UK REGULATIONS AND THE SAFETY ASSESSMENT OF RADIOACTIVE WASTE REPOSITORIES

D.E.Billington, D.A.Lever and S.J.Wisbey
Theoretical Physics Division
AEA Technology
Harwell Laboratory
Oxfordshire, United Kingdom

ABSTRACT

The nuclear industry in the UK has high standards in placing safety requirements as a first priority. Nevertheless, a regulatory framework is in place to provide an independent and overriding mechanism to ensure that high standards are set and achieved.

In considering the safety of a proposed repository, it is necessary to carry out as comprehensive an assessment as possible, to focus on the important issues, and to demonstrate that predictions are consistent with experimental results and natural evidence. In the UK, this task is being undertaken for UK Nirex Ltd. by the Disposal Safety Assessment Team in close collaboration with the extensive research programme, centered on the Harwell Laboratory of AEA Technology, and with a programme of site characterization currently under way.

In funding these extensive programmes of safety studies, UK Nirex Ltd. is following the established scientific approach and building on experience gained worldwide in the area of radioactive waste disposal. Nevertheless, in view of the geological time-scales involved in the containment of these wastes, it is essential to recognize the limitations inherent in the scientific approach and to present all the issues clearly to the regulators and the public.

The numerical target on individual risk imposed by the UK authorizing Departments must be viewed in this context. It represents a 'bottom line', which must be addressed in as much detail as possible, but constitutes only one important aspect of the required safety case. Indeed, the authorizing Departments have called for further information, for example on fieldwork and data collection.

In addition, there is a requirement that future movement of radioactivity from a facility should not lead to a significant increase in the radioactivity naturally occurring in the general vicinity of the facility. This demands a comparison with natural radioactivity and provides a useful context for judging the acceptability of a proposed development.

In carrying out assessments, it is important to remember that it is impracticable to predict the future in every detail, nor could such detail be confirmed or contradicted if the attempt were made. Rather, it is necessary to judge what degree of detail in the modelling is both justified and sufficient for the demonstration of adequate safety. This judgment will determine both the scope of the supporting research and the factual basis for the safety argument.

INTRODUCTION

UK Nirex Ltd. is charged with the responsibility to develop a suitable disposal facility for the ultimate disposal of intermediate- and low-level solid radioactive waste (ILW and LLW). Over the past few years, Nirex have been evaluating the relative merits of a number of concepts for the deep disposal of such wastes. A number of geological environments have been considered and compared (1, 2):

- low-relief hard rock ;
- small island;
- seaward-dipping sediments ;
- hard basement rock under a sedimentary cover;
- Sellafield;
- an offshore repository in sedimentary rock beneath shallow water;
- an offshore repository in hard rock beneath deep or shallow water.

For most of these, either inland or coastal locations could be envisaged. For coastal sites, the repository could be constructed either under the land or under the sea bed, accessed by tunnels from a land base.

The Nirex work is focused on the deep geological disposal of the wastes. The decision process leading to the selection of a site is guided by work in a number of technical areas. For example, consideration must be given to costs, planning and environmental issues, and safety during construction, operation, transport and after closure of the repository. Following an initial selection exercise, Nirex is currently evaluating Dounreay and Sellafield to see if either, or both, are suitable for the construction of a repository, or whether other locations should be similarly evaluated (2).

The Disposal Safety Assessment Team (DSAT) was formed within AEA Technology to conduct assessments of post-closure radiological safety. The work of the team is carried out as a collaboration between AEA Technology and other technical organizations, according to the availability of expertise. The assessments are supported by a major programme of research and development, centered on Harwell Laboratory.

In this paper we review the regulations against which the post-closure safety case for the proposed development will be judged and consider, from the point of view of the developer, how these may be met in the context of the inevitable uncertainties that surround the performance of natural and man-made systems over geological time-scales.

REGULATORY REQUIREMENTS IN THE UK

The operations of Nirex will be subject to the legal requirements that are applicable to comparable operations in any other industrial concern in the UK. Thus the requirements of the Town and Country Planning Acts must be met. Application for planning permission, to develop a site by constructing a disposal facility, will have to be made to the local planning authority within whose boundaries the site is situated. The initial action of the planning authorities on receiving an application will be to carry out the normal consultations. It is the intention of the Secretary of State for the Environment to call in any application for his own determination and there would then be a Public Inquiry.

The UK bodies concerned with the regulation and authorization of facilities handling radioactive materials are the Health and Safety Executive (HSE), of which the Nuclear Installations Inspectorate (NII) form a part, and the Authorizing Departments of England, Scotland, Wales and Northern Ireland. In England, the authorizing Department is the Department of the Environment, acting jointly with the Ministry of Agriculture, Fisheries and Food. The Scottish Office, the Welsh Office, and the Department of the Environment for Northern Ireland are the authorizing Departments in their respective countries.

The main radiological regulatory requirements in the selection, design, construction and operation of a waste repository arise from:

- The Ionizing Radiations Regulations 1985 (3), which are made under the Health and Safety at Work etc Act 1974 (4). Under this Act, the HSE has responsibility for securing the health, safety and welfare of persons at work and for protecting others against risks to health or safety in connection with the activities of persons at work;
- The Nuclear Installations Act 1965 (5), as amended, under which a repository will require a nuclear site licence from the NII;
- The Radioactive Substances Act 1960 (6), under which disposals to and at a repository will require appropriate certificates of authorization from the Departments.

At a Public Inquiry under the Town and Country Planning Acts and Regulations (7,8) into the proposed use of a site for a disposal facility, the status of the proposals under the Radioactive Substances Act 1960 and the Nuclear Installations Act 1965 would be a material consideration. Prior to such an Inquiry, the authorizing Departments would give their provisional view on whether the proposed facility would be suitable for authorization. The NII would be expected to give to the Inquiry its provisional view on whether a licence could be issued.

Nevertheless, the jurisdictions under the Radioactive Substances Act 1960 and the Nuclear Installations Act 1965 would remain legally separate from decisions under the Town and Country Planning Acts and decisions on whether or not to grant an authorization or a licence would not be taken until later stages of the project.

The requirements for radiological protection can be considered in terms of three phases of the project:

- the pre-closure institutional management period;
- the post-closure institutional management period;
- the post-institutional management period (that is, the period during which no action will be taken to assure the safety of the repository, beyond those already in force in the general vicinity).

The first two phases are referred to as collectively the 'institutional management period'. The work of the DSAT is primarily concerned with the last two phases, which are customarily referred to as collectively 'post-closure'.

The NII will assess the design and operation of the facility under the Nuclear Installations Act, using its 'Safety Assessment Principles for Nuclear Chemical Plant', issued in 1983 (9). These considerations are relevant to the pre- and post-closure institutional management periods.

The authorizing Departments are concerned with the protection of the public in all three phases, jointly with the NII in the institutional management period. Their requirements of the developer of a proposed facility are presented in 'Disposal Facilities on Land for Low and Intermediate-level Radioactive Wastes: Principles for the Protection of the Human Environment', issued in 1984 by the UK authorizing Departments(10).

That document lays out a set of basic radiological requirements and other information requirements, together with a set of general principles against which the long-term radiological safety of a proposed facility will be judged; these are the guidelines against which the DSAT carries out its work. In the next Section we present our interpretation of the requirements of the authorizing Departments, set out in terms of a set of information requirements and a set of formal measures of the impact of the proposed repository on Man's environment.

AN INTERPRETATION OF THE REQUIREMENTS OF THE UK AUTHORIZING DEPARTMENTS

The items discussed in this Section do not represent a comprehensive description of the requirements of the authorizing Departments. Rather, they constitute the set of requirements set out in Ref. 7 that is relevant to the work of the DSAT.

The authorizing Departments set out a number of information requirements, including:

I1:provide an analysis of the contribution to radionuclide containment made by each barrier in the system;

I2:provide the results from the application of mathematical models used to predict radiological impacts;

I3:provide comprehensive radiological assessments to enable the authorizing Departments to make their own assessment;

I4:explain how the basic radiological requirements and general principles are met;

I5:although the developer will not be expected to show that his proposals represent the best choice from all conceivably possible sites, he must show that he has not ignored a clearly better option for limiting radiological risks.

Further to the above information requirements, seven required formal measures relevant to the work of the DSAT can be identified:

M1:individual and collective doses to be ALARA, economic and social factors being taken into account;

M2:use the best practicable means to ensure that, during the institutional and post-institutional management periods, any radioactivity coming from a facility is ALARP. The effect of this will be to ensure that exposures are ALARA;

M3:in the institutional management period, the average individual effective dose equivalent from all sources must not exceed the limit of 5mSv, although it must be remembered that since the principles were published, the emphasis in radiological protection has shifted to a 1mSv limit on annual individual dose;

M4:the appropriate target applicable to a single repository at any time is a risk to an individual in a year equivalent to that associated with a dose of 0.1mSv (about one chance in a million);

M5:future movement of radioactivity from a facility should not lead to a significant increase in the radioactivity naturally occurring in the general vicinity of the facility;

M6:a site must be selected where it is unlikely that future development of natural resources, or of the site, will disturb the facility;

M7:provide an analysis of the probability that the facility might be disrupted by discrete external events.

The authorizing Departments specify that after the institutional management period, the proper objective to apply is one based, not on dose, but on risk to the individual. Furthermore, they state that the risk may be defined as the probability that a given dose will be received multiplied by the probability that such a dose will result in a fatal cancer. The risk computed in this way will be considered against the target, which is a risk corresponding to an annual dose of 0.1mSv (M4).

Thus measure M4 above has tended to be regarded as the 'bottom line' and, since it is based on risk to the individual, it implies that human dosimetry and the transport of radionuclides through a future biosphere must be treated. However, it can be seen from the above that the requirements of the authorizing Departments represent far more than a bottom line approach; indeed, taken together, the requirements are comprehensive and open-ended. This is particularly true of requirements I1 to I4.

This is in accord with the traditional approach in the UK, in which the onus is placed on the developer to address safety in a responsible and comprehensive way. A safety case has to be constructed against the general guidelines provided in the principles and that safety case will be subjected to an exhaustive examination during which the authorizing Departments may call for additional information or further safety analysis. The emphasis on ALARA (M1 and M2 above) is one example of how the Departments reserve the right to judge when enough has been done, without being overly prescriptive.

This approach can sometimes be uncomfortable for the safety analyst involved in the project, since the onus is on him to judge what is an adequate safety case. Nevertheless, this leads ideally to high motivation and a thorough approach that can go beyond what might be done in satisfying a more prescriptive set of regulations. Essentially, the requirement is to satisfy oneself that adequate safety has been assured, rather than that a set of regulations formulated in advance have been adequately met.

In the next Section we discuss the disposal system that UK Nirex are proposing, the safety of which must be demonstrated to the authorizing Departments and to the Inspector at any Public Inquiry.

THE PROPOSED DISPOSAL SYSTEM

The philosophy adopted by Nirex to the disposal of the radioactive wastes is first and foremost one of containment. To this end the proposed solution is that the waste should be enclosed in metal or concrete containers, placed in a cavern deep underground and surrounded by a cement-based backfill. As the repository would be deep underground, it would be well away from Man's environment (the biosphere).

Thus there are a number of barriers between the radioactive waste and Man. These are provided by the materials of the repository and the rock between the repository and the biosphere. Finally, once radionuclides enter the biosphere, they have to be transported through it before they reach Man. The biosphere has a capacity to dilute, which generally acts to reduce the concentrations of radionuclides and thus the computed dose.

There are a number of pathways whereby the radionuclides can return to the biosphere, and the first task in an assessment is to identify them. Work on Scenario Development is currently in hand to identify such pathways and ensure that the assessments are as comprehensive as possible. At present the following four have been considered in some detail:

- transport in groundwater;
- natural disruptive events;
- release of radioactive gases; and
- human intrusion into the repository.

Different barriers are effective for different pathways. For the groundwater pathway, the first barrier is the physical containment provided by the metal containers and the cement-based repository materials. These will provide a resistance to groundwater flow and the advection and diffusion of radionuclides, limiting the flux of radionuclides leaving the repository.

Next, there is the containment provided by the chemical environment in the repository. The corrosion of the canisters will impose a low Eh, and the cement a high pH, on the porewater in the repository. This environment will limit the solubility of many radionuclides. Sorption onto the materials within the repository will also reduce concentrations in solution of many radionuclides.

The rock around the repository will provide an important barrier; this is particularly true for the deep geological environments under consideration. For a suitable geological environment, it is expected that the groundwater fluxes will be low in the vicinity of the repository and the groundwater return times from the repository to the biosphere will be long. The transport of many radionuclides through the geosphere will be further retarded because of sorption to the geological materials.

A deep repository will be well isolated from natural disruptive events on the surface; the geological barrier is expected to play a key role. The only natural event identified that might potentially transfer bulk quantities of materials back to the surface is the impact of a large meteoroid. The assessed frequency is 10^{-11} per year or less and so the associated risk is judged to be negligible (M7).

The chemical environment in the repository will limit the rate at which gases such as hydrogen, methane and carbon dioxide are generated. The materials in the repository can also be chosen to control the way the gas leaves the repository, and the type of rock may also be important in controlling the way it returns to the biosphere. Finally, the small content of radioactive gas will mix with air at the surface, further diluting the concentration of radionuclides and therefore limiting the *potential exposure* of individuals.

The choice of a deep geological environment is also important in reducing the importance of human intrusion. Such a repository will not be prone to being disturbed by the excavation of foundations as could a shallow repository. Furthermore, in an appropriately chosen geological environment, the probability of disturbance by a deep drill hole as part of an exploration for natural resources is very low (M6).

WHAT IS THE PROBLEM?

No barrier is perfect; different barriers play different roles at different times for the different pathways. It is one of the jobs of the assessment team to consider the role and performance of the various barriers and, indeed, this is necessary to meet requirement I1 of the authorizing Departments.

For the groundwater pathway, the physical containment provided by the repository materials is of relatively short duration. The metal containers are expected to have small vents to let gas out, and over time are expected to corrode away. Eventually the materials that control the chemical environment will be leached from the repository and so, for example, the pH will fall. Although an environment may be chosen that has a low groundwater flux and long groundwater return time, nevertheless radionuclides are expected to be gradually leached out of the repository and to be transported back to the biosphere. Even if a site is chosen to be far away from potential resources, there is still a small probability that an intrusion will occur, leading to the return of a limited amount of radioactive material to the biosphere.

Therefore computations have to be undertaken to examine the implications of such potential pathways for the return of radionuclides to the biosphere. These computations are the responsibility of the DSAT, utilizing the results obtained from the Nirex Safety Assessment Research Programme (NSARP) and from the programme of geological characterization.

The assessment process is carried out in two complementary phases. First, deterministic models are used to represent processes in considerable detail. These computations are carried out with best estimates of the values of data, and in addition sensitivity studies are undertaken to examine the implications of uncertainties that exist in many of the data. 'What if?' computations are also undertaken in which hypothetical assumptions are made to explore the robustness of the assessment against gross deviations of the system from expected behavior.

In the second phase of computation, the effects of data uncertainty are examined using a probabilistic approach. A large number of simulations are undertaken, in which parameter values are selected from probability distribution functions. In this way, a more comprehensive survey of the implications of data uncertainty can be achieved. However, it is not practicable to undertake these computations to the same level of detail as in the deterministic computations. Rather than modelling processes, it is important to model the behavior predicted in the deterministic analysis.

Confidence in the overall approach is built up by iterating between the deterministic and probabilistic phases. The probabilistic computations will allow a realistic comparison of repository performance with the regulatory risk target.

An important area of data acquisition is to characterize the geological context of the repository and to determine as far as possible the hydrogeological parameters needed to carry out computations of groundwater flow and groundwater flux through the repository. There will always be a degree of uncertainty in such data and the assessments must reflect the effect of such uncertainty on the estimated risk. This is done through the probabilistic approach discussed above.

Some idea of the results of the probabilistic assessment can be gained by reference to Fig.1, which presents results obtained for the low-relief hard rock concept, using uncertainty ranges appropriate to a limited degree of geological characterization .

This Figure shows the variation of the expected risk with time. At any particular time, the expectation value of risk is obtained as an average over a probabilistic distribution of risk, which is illustrated in Fig. 2 for the time of maximum risk in Fig.1. Clearly, the possibility arises that, although the predicted risk may be below the target laid down by the authorizing Departments, there may be a finite probability that the risk could be above that target. The question arises as to how compliance with the target might then be judged.

In considering this question, it is useful to introduce the concept of Time-frames, which is the subject of the next Section.

TIME-FRAMES

Different pathways and processes are expected to be important at different times in the future. Thus it is helpful to focus the assessment in terms of a number of different Time-frames, based in part on Man's experience and partly on the expected natural evolution of the environment. These Time-frames are also useful as an aid to the interpretation and presentation of the results. The Time-frames considered at present are as follows:

0 - 3 10^2 years: Institutional control of the repository environment is envisaged over a substantial part of this period. The only changes in the climate potentially of im-

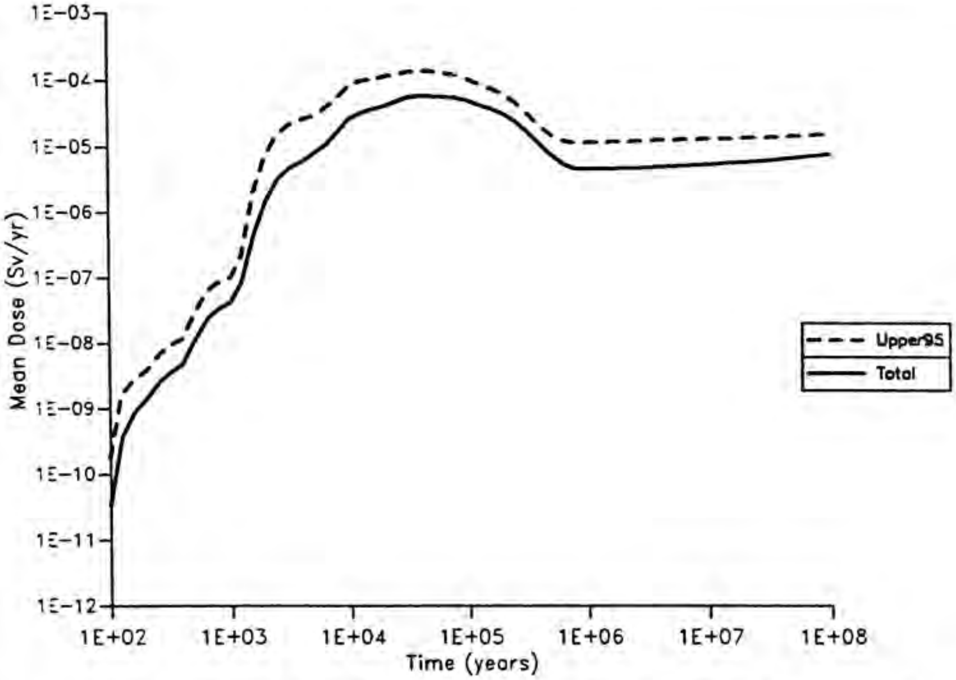

Fig. 1. Mean total dose and upper 95% cofidence limit for the release of radionuclides from a repository in low relief hard rock into postulated arctic conditions.

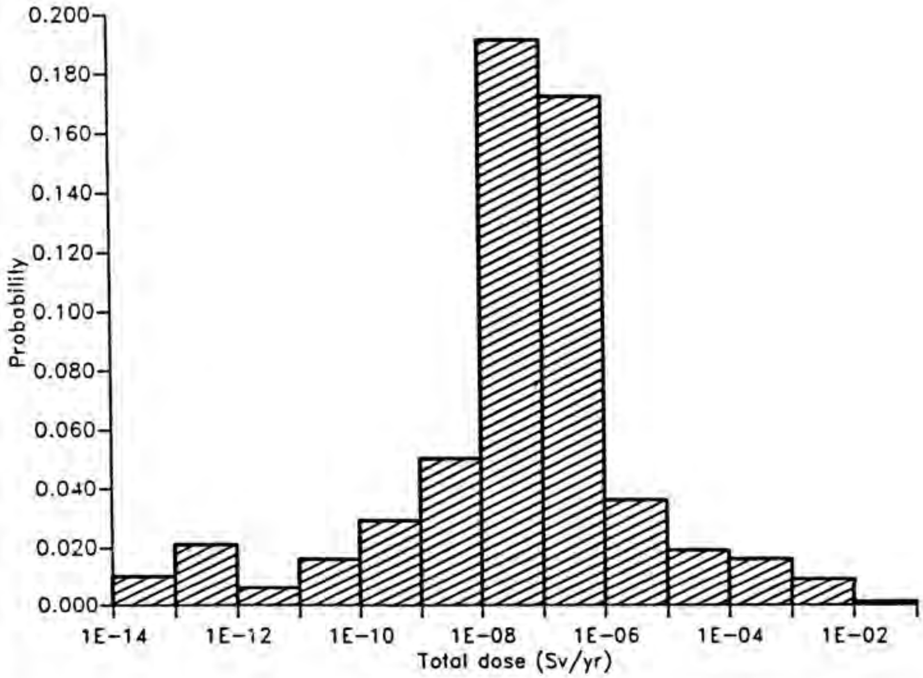

Fig. 2. Histogram of distribution of total dose at 4 10^4 years for the release of radionuclides from a repository in low relief hard rock into postulated arctic conditions.

portance are those that may arise from the 'greenhouse gas' effect.

3 10^2 - 10^4 years: The current temperate interglacial conditions are expected to persist for most of this Time-frame. Institutional controls are assumed to have lapsed.

10^4 - 10^6 years: Unless the 'greenhouse gas' effect leads to a radical change in the climate system, glacial/interglacial cycling is expected over this Time-frame. The sea level would fall by up to 140m during glacial periods, and glacial or periglacial conditions would occur in Britain for a substantial proportion of the time.

10^6 - 10^8 years: Although general tectonic stability should be preserved regionally, global plate movements will change the boundary conditions of the climate system and it may revert to greater stability over part of the final Time-frame. Limited tectonic changes could occur over much of the Time-frame and beyond 10^8 years gross tectonic changes provide a physical argument for a time cutoff.

Consideration of these Time-frames suggests that it is reasonable to develop a very detailed assessment up to 10^4 years, since to that time the climate is expected to remain broadly similar to that existing at present. Furthermore, the evolution of the hydrogeological context of the repository can be addressed with some confidence. Between 10^4 and 10^6 years, predictions can be made, albeit with greater uncertainty. Beyond 10^6 years, arguments become speculative. The nature of the uncertainties in the more distant Time-frames is such that lesser detail can be expected.

HOW MAY ACCEPTABILITY BE JUDGED?

The nuclear industry in the UK has high standards in placing safety requirements as a first priority. Nevertheless, as discussed earlier, a regulatory framework is in place to provide an independent and overriding mechanism to ensure that high standards are set and achieved.

The requirements of the authorizing Departments have been shown to encompass five information requirements and seven formal measures of safety. These requirements will all have to be addressed in the safety case, but it is essential to provide a context in which the acceptability of the response on each can be judged.

Requirement M5 provides the opportunity for such a context, as can be demonstrated by considering it alongside the requirement to address safety against the regulatory risk target (M4). Thus the authorizing Departments have set out a quantitative risk target and a qualitative requirement that entails a comparison with naturally occurring radioactivity.

The risk target is provided as one criterion against which acceptability may be judged. The authorizing Departments do not specify the nature of the required analysis, nor the degree to which it must be quantitative at any particular time; it is for the developer to justify the approach adopted. Nevertheless, for any time at which an estimate of risk is produced, acceptability can be judged by reference to the target.

The intention behind the principles is to protect future generations as we do ourselves and the numerical value of the risk target is set at an extremely low level. Nevertheless, in considering the results of assessments against the target, it is proper to present, in future time periods, full quantitative detail only for as long as it is reasonably justifiable. On longer time-scales, more reliance should be placed on qualitative arguments.

The qualitative principle laid down by the authorizing Departments falls naturally into this scheme of things. It must be addressed in parallel with the risk target and more weight can be placed on it for the longer time-scales. Since the quantitative results of the risk assessment need to be considered in the light of increasing uncertainties at longer time-scales, the uncertainties inherent in the assessment of the risks from naturally occurring radioactivity provide a helpful context.

The question then arises as to whether a time exists beyond which it is appropriate to rely wholly on qualitative arguments and to stop the computation of risk as a function of time. This might be possible if, taking account of the uncertainties in the quantitative approach, it is judged that there is no substantial increase in risk beyond that assessed for earlier times. One corollary of this would be that the results of the quantitative analysis at earlier times would be taken into account in repository design, whereas the qualitative arguments used for later times might not.

There is some precedent for this in reactor safety analysis, in which the consequences of the more frequent Design Basis Accidents are addressed in detail to show that, if they were to occur, in practical terms they would not matter to the Public; consideration of such possible accidents may lead to the introduction of mitigating design features. The frequencies of Degraded Core Accidents are considered, to provide assurance that, in practical terms, they will not occur. Attention is paid to demonstrating that there is no substantial increase in risk, just beyond the boundary of the design basis.

In some countries, the regulations imposed for repository safety have incorporated a cutoff at 10^4 years on the assessment period. The above line of reasoning suggests that this is inappropriate since, if the containment systems operate as expected, the return of radionuclides to the biosphere will commence at longer times. Indeed, it is notable that where regulatory criteria are based on 10^4 years, safety analysts have seen the need to present quantitative results at longer times (see for example Ref. 11). The argument is even stronger for disposal concepts with a marine receptor in the present temperate climate, because of the transition to a terrestrial receptor during the modified climates in glacial cycling. This is particularly relevant to the disposal concepts in the UK.

Thus it is necessary to address radiological safety beyond 10^4 years in a degree of quantitative detail, although that degree needs to be judged in the light of the greater uncertainties. Beyond 10^6 years, it may be possible in the UK context to rely on qualitative arguments to suggest that (for example) the expected tectonic changes will not lead to a further substantial increase in risk from the repository.

CONCLUDING DISCUSSION

In considering the safety of the proposed repository, it will be necessary to carry out as comprehensive an assessment as possible, to focus on the important issues, and to demonstrate that predictions are consistent with experimental results and natural evidence. This task is being undertaken by the assessment team in close collaboration with the extensive research programme, centered on the Harwell Laboratory of AEA Technology, and with the programme of site characterization currently under way.

In funding these extensive programmes of safety studies, UK Nirex Ltd. is following the established scientific approach and building on experience gained worldwide in the area of radioactive waste disposal. Nevertheless, in view of the geological time-scales involved in the containment of these wastes, it is essential to recognize the limitations inherent in the scientific approach and to present all the issues clearly to the regulators and the public.

The numerical target on individual risk imposed by the UK authorizing Departments must be viewed in this context. It represents a 'bottom line', which must be addressed in as much detail as possible, but constitutes only one important aspect of the required safety case. Indeed, the authorizing Departments have called for further information, for example on fieldwork and data collection, but it will be for the developer to decide what is required for presentation to the Inspector at any Public Inquiry.

In making these judgments, it is important to remember that it is impracticable to predict the future in every detail, nor could such detail be confirmed or contradicted if the attempt were made. Rather, it is necessary to judge what degree of quantification in the modelling is both justified and sufficient for the demonstration of adequate safety. This judgment will determine both the scope of the supporting research and the factual basis for the safety argument.

The authorizing Departments in the UK have imposed a requirement that future movement of radioactivity from a facility should not lead to a significant increase in the radioactivity naturally occurring in the general vicinity of the facility. This demands a comparison with *natural* radioactivity and provides a useful context for judging the acceptability of a proposed development.

ACKNOWLEDGMENT

The work of the DSAT is funded by UK Nirex Ltd. The views expressed are those of the authors and do not represent the policy of UK Nirex Ltd.

REFERENCES

1. Billington D.E., Lever D.A. and Wisbey S.J., Radiological Assessment of Deep Geological Disposal: Work for UK Nirex Ltd., Proc. Int. Symp. on the Safety Assessment of Radioactive Waste Repositories, OECD, Paris 1989.
2. Deep Repository Project: Preliminary Environmental & Radiological Assessment and Preliminary Safety Report, Nirex Report No.71.
3. The Ionizing Radiations Regulations 1985. S.I. No. 1333, HMSO.
4. Health and Safety at Work etc. Act 1974. Chapter 37, HMSO.
5. Nuclear Installations Act 1965. Chapter 57, HMSO.
6. Radioactive Substances Act 1960. 8 & 9 ELIZ.2, Chapter 34, HMSO.
7. Town and Country Planning Act 1971, HMSO.
8. Town and Country Planning (Assessment of Environmental Effects) Regulations 1988, HMSO.
9. Safety Assessment Principles for Nuclear Chemical Plant.HM Nuclear Installations Inspectorate, October 1983.
10. Disposal facilities on land for Low and Intermediate-Level Radioactive Wastes: Principles for the Protection of the Human Environment. HMSO, 1984.
11. Doctor P.G. et al, Some Results from the Preliminary Risk Assessment for the Yucca Mountain, Nevada Candidate High-level Radioactive Waste Repository, Proc. Int. Symp. on the Safety Assessment of Radioactive Waste Repositories, OECD, Paris 1989.