the same scenarios but considered both HLW and spent-fuel containers [C26]. In general, consequences for intrusions into the HLW containers were about an order of magnitude lower than in comparable spent-fuel cases. Differing aquifer properties were assumed and were found to be important to cumulative releases to the accessible environment.

C.6 Repositories in Unconsolidated Sediments

United States

The Greater Confinement Disposal (GCD) Facility consists of 13 boreholes augured into basin-fill sediments in Area 5 of the Nevada Test Site. These boreholes are approximately 3 m in diameter and 37-m deep. Waste is disposed in the lower 17 m of the boreholes. Four of the boreholes contain transuranic waste, five contain LLW, and four are still empty. All but two of the boreholes containing waste have been backfilled with sedimentary material.

A preliminary performance assessment [C27] included analyses of exploratory drilling into a borehole containing TRU waste. A calculation was made of the quantity of radionuclides brought to the surface in circulating drilling fluid.

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