Radiological Protection Objectives for the Land-based Disposal of Solid Radioactive Wastes

Advice from the Health Protection Agency

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Abstract

The Health Protection Agency has revised its advice on solid radioactive waste disposal which is described in this document. The new advice replaces that published in 1992 by the National Radiological Protection Board (now part of the Health Protection Agency). There are two main reasons for revising the advice. First, the previous advice was based on recommendations from the International Commission on Radiological Protection which have recently been updated. Second, there have been a number of recent policy reviews by the UK Government and others looking at the options for radioactive waste disposal.

The advice is intended for the detailed risk assessment of solid radioactive waste disposal facilities at the planning stage. Given the long half-lives of some radionuclides, an important principle behind the proposed advice is that people in the future should be afforded the same level of protection as people have today. The primary focus is therefore on the situation after a facility has closed rather than the operational period when it is receiving waste for disposal.

The key advice topics include:

a criteria and methods for assessing the radiation risks from processes and events that could affect the waste disposal facility in the future,

b criteria for assessing the doses to people inadvertently intruding into the facility far in the future. Different approaches are specified for inadvertent intrusion into near-surface disposal facilities, compared to those used to assess inadvertent intrusion into geological disposal facilities.

This paper from the Health Protection Agency reflects understanding and evaluation of the current scientific evidence as presented and referenced in this document.

Executive Summary

Scope

The Health Protection Agency (HPA) is responsible for advising government departments on radiological protection criteria to be applied to the disposal of all types of solid radioactive waste, including wastes arising in gaseous or liquid form which will be converted to solid form prior to disposal. Previous advice was issued in 1992 by the National Radiological Protection Board (now part of the HPA). This advice was reviewed and revised for two main reasons. First, the previous advice was based on recommendations from the International Commission on Radiological Protection (ICRP) which have recently been updated (ICRP, 2007). Second, there have been a number of recent policy reviews by the UK Government and others looking at the options for radioactive waste disposal.

The advice is intended to be applied at the planning stages of a disposal facility. If the disposal facility already exists then the advice is intended to apply at the planning stages of any future disposals there.

The advice is intended to apply to all types of disposal facilities for solid radioactive waste management, ranging from purpose-built facilities near surface and deep underground to existing landfill sites that accept small quantities of low level or very low level waste. Disposal of waste in accordance with an Exemption Order made under the Radioactive Substances Act (GB Parliament, 1993) is not included in the scope of the advice.

Protection of the public

The main recommendations made by the HPA for the protection of the public following the disposal of solid radioactive wastes are as follows.

a Individuals and populations who might be alive at any time in the future should be accorded a level of protection at least equivalent to that which is accorded to individuals and populations alive now.

b The radiological risks to workers and to individual members of the public should be as low as reasonably achievable, economic and social factors being taken into account (ALARA).

c For the operational and active institutional control phases the HPA recommends that a dose constraint of 0.15 mSv (annual dose) should also apply to exposure to the public from a new disposal facility for radioactive waste.

d To ensure that individual members of the public are not exposed to unacceptable risks, the HPA recommends that for processes and events affecting the disposal facility a risk constraint of 1 in 100,000 per year should be applied to the exposure of an individual representative of the more highly exposed individuals in the population and is applied to the exposure from a single waste disposal facility.

e Since the likelihood of inadvertent human intrusion is highly uncertain but there is the potential for higher doses should inadvertent intrusion occur, the HPA recommends dose criteria for inadvertent human intrusion for near-surface disposal facilities rather than risk criteria. The HPA recommends an annual dose guidance range of around 3–20 mSv related to the exposure of an individual representative of the more highly exposed individuals in the population following inadvertent intrusion. Values towards the lower end of this range are applicable to assessed exposures continuing over a period of a year or more (prolonged exposures), excluding the contribution from radon and its decay products. Values towards the upper end of the range are applicable to assessed exposures that are only short term (transitory exposures), ie where the dose is received within one year and none is received in subsequent years (the 20 mSv therefore applies to the total transient dose).

f For geological disposal facilities the potential for inadvertent human intrusion has already been reduced by placing the waste at depth. Although the potential for intrusion and resulting doses, including deterministic ones for higher activity waste, cannot be completely eliminated, the principle of optimisation applies, ie to show that all that can reasonably be done has been done. Therefore the HPA considers that it is not useful to specify a dose constraint or dose guidance level. However, it is still important that a few scenarios are used to explore the range of likely probabilities of intrusion and the consequences of intrusion into a geological disposal facility and to demonstrate that protection has been optimised.

Assessment of doses and radiological risks

Calculations to estimate doses and radiological risks in the future should take account of the uncertainties inherent in such assessments. The level of calculational detail should reflect the reliability of the information available, and should therefore change according to the length of time into the future being considered.

The radiological protection principles and criteria that apply to a facility using radioactive material should also apply to the operational and active institutional control phases of a facility disposing of the waste. Any assumptions about the natural environment more than 1,000,000 years or so into the future are highly speculative and unlikely to be supportable, and therefore quantitative risk calculations should not be continued beyond this time. Qualitative arguments should be used, however, to show that the likelihood of any sudden, significant increase in risk after this time is low. The specified risk constraint and dose guidance range should therefore apply from the time that active institutional control of the site ceases until such time as the calculations cease to be valid, taken to be 1,000,000 years or so from the present day.

Calculations to assess doses and radiological risks should include estimates of the uncertainty in these calculations due to incomplete or inadequate knowledge of the system being modelled and the environmental behaviour of the radionuclides.

Deterministic effects

Low probability events which, should they occur, could lead to the exposure of individuals to doses or dose rates high enough to cause serious deterministic health effects should be treated separately. Steps should be taken in the selection and design of a disposal facility to ensure that the probability of occurrence of such events is ALARA.

Optimisation of protection

As the best waste management option will always be specific to the exposure situation, the waste and the waste disposal facility, it is not relevant to specify a dose level below which optimisation is no longer required. Nevertheless, if the radiological impact is very small then inappropriate levels of effort could be expended on comprehensive and detailed optimisation studies in order to reduce the risk further. It is important that the level of effort expended on reducing the dose or risk is proportionate to the dose or risk associated with the waste management option. Calculations of collective dose, for input into optimisation studies, extending far into the future are unlikely to be reliable and therefore such calculations are not, in general, recommended.

References

GB Parliament (1993). The Radioactive Substances Act 1993, Chapter 12. London, HMSO.

ICRP (2007). Recommendations of the ICRP. ICRP Publication 103. *Ann ICRP,* **37**(2–3).

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1 Introduction

One of the functions of the Health Protection Agency (HPA) is the provision of information and advice on protection of the UK population from risks connected with radiation exposure. This function is inherited from one of the predecessor organisations of the HPA – the National Radiological Protection Board (NRPB). The purpose of this document is to provide advice, in particular to government departments, on the radiological protection objectives to be applied to the disposal of all types of solid radioactive waste, including wastes arising in gaseous or liquid form which will be converted to solid form prior to disposal. The HPA role is an advisory one; it is not a regulator of the disposal of radioactive waste.

In 1992, the NRPB published advice on the radiological protection objectives for the land-based disposal * of solid radioactive wastes (NRPB, 1992). The HPA has updated this advice, following a public consultation in 2008, and the revised advice is described in this document. The HPA response to the comments received during the consultation is given elsewhere (HPA, to be published – a).

This section summarises existing HPA, national and international advice, and subsequent sections give details of the updated HPA advice.

1.1 Previous NRPB and HPA advice on disposal of solid radioactive wastes

In 1992 the NRPB published a statement on radiological protection objectives for the land-based disposal of solid radioactive wastes (NRPB, 1992). The NRPB recommended that for the post-closure phase, the individual risk † to an average member of the critical group, attributable to any single disposal facility for solid radioactive waste, should not exceed a risk constraint of 1 in 100,000 per year. It further recommended a design target for a single waste disposal facility of 1 in 1,000,000 per year (a level of risk which is generally regarded as being of little concern). When that document was published, the International Commission on Radiological Protection (ICRP) estimate of the risk of harm caused by radiation exposure was about 0.06 per Sv (comprised of 0.05 per Sv for the risk of fatal cancer to an individual and 0.01 per Sv for the risk of serious hereditary disease in all subsequent generations). In its response to the 1990 ICRP recommendations (ICRP, 1991), the NRPB had also recommended a dose constraint for members of the public of 0.3 mSv per year from a new source, where a source is defined as one or more practices under common management (NRPB, 1993a). Since this is equivalent to a risk of the order of 1 in 100,000 per year, the risk constraint proposed by the NRPB for solid waste disposal was therefore broadly consistent with the dose constraint recommended for discharges.

* See the glossary for definitions of terms used in this document.

† Where risk is defined as the probability of harm, eg fatal cancer in a year.

The 1992 NRPB advice also contained a discussion on the calculation of individual risk over long timescales, the treatment of uncertainty, the presentation of results and the optimisation of protection. The NRPB advice was adopted by the HPA when the two organisations merged in 2005.

1.2 Environment agencies' guidance

The authorising departments *, together with the Food Standards Agency (FSA) and the NRPB, have produced guidance on dose calculations for discharges of wastes in their document on principles for the assessment of prospective public doses (Environment Agency et al, 2002). This specifies that the effective dose † to a representative member of the critical group from controlled discharges from a facility should not exceed a source-related constraint. The constraints are defined in the Radioactive Substance Directions (DETR, 2000; Scottish Executive, 2000; GB Parliament, 2003) as 0.3 mSv per year from any source and 0.5 mSv per year from the discharges from any site for use at the planning stage. For solid waste disposal, the authorising departments have issued guidance on requirements for authorisation (Environment Agency et al, 1996). It contains a number of principles and requirements that the disposal facility should address, eg sound engineering, independence of safety from controls and optimisation, and specifies a numerical criterion for the radiological impact after control is withdrawn from the site. The criterion is that the assessed radiological risk from the disposal facility to a representative member of the potentially exposed group at greatest risk should be consistent with a risk target of 10^{-6} per year (ie 1 in 1,000,000 per year). The environment agencies' guidance document explains that this risk target is not the only criterion to be addressed and that a disposal facility that just fails to meet the target may be acceptable if the other requirements are met. The authorising departments are in the process of updating their guidance and issued consultation documents in 2008.

1.3 ICRP recommendations

In Publication 81 the ICRP published recommendations specifically for solid waste disposal (ICRP, 1998). The main focus of the document is on the long-term, post-closure phase but the ICRP also recommended that '... the optimisation principle should be applied in an iterative manner during the disposal system development process and should particularly cover both the site selection and the repository ‡ design phases'. For the post-closure phase, the ICRP considered that there are two broad categories of exposure situations to be assessed: natural processes and inadvertent human intrusion. (Intentional intrusion in full knowledge of the site was not included as this would be considered in the future by anyone planning intrusion.) The document discussed the uncertainties inherent in assessments over long timescales and the difficulty in estimating the probabilities of possible inadvertent intrusion into

* The Environment Agency (EA), the Scottish Environment Protection Agency (SEPA) and the Northern Ireland Environment Agency (NIEA).

† Unless otherwise stated, the term 'dose' refers to 'effective dose' as defined by the ICRP (1991). A definition of effective dose is given in the glossary.

‡ Disposal facility.

the site in the future and recommended that natural processes should be treated separately from inadvertent human intrusion in a radiological assessment. For natural processes, which include all processes that lead to the exposure of individuals other than inadvertent human intrusion, eg migration with groundwater, the ICRP recommended that assessed doses or risks should be compared with a constraint of no more than about 0.3 mSv per year or its risk equivalent of around 1 in 100,000 per year. For inadvertent human intrusion, the ICRP recommended that reasonable efforts should be made at the development stage of the disposal facility to reduce the probability of inadvertent human intrusion or to limit its consequences if the assessed doses to those living around the site following inadvertent intrusion were sufficiently high that intervention (based on current criteria) would almost always be justified. In a related document on prolonged exposure situations – Publication 82 – the ICRP gave advice on the level of dose to which this corresponds (ICRP, 2000). The ICRP advised that, in situations where people are already being exposed over several years, a total annual dose of around 10 mSv may be used as a generic level below which intervention is unlikely to be justifiable and an annual dose of around 100 mSv as a generic level above which intervention should almost always be justifiable.

The ICRP also recognised the basic principle that individuals and populations in the future should be afforded at least the same level of protection as the current generation.

In 2007 the ICRP issued new recommendations (ICRP, 2007), updating its 1990 recommendations (ICRP, 1991). The system of radiological protection described in these new recommendations is still based on the same three fundamental general principles given in the 1990 recommendations.

a. Any decision that alters the radiation exposure situation should do more good than harm (*justification – source-related principle for all exposure situations*).

b. The likelihood of incurring exposures, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and social factors (*optimisation – source-related principle for all exposure situations*).

c. The total dose to any individual from regulated sources in planned exposure situations, other than medical exposure of patients, should not exceed the appropriate limits recommended by the ICRP (*dose limitation – individual-related principle for planned situations*).

The other main features of these new recommendations which are relevant here are as follows.

d. The ICRP has reviewed the risk from radiation exposure, confirmed that the 'linear non-threshold' (LNT) dose-response model is appropriate for the projection of risk at acute or annual doses below 100 mSv (effective dose), and updated the radiation and tissue weighting factors and the concept of radiation detriment. The total risk of radiation detriment for a typical population of all ages is now estimated to be 0.057 per Sv. This value is the sum of the estimate of the risk of detriment-adjusted cancer (ie fatal cancer adjusted for loss of life expectancy and non-fatal cancer adjusted for life impairment), which is estimated to be 0.055 per Sv, and the risk of heritable effects (in the first two generations), estimated to be 0.002 per Sv. However, the ICRP recommends that, given the uncertainties, a value of 0.05 per Sv should be used as the approximate risk of fatal cancer. This risk coefficient is wholly compatible with that presented by the ICRP in its 1990 recommendations (ICRP, 1991).

e The ICRP has discarded the process-based protection approach using practices and interventions, and has moved to a situation-based approach applying the same source-related principles to all controllable exposure situations.

Planned exposure situations These are situations involving the deliberate introduction and operation of sources. Planned exposure situations may give rise both to exposures that are expected to occur (*normal exposures*) and to exposures that are not expected to occur (*potential exposures*).

Emergency exposure situations These are situations that may occur during the operation of a planned situation, or from a malicious act, or from any other unexpected situation and require urgent action in order to avoid or reduce undesirable consequences.

Existing exposure situations These are exposure situations that already exist when a decision on control has to be taken, including prolonged exposure situations after emergencies.

f The ICRP has maintained the dose limits for application in planned exposure situations at the same values as those previously applied to practices.

g The ICRP has reinforced the principle of the optimisation of protection, which should be applicable in the same way to all exposure situations with restrictions on individual doses, called dose constraints for planned exposure situations and called reference levels for emergency and existing exposure situations.

h The ICRP confirmed that its previous advice on solid waste disposal and prolonged exposures, given in Publications 81 and 82, is still valid (ICRP, 1998, 2000).

In a planned exposure situation as described by the ICRP (2007), a certain level of exposure is reasonably expected to occur. However, higher exposures may arise following deviations from planned operating procedures. The ICRP refers to these as potential exposures (ICRP, 1997a) which should be considered at the planning stage of the introduction of a planned exposure situation. It states that it should be recognised that the potential for exposures may lead to actions both to reduce the probability of occurrence of the events, and to limit and reduce the exposure (mitigation) if any event were to occur. For potential exposures that could occur far in the future and where doses would be delivered over long periods, eg situations relevant to solid waste disposal in geological disposal facilities, the ICRP comments that considerable uncertainties surround the exposure estimates. Thus dose estimates should not be regarded as measures of health detriment beyond timescales of around several hundreds of years into the future. Rather, they represent indicators of the protection afforded by the disposal system. The ICRP (1998) recommends that the objective of protecting individuals from exposures is best achieved by considering both the probability of occurrence and the magnitude of these exposures.

The 2007 ICRP recommendations are not discussed in detail here as the HPA response to the revised advice will be published elsewhere (HPA, to be published – b). However, the key issues for waste disposal are outlined in Sections 5, 7 and 8.

1.4 IAEA safety standards

In its document on fundamental safety principles the IAEA gives the conceptual basis for its safety standards programme including the management of radioactive waste (IAEA, 2006a). It states that the fundamental objective is to protect people and the environment from harmful effects of exposure to ionising radiation and ten safety principles are given. All of the ten safety principles apply to the management of radioactive waste but of particular note are:

Principle 5 optimisation of protection,

Principle 6 limitation of risks to individuals,

Principle 7 protection of present and future generations.

Principle 6 states that 'measures for controlling radiation risks must ensure that no individual bears an unacceptable risk of harm'. Principle 7 states that 'radioactive waste must be managed in such a way as to avoid imposing an undue burden on future generations'.

An IAEA document on the geological disposal of radioactive waste (IAEA, 2006b) established the requirements relating to the disposal of radioactive waste in geological disposal facilities, for the operational and post-closure phases. This document states that 'the dose limit for members of the public from all practices is an effective dose of 1 mSv in a year, and this or its risk equivalent is considered a criterion not to be exceeded in the future. To comply with this dose limit, a geological disposal facility is designed so that the estimated average dose or average risk to members of the public who may be exposed in the future as a result of activities involving the disposal facility does not exceed a dose constraint of not more than 0.3 mSv in a year or a risk constraint of the order of 10^{-5} per year'.

A draft IAEA document on the disposal of radioactive waste (IAEA, to be published) is intended to form the basis of the safety requirements relating to the disposal of all types of radioactive waste. It sets out the radiological protection criteria specified for the post-closure period, derived from the recommendations of the ICRP (1991, 1997b, 1998) that were summarised in Section 1.3. For the operational phase of a disposal facility, the draft IAEA document states that the safety requirements are the same as for any other nuclear facility. These are set out in the IAEA Basic Safety Standards (IAEA, 1996) which are currently under review and the revised version will take into account the new ICRP recommendations (ICRP, 2007).

The IAEA has also supported an extensive programme of work on assessment methodologies for estimating radiological impact in the post-closure period (IAEA, 2003b, 2004; Koehler et al, 1991).

1.4.1 Joint Convention on the safety of spent fuel management and on the safety of radioactive waste management

The UK has ratified the Joint Convention on the safety of spent fuel management and on the safety of radioactive waste management (IAEA, 1997) sponsored by the IAEA. One of the main objectives of the Convention is:

> 'to ensure that during all stages of spent fuel and radioactive waste management there are effective defences against potential hazards so that individuals, society and the environment are protected from harmful effects of ionizing radiation, now and in the future, in such a way that the needs and aspirations of the present generation are met without compromising the ability of future generations to meet their needs and aspirations.'

The Convention also states that the contracting parties should:

> 'strive to avoid actions that impose reasonably predictable impacts on future generations greater than those permitted for the current generation.'

2 Need for New Advice

The HPA now considers that the advice given in the NRPB statement on the radiological protection objectives for the land-based disposal of solid radioactive wastes (NRPB, 1992) requires updating in the light of the recently published ICRP recommendations (ICRP, 2007) and other relevant publications by the IAEA and the UK environment agencies, as discussed in the previous section.

The HPA also considers that it is timely to review and update its advice now that the Managing Radioactive Waste Safely (MRWS) programme for high and intermediate level waste of the UK Government and devolved administrations * (Defra et al, 2001) is entering Stage 3, its implementation phase. As part of Stage 2 of the MRWS programme, the Committee on Radioactive Waste Management (CoRWM) advised that a programme of robust interim storage followed by geological disposal would be the best approach for the long-term management of intermediate level waste (CoRWM, 2006). The UK Government and devolved administrations have adopted these recommendations and have outlined how they intend to implement the long-term management of intermediate and high level waste (Defra et al, 2006). The UK Government, the Welsh Assembly Government and the Northern Ireland Assembly Government † have developed a framework for implementing geological disposal (Defra et al, 2008a). In addition, the UK Government and devolved administrations have recently revised their policy on the long-term management of low level waste (Defra et al, 2007).

The HPA has considered all of these issues in the formulation of its present advice. This advice relates to current knowledge and understanding and the HPA will continue to monitor developments and new information and review it again as and when appropriate.

* Department for Environment, Food and Rural Affairs, Scottish Executive (now Scottish Government), Welsh Assembly Government and Northern Ireland Department of the Environment.

† The Scottish Government did not sponsor the 2007 Managing Radioactive Waste Safely framework for implementation following the announcement on 25 June 2007 that the Scottish Government does not accept that geological disposal is the right way forward. See http://www.scotland.gov.uk/News/Releases/2007/06/25101822. It continues to support long-term interim storage and an ongoing programme of research and development.

3 Scope of the HPA Advice

The advice is intended to be applied at the planning stages of a radioactive waste disposal facility. If a disposal facility already exists then the advice is intended to apply at the planning stages of any future disposals at the facility. This advice does not apply to any disposals that have already occurred. In addition, the dose and risk criteria are not intended to be applied directly to any exposures that actually occur in the future from the disposal facility as this would then be an existing exposure situation and would be dealt with as such, at the time.

There are many factors that need to be considered in the planning of a disposal facility but this advice is intended to apply to protection of human health from radiological risks, as in the previous advice. Formal advice on the chemical hazards associated with radioactive waste is not addressed in this document, although the HPA will continue to provide general guidance as required. Radiological protection of non-human species will also not be addressed in this document because it is outside the remit of the HPA. However, protection of non-human species is an area of responsibility covered by the environment agencies (EA, SEPA and NIEA) and will be addressed in their guidance on the requirements for authorisation, which is in the process of being updated.

The HPA advice applies to all types of solid radioactive waste, including wastes which arise in liquid or gaseous form but are converted to solids prior to disposal. It is intended to apply to all types of disposal facilities for solid radioactive waste management ranging from purpose-built facilities near surface or deep underground to existing landfill sites that accept small quantities of low level or very low level waste. Disposal of waste in accordance with an Exemption Order made under the Radioactive Substances Act (GB Parliament, 1993) is not included in the scope of the advice.

4 Main Principles

Many radiological protection and waste management principles were considered in the development of this advice. This section describes some of the main principles that are relevant to radiological protection.

The three fundamental principles of radiological protection, as recommended by the ICRP (1991, 2007), are as follows.

Justification Any decision that alters the radiation exposure situation should do more good than harm.

Optimisation of protection The likelihood of incurring exposures, the numbers of people exposed, and the magnitude of their individual doses should be kept as low as reasonably achievable, taking into account economic and social factors. In order to avoid severely inequitable outcomes of this optimisation procedure, there should be restrictions on the doses or risks to individuals from a particular source (dose or risk constraints and reference levels).

Application of dose limits The total dose to any individual from regulated sources in planned exposure situations should not exceed the appropriate limits.

The primary aims of these principles are to prevent harmful effects (called tissue reactions or serious deterministic effects by the ICRP) and to minimise exposures which could lead to cancer and heritable effects (called stochastic effects by the ICRP). The latter is achieved by optimisation: keeping doses or risks as far below a dose or risk constraint as reasonable, economic and social factors being taken into account.

The ICRP recommendations as applied to the disposal of long-lived solid radioactive waste (ICRP, 1997b) state that:

> 'the principal objective of disposal of solid radioactive waste is the protection of current and future generations from the radiological consequences of waste produced by the current generation.'

The recommendations further state that:

> 'doses to individuals and populations over such long time-scales can only be estimated and the reliability of these estimates will decrease as the time period into the future increases. Nevertheless, the Commission acknowledges a basic principle that individuals and populations in the future should be afforded at least the same level of protection from actions taken today as is the current generation.'

and

> 'the principal means of achieving protection of the public is through a process of constrained optimisation, taking account of the Commission's recommended upper value for the dose constraint of 0.3 mSv y^{-1} or its risk equivalent.'

The ICRP acknowledges that:

> 'doses and risks as a measure of health detriment, cannot be forecast with any certainty for periods beyond around several hundreds of years into the future. Instead, estimates of dose and risk for longer time periods can be made and compared with appropriate criteria in a test to give an indication of whether the disposal facility is acceptable given current understanding of the disposal system. Such estimates must not be regarded as predictions of future health detriment.'

Other principles that are relevant to radiological protection and waste management are the minimisation of waste, the proximity principle and the precautionary approach. The HPA is pleased to note that many of these have been incorporated in UK waste management policy. The HPA has considered all these principles in the formulation of this advice; the overriding principle is optimisation.

5 Relationship between Dose and Radiological Risk

The radiological protection objectives for waste management recommended by the ICRP (1998) are expressed in terms of dose and in terms of risk, depending on the type of situation being considered. The HPA also recommends criteria in terms of both dose and risk. The relationship between the two is defined here:

$$R = \gamma \sum_i p_i \, E_i$$

where R is the excess risk of harm, eg cancer, in the year considered,

γ is the excess risk of harm, eg cancer, per unit effective dose (Sv^{-1}),

p_i is the probability of scenario i, which if it occurs gives rise to an effective dose of E_i in the year considered,

E_i is the effective dose in a given year (Sv) resulting from an event, defined to be the sum of the effective dose from external exposure during that year and the committed effective dose from intakes of radionuclides during that year resulting from the event.

Effective dose is a quantity defined by the ICRP that is used to quantify low doses and relates to protection against the occurrence of stochastic effects (cancer and heritable effects). It is not applicable to high doses where there is a possibility of tissue reactions. In these cases doses to the relevant organ should be calculated using the appropriate relative biological effectiveness. It should be noted that effective dose is intended for use as a protection quantity and is calculated using reference values, applying to reference persons. Since it is an 'averaged' quantity it cannot be used to determine the actual dose to a particular individual.

The equation above is valid when the risk associated with effective dose is linearly related to dose and this linear relationship is valid up to a particular level of effective dose. In its new recommendations the ICRP maintains that for radiological protection purposes a linear non-threshold model is appropriate for the projection of risk at acute or annual effective doses below 100 mSv (ICRP, 2007). In the HPA consultation document on the application of the ICRP recommendations to the UK, the HPA agrees with the ICRP statement and furthermore suggests that between 100 and 500 mSv, effective dose may be used for practical radiological protection purposes, although the results should be treated with some caution (HPA, 2008a). Greater caution is needed where the exposure of the organs is due to internal exposure to the radionuclides. The excess risk of harm associated with acute effective doses above 100 mSv may not be linearly related to the dose. Therefore acute effective doses above 100 mSv should be treated separately. For the purposes of waste management disposal assessments the HPA advises that the equation should be used for acute or annual effective doses less than 100 mSv (see Section 9).

There are different possible measures of stochastic effects. Detriment is a concept used to quantify the harmful health effects of radiation exposure in different parts of the body. It includes the weighted probability of attributable non-fatal cancers and the length of life lost as well as the probability of attributable fatal cancers and the weighted probability of severe heritable effects in all subsequent generations (the latter is represented by the risk factor for the next two generations). The HPA recommends the use of the detriment-adjusted risk coefficient. The estimate of the detriment-adjusted risk coefficient for the whole population is given in the new ICRP recommendations as 0.057 per Sv. The HPA recommends that the rounded value of 0.06 per Sv be used for waste management assessments. It should be noted that, for the purposes of radiological protection, the risk coefficient for fatal cancer for the whole population given in the ICRP recommendations is 0.05 per Sv (ICRP, 2007). This is not significantly different from the detriment-adjusted risk coefficient, given all the other uncertainties inherent in assessments of the radiological impact of waste disposal. Therefore the risk of detriment could also be used to estimate a number of fatalities for comparison purposes because the risk coefficients are essentially the same.

In this document dose and risk are used as a means of evaluating the safety of a disposal facility in radiological protection terms. There are many other radiological protection indicators that might usefully be considered besides dose and risk including, for example, the flux of radionuclides reaching the biosphere, the time taken for radionuclides to reach the biosphere and environmental concentrations, as well as consideration of natural analogues (IAEA, 1989). They should not be seen as alternatives to dose and risk, but rather as supplementary indicators of radiological protection.

6 Timeline of a Disposal Facility

It is useful to consider the timeline of a disposal facility that accepts solid radioactive waste. Four distinct phases can be identified once the site has been selected and the disposal facility (or the first disposal module) has been constructed:

a operational phase,

b active institutional control phase,

c passive control phase,

d uncontrolled phase.

The operational phase covers the period when the disposal facility is receiving radioactive waste. This will start when authorisation for disposal has been received from the relevant authorising department and will end when the disposal facility is full and has been closed. The disposal facility may be modular in design with different sections at different stages (some under construction, some receiving waste and some closed) and hence closure of the disposal facility may be progressive. It may also be designed for phased disposal, enabling it to stay open and function as a storage facility for several hundred years. Depending on the design of the disposal facility, closure can take different forms, such as capping (landfill site) or backfilling and sealing (geological facility). The operational phase may therefore last several decades or more, especially in the case of a geological facility.

The second stage is the active institutional control phase which covers the time from closure of the disposal facility to the time when active care and maintenance of the site cease after several decades or more. It is not reasonable to expect that active care and maintenance of the site will be possible forever and therefore it is assumed that they will cease at some time in the future, either as a result of a review of the hazard potential of the site or as a result of changed priorities or lack of resources. The period for active institutional control may vary depending on the type of facility and could be of the order of decades. Examples of active institutional control given by the IAEA (2003a) are monitoring, surveillance and remedial work.

For the purposes of this document, the end of active institutional control is represented by the point at which there is no longer any onsite management; for a purpose-built licensed facility this may, but does not necessarily, correspond to the time when the site is delicensed by the Nuclear Installations Inspectorate (NII). For a landfill style site this may be when the decision is made to cease routine maintenance and monitoring, several decades after closure.

The site then enters the third stage, the passive control phase, when records are expected to inform future generations of the presence of the radioactive waste. Eventually, it could be expected that the records will become lost and this marks the end of the passive control phase and the start of the fourth and final stage, the uncontrolled phase.

The length of time spent in each stage will depend on many factors including the type and size of facility, the properties of the waste disposed there (in particular its half-life), regulatory requirements and societal preferences. Some stages have definite endpoints, others are more vague and judgement has to be used in estimating when they will occur.

The primary focus of this advice is on the post-closure phase for existing and future purpose-built radioactive waste disposal facilities for solid radioactive waste (ie the second, third and fourth stages described above). However, landfill sites accepting other wastes are included and the operational phase is also briefly discussed.

7 Operational and Active Institutional Control Phases

The operational and active institutional control phases of any disposal facility for radioactive wastes will be subject to the regulatory regime existing at that time. The same radiological protection principles and criteria that apply to facilities using radioactive materials should also apply to those disposing of the waste.

In its previous advice the NRPB (1993a,b) recommended a maximum dose constraint of 0.3 mSv per year for exposure of the public from proposed controlled sources. The advice also stated that dose constraints lower than this could be set where such doses are readily achievable (NRPB, 1993b). The HPA now recommends that the lower dose constraint of 0.15 mSv (annual dose) should apply to exposure to the public from a new disposal facility for radioactive waste.

It is important that the balance between the consequences of different waste management options for operational wastes is considered since the optimisation of health protection does not necessarily mean minimisation of discharges. For example, storing radioactive waste that would otherwise be discharged to the environment may reduce the dose to the local population, but can sometimes increase the dose to site workers, potentially by significantly more than the reduction in dose to individuals within the local population. Equally, reducing liquid discharges by evaporation could increase atmospheric discharges and result in an increase in solid radioactive waste for disposal.

8 Passive Control and Uncontrolled Phases

This section discusses the radiological protection objectives recommended by the HPA for near-surface and geological disposal facilities for the passive control and uncontrolled phases. Clear presentation of the methodologies and assumptions used in the dose and risk calculations is extremely important so that the calculations can be critically reviewed. Guidance on the assessment of doses and risks is given in Section 10. There are many possible pathways by which people may become exposed in the post-closure period. Internationally agreed assessment methodologies, eg BIOMOVS (Koehler et al, 1991), recommend that all the features, events and processes that could affect the disposal facility are explicitly reviewed and that they are considered in the assessment of the radiological impact if they are relevant to the particular situation and context being assessed. There are two broad categories of exposure scenarios that can be considered: processes and events affecting the disposal facility, and human intrusion directly into the disposal facility.

8.1 Processes and events affecting the facility

This category is intended to capture all processes and events that lead to exposure of individuals, other than human intrusion directly into the disposal facility. This includes processes that have a gradual and continuous interaction with the system being modelled, such as groundwater-driven flow of radioactive contaminants from the disposal facility, climate change effects, uplift and subsidence. It also includes events that occur over a limited time duration – for example, landslips, flooding and aircraft crashes.

Processes and events will result in the degradation of the disposal facility and its waste. As part of this process, gases and liquids will be formed and these will need to be considered in any assessment.

8.1.1 Criteria for processes and events

Once active institutional control has ceased – and for all processes and events that lead to exposure of individuals (other than human intrusion directly into a waste disposal facility) – the HPA recommends that a risk constraint of 1 in 100,000 per year is applied to the exposure of an individual representative of the more highly exposed individuals in the population, and is applied to the exposure from a single waste disposal facility. This risk constraint is intended to apply at the planning stages of a new disposal facility. In the case of an existing disposal facility already containing wastes in closed modules, the advice is intended to apply at the planning stages of all future disposals at the facility. This annual risk constraint applies irrespective of whether the exposure is received over a few weeks or remains roughly constant over decades or more. In line with the basic philosophy of radiological protection, meeting this risk constraint is not sufficient in itself: optimisation is required to reduce the risk to a value below this risk constraint, economic and social factors being taken into account. Optimisation is discussed further in Section 10.5.

The risk value of 1 in 100,000 per year is approximately equivalent to a dose of 0.15 mSv per year using the detriment-adjusted risk coefficient of 0.06 per Sv given in the new ICRP recommendations (ICRP, 2007). It is therefore approximately equivalent to the maximum dose constraint of 0.15 mSv per year recommended for new waste disposal facilities in Section 7. Hence there is continuity in radiological protection objectives from the operational to post-closure phases.

Although the criterion is expressed in terms of risk, the HPA recommends that the doses and associated probability should also be presented to aid understanding of the main contributions to the risk.

Comparison of estimated risks to individuals from a single waste disposal facility against the constraint requires judgement, especially for risks that are estimated to occur at long times in the future. If risks are estimated to be lower than the constraint, it does not mean that the disposal facility is acceptable with no further consideration; the level of protection must also be demonstrated to be optimum by means of an optimisation study. Conversely, if the constraint is exceeded this does not necessarily mean rejection of the safety case for the proposed disposal facility. Further considerations would be required, involving either further evaluation of the safety case (for example, re-examination of the uncertainties or the extent of the conservatism used in the estimation of the risk) or further justification (for example, the safety case being supported by other evidence). It should also be noted that the further into the future that the assessment is made, the more uncertain the assessments of doses and risks become and consequently the greater the flexibility in the application of the constraint.

If there is another disposal facility which might be affected by the same natural processes and events as the facility being proposed then consideration should be given to the combined doses and risks to any relevant groups of individuals.

Naturally occurring catastrophic events whose non-radiological consequences on individuals and society would clearly outweigh any radiological consequences (for example, a large meteorite impact) may be excluded from an assessment.

Over time, processes and events mean that the radioactive material will disperse from the facility into the geosphere. Human actions that result in exposure to contamination that is located outside the disposal facility itself (for example, doses resulting from drinking water from a well which has been drilled into a plume of contamination) should be considered as part of the processes and events and should be compared to the risk constraint.

8.2 Human intrusion into a disposal facility

Intrusion is intended to mean:

a human intrusion directly into a disposal facility – this includes intrusion into the engineered barriers,

b other human actions that damage engineered barriers or degrade their functions (such as removing material from a disposal facility cap) – this may result in changes to processes and events (for example, changing the local hydrogeology) and these effects will need to be considered.

There are two main types of intrusion, intentional and inadvertent, which are discussed below.

Intentional intrusion, ie deliberate intrusion into a facility in the full knowledge of its presence and its contents, for good or bad intent, is not considered further in this document for the following reasons. First, if the actions are intended to deliberately retrieve the waste then the actions would be planned and managed. Second, it is widely accepted that the current society cannot protect future generations from their own actions if they (the future society) are aware of the consequences. Finally, if the actions are intended to deliberately compromise the safety of the disposal facility (for example, a terrorist attack) the consequences for the deliberate intruder are primarily considered the intruder's responsibility and existing procedures for dealing with the consequences of such actions as a terrorist attack would come into play.

Hence, only inadvertent human actions which might disrupt a waste disposal facility are considered. In this sense, 'inadvertent' is taken to mean that, although the action itself may be intentional, it is done without full knowledge of the location and nature of the disposal facility. For example, it might be known that human activity has taken place at the site but the radioactive nature of the contents of the site might not be known. Someone stealing material from the site for scrap but not realising it was contaminated with radionuclides would be an example of inadvertent intrusion.

8.2.1 Criteria for inadvertent human intrusion into the disposal facility

The HPA recommends different radiological protection objectives for inadvertent human intrusion for near-surface disposal facilities to those for disposal facilities at greater depths. The reasoning behind this is that for near-surface disposal facilities there is always the option of placing the waste at greater depths if the consequences of intrusion are considered to be unacceptable. For deeper disposal facilities the probability of inadvertent intrusion has already been significantly reduced by placing the waste at depth.

The facility should be assumed to be a near-surface one unless the developer can demonstrate that the safety assessment for processes and events depends on the very-long-term containment of the waste in the geosphere.

8.2.1.1 Near-surface disposal facilities

It should be recognised that for near-surface disposal facilities, especially ones that are not purpose-built for radioactive waste only, it is probable that inadvertent human intrusion into the facility will occur at some stage during the next thousand years. However, the probability of intrusion in any given year will be low and can be assumed to be zero during the active institutional control period. Certain measures can be taken to reduce the annual probability of intrusion (such as the use of markers and anti-intrusion barriers and the location of a disposal facility in a remote area), but such measures are only likely to delay rather than prevent intrusion into near-surface disposal facilities. If only short-lived waste is present in the disposal facility, this delay may be adequate to ensure that the intrusion does not result in significant doses. If the facility contains long-lived radionuclides in significant amounts, delay of the intrusion event for a few tens of years may have little or no impact on the received doses. Since the likelihood of inadvertent human intrusion is highly uncertain, the emphasis for protection of human health should be on mitigating the consequences of intrusion that could occur after the end of the active institutional control period, ie controls should be placed on the doses likely to be received. For this reason the HPA recommends dose criteria for inadvertent human intrusion rather than risk criteria.

In specifying the dose criteria, the HPA considered both transitory and prolonged exposures as a result of inadvertent intrusion. To avoid confusion with the terminology in the new ICRP recommendations (ICRP, 2007), and recognising that there are many sources of uncertainty in performing dose calculations, the HPA calls these dose criteria for inadvertent intrusion 'guidance levels'.

As discussed in Section 1.3, the ICRP recommended that reasonable efforts should be made at the development stage of the disposal facility to reduce the probability of inadvertent human intrusion or to limit its consequences if the assessed doses to those living around the site following inadvertent intrusion were sufficiently high that intervention (based on current criteria) would almost always be justified (ICRP, 2007). In a related document on prolonged exposure situations the ICRP gave advice on the level of dose to which this corresponds (ICRP, 2000). The ICRP advised that, in situations where people are already being exposed over several years, a total annual dose, including the contribution from natural sources, of around 10 mSv may be used as a generic level below which intervention is unlikely to be justifiable and a total annual dose of around 100 mSv may be used as a generic level above which intervention should almost always be justifiable. However, in its recommendations, the ICRP states that the reference levels for existing exposure situations should be set typically in the 1–20 mSv band of projected dose (ICRP, 2007). The recommendations state that the guidance in Publication 81 (ICRP, 1998) still remains valid, but it is the opinion of the HPA (2008a) that the sections in Publication 81 relating to the criteria to evaluate human intrusion should be considered to be superseded by the 2007 recommendations.

Examples of criteria applied to existing prolonged exposure situations are discussed here as it can be argued that future generations should be treated with the same consideration as the present generation. The HPA recently recommended that an annual dose criterion of 3 mSv from the contamination should be used for the designation of radioactively contaminated land in the UK, ie the level above which intervention would need to be considered (though not necessarily implemented) (HPA, 2006). This criterion does not include the dose from exposure to radon gas * in the building. Exposure to radon in homes is another example of an existing prolonged exposure situation. The UK Action Level for radon in homes is currently 200 Bq m^{-3} (NRPB, 1990). This corresponds to exposures in the region of 10 mSv per year.

* The dose from exposure to radon gas is assumed to include contributions from its short-lived decay products.

Given the variety of exposure scenarios that could be considered it is not helpful to give one dose guidance level for transitory exposures and another for prolonged exposures since, for example, a scenario could be conceived where the exposures lasted months but not years. In addition, a guidance level for transitory exposures and another for prolonged exposures implies a level of precision in the dose assessments which is not realistic. Therefore the HPA recommends an annual dose guidance range of around 3–20 mSv related to the exposure of an individual representative of the more highly exposed individuals in the population following inadvertent intrusion. Values towards the lower end of this range are applicable to assessed exposures continuing over a period of a year or more (prolonged exposures), excluding the contribution from radon. If the radon contribution is included then the appropriate values could be up to a factor of three higher. Values towards the upper end of the range are applicable to assessed exposures that are only short term (transitory exposures), ie where the dose is received within one year and none is received in subsequent years (the 20 mSv applies to the total transient dose). An example of a transitory exposure would be the handling of soil specimens taken from the disposal facility.

The dose guidance range indicates the standard of environmental safety expected but it is not intended to be an absolute requirement for this level to be met. However, if estimates of transitory exposure were close to or above 20 mSv in any one year then the HPA would expect a comprehensive optimisation study to be performed to consider ways to reduce the dose and/or the probability of receiving the dose, including consideration of disposal at greater depth. Similarly, if estimates of prolonged exposure (excluding radon) were close to or above an annual dose of 3 mSv then the HPA would expect a comprehensive optimisation study to be performed to consider ways to reduce the dose and/or the probability of receiving the dose, again including consideration of disposal at greater depth. A disposal facility that is estimated to give rise to doses above these levels would therefore only be acceptable if it was shown to be the overall optimum solution for the waste being considered (for example, taking into account other factors such as transport and environmental impacts). If estimates of exposure are significantly below the guidance range then, although the waste management options should be optimised, the level of effort expended should be proportionate to the level of risk.

8.2.1.2 Geological disposal facilities

For geological disposal facilities, eg those proposed by the UK Government in conjunction with the devolved administrations for Wales and Northern Ireland for the management of higher activity waste in the UK, the potential for inadvertent intrusion has already been reduced by placing the waste at depth. Hence significant effort and technology would be required in order to intrude into the geological disposal facility. The process of site selection will also have reduced the potential for inadvertent intrusion by screening out sites with natural resources and groundwater (Defra et al, 2008a). Although the potential for inadvertent intrusion and resulting doses cannot be completely eliminated, including deterministic doses for higher activity waste, the principle of optimisation applies, ie to show that all that can reasonably be done has been done. (This assumes that, in line with the approach taken by the Government for discharges (Defra et al, 2008b) deliberate dilution of the waste to give lower activity concentrations and hence lower doses is not a preferred option.) The new ICRP recommendations state that ‘Optimised protection is the result of an evaluation, which carefully balances the detriment from the exposure and the resources available for the protection of individuals. Thus the best option is not necessarily the one with the lowest dose' (ICRP, 2007). Therefore it is not useful to specify a dose constraint or dose guidance level. However, it is still important that a few reference scenarios are used to explore the range of likely probabilities and the consequences of inadvertent intrusion into a geological disposal facility and to illustrate that protection has been optimised. Examples could include changing the depth or the area of the facility.

These reference scenarios should illustrate the potential impacts of inadvertent human intrusion on the intruder and others affected by the intrusive actions. They should not be seen as a definitive statement about the possible evolution of the waste disposal facility and the state of the human society that may come into contact with it but are designed to provide illustrations of potential impacts of inadvertent human intrusion. Examples of scenarios that could be considered are individuals coming into contact with sample cores containing radioactive material following exploratory drilling and individuals coming into contact with radioactive material following excavation of access tunnels.

9 Deterministic Doses

Deterministic effects or harmful tissue reactions occur when a certain threshold dose is exceeded and are the result of extensive cell damage. The severity of the effect is dependent on the dose received by the part of the body exposed, ie the higher the dose, the more cells killed and the more serious the injury. The HPA (2008a) defines severe deterministic injuries as 'injuries that are directly attributable to the radiation exposure, that are irreversible in nature and that severely impair the health and/or quality of life of that individual, for example, lung morbidity and early death'.

The definition of risk given in Section 5 is not applicable to deterministic doses and therefore it is inappropriate to combine risks of stochastic effects with risks of deterministic effects. The point at which deterministic effects will occur depends on the type of tissue exposed. The HPA (2008a) suggests that between 100 and 500 mSv, effective dose may still be used for practical radiological protection purposes, although the results should be treated with some caution. Therefore for simplicity the HPA recommends that, for radioactive waste management, if the estimated effective dose is greater than 100 mSv it should not be combined with the risk factor and the probability of receiving the dose to give an estimated risk but that they should be presented separately.

For near-surface disposal facilities the HPA guideline dose range for inadvertent human intrusion (annual dose of 3–20 mSv, total transient dose) will ensure that the doses from inadvertent human intrusion are well below the level that could give rise to severe deterministic effects. The HPA does not expect that any processes and events could lead to higher doses than those estimated for inadvertent intrusion directly into the waste disposal facility. Therefore the HPA expects that, for the types of waste that are suitable for disposal into near-surface facilities, processes and events affecting the disposal facility are unlikely to give rise to severe deterministic injuries. Hence, it is not necessary to set a specific numerical criterion for deterministic doses for near-surface facilities.

Doses leading to deterministic effects might occur in a scenario where intermediate or high level waste is brought to the surface by some dramatic environmental event or inadvertent human intrusion. For a geological disposal facility, the probability of this scenario is very low and it might therefore not be sensible to modify the disposal facility design solely to limit the consequences of such an event, particularly if the modification might detract from the performance of the disposal facility in 'normal' situations. Hence no numerical criterion is specified for deterministic doses for geological disposal facilities. However, the likelihood of deterministic effects arising should be one of the factors considered in the optimisation study. The probability of such events might be reduced by, for example, making the disposal facility deeper and/or smaller.

It should be remembered that events which lead to individuals receiving a dose which could cause deterministic effects may also result in doses in the stochastic region to another group of individuals, and these associated risks should be calculated in the assessment.

10 Assessment of Doses and Radiological Risks

In view of the timescales over which risk estimates are likely to be made, the sophistication of the models should reflect the amount and reliability of information available. In addition, the level of detail, complexity and effort expended on the assessment of doses and risks to demonstrate compliance with appropriate criteria should be commensurate with the level of hazard presented by the waste. As an example, the assessment required for a disposal facility designed to contain long-lived high level waste will be much more complex and detailed than that for a facility designed to take small quantities of very low level waste. Similarly, if the facility is designed to be used for the disposal of radionuclides with short half-lives then it may not be necessary to do calculations over timescales of hundreds or thousands of years if it can be demonstrated that sufficient radioactive decay has occurred for the waste no longer to present a hazard. In most cases the assessment process will be iterative as the understanding of the system increases and additional data become available. The iterations need only proceed until the assessment is judged to be adequate for its purposes.

It should be noted that any assessments of doses and risks to people in the future should be regarded solely as estimates of potential impacts based on the documented assumptions. They should be seen as indicators of safety rather than predictors of safety.

Where radium or its parent radionuclides are present in significant quantities in the waste being disposed of to the facility, radon gas * may make a significant contribution to the estimates of dose. Estimates of the radon concentration and hence dose can vary by over an order of magnitude depending on the assumed characteristics of the building, habits of the occupants and the geological characteristics of the ground underneath the building (Wrixon et al, 1988). These parameters generally do not influence the estimates of dose from other radionuclides and other pathways. The HPA therefore recommends that where radon is a significant contributor to the estimated doses the assumptions made in the assessments for radon should be clearly stated. The doses and risks estimated for radon should also be presented separately so the contribution of radon gas can be clearly seen and understood. It should be noted that naturally occurring radon should be excluded from the assessments of dose for comparison with the dose criteria. However, doses from naturally occurring radon can be used for comparison when determining the significance of the estimated radon doses.

There are large uncertainties involved in biosphere modelling over timescales of thousands of years, especially with respect to the landscape and future behaviour of human populations, which cannot be predicted with any confidence for periods of more than a few decades. Over still longer timescales there will also be changes to the geosphere. Hence, the further into the future that the assessment is made, the more uncertain the estimates of doses and risks become. The following sections discuss changes in

* The dose from exposure to radon gas is assumed to include contributions from its short-lived decay products.

the geosphere and the biosphere (including human behaviour) over time and how these link to approaches to the assessment of doses and risks.

10.1 Operational phase

Assessments of doses to workers and doses to the public from any operational discharges during the operational and active institutional control phases should be performed in the same way as for any site authorised to discharge radioactive waste. Further guidance on the assessment methodology for discharges is addressed elsewhere (Environment Agency et al, 2002). This guidance recommends that assessments of the radiological impact of discharges should consider pathways and exposed groups that are representative of the situation over the next five years (the period until the next discharge review) and consider the build-up in the environment over 50 years. Uncertainty in the doses should also be addressed. In terms of assessing doses to members of the public from any releases occurring during this period, dose coefficients and habit data for three age groups should be calculated based on the representative person concept defined in the recent dose assessment recommendations of the ICRP (2006). The HPA considers that the ‘representative person’ is essentially the same as the ‘representative member of a critical group’ discussed by the Environment Agency et al (2002) and that therefore this is only a change in terminology.

10.2 Post-closure phase

Some radionuclides have half-lives of millions of years and hence assessments need to consider these very long timescales if these radionuclides are present in the waste.

As discussed in the BIOCLIM biosphere modelling report (Texier et al, 2004), global warming may cause the onset of the next glaciation to be delayed, but it is expected that glacial cycles will continue with a period of 10,000 years or so.

Guidance on assessment methodologies for the post-closure phase has been developed by the IAEA BIOMASS and ISAM projects (IAEA, 2003b, 2004). In general, assessments consider several scenarios, the main one being the most likely evolution of the waste together with a number of ‘what if’ scenarios to span the range of possibilities, eg the possible effects of global warming over next few thousand years.

One approach to the problems of risk assessment over very long timescales is to introduce a regulatory ‘cut-off’ time at say, 1,000 or 10,000 years, beyond which risk calculations would not be required for licensing purposes. However, such a cut-off could lead to significant underestimation of the maximum risk to the public: for a geological disposal facility, the time until activity first reaches the biosphere may be considerably greater than 10,000 years (see, for example, European Commission, 1988). Therefore the HPA does not consider such a cut-off in assessments to be appropriate.

Instead, the emphasis of assessments should be changed as the timescale increases, to reflect the scientific basis upon which calculations are made. In particular, attempts to make detailed assumptions about the biosphere and human behaviour in the far future (more than a few thousand years, say) are unlikely to be justified; for these timescales, effort would be better concentrated on more reliable assessment of radionuclide transport through the geosphere.

The principle that future generations should be afforded a level of protection consistent with that provided today should not be interpreted too rigidly; for example, it should not be taken to imply that the modelling of risks to individuals must maintain a constant level of detail for all times in the future. The table overleaf gives, for perspective, a chronological list of a number of historical and (predicted) future events. It is clear that assessments which extend into the very far future (beyond times of, say, 1,000,000 years) can have little scientific credibility, and even those with timescales of 10,000 or 100,000 years will be subject to considerable uncertainty.

It is useful to divide the future into a series of different timescales as the uncertainties associated with the dose or risk assessment increase with time and therefore the appropriate approach changes from a more quantitative one to a more qualitative one. Suggested timescales are discussed in the following sections. The 'boundaries' between the periods are, for simplicity, given below in terms of orders of magnitude; in practice, more convenient times (of similar order) could be selected as appropriate.

10.2.1 From closure up to around 10,000 years

During this period, which essentially covers the time prior to the next glaciation, the biosphere in the UK may be expected to remain broadly temperate, ie comparable to present-day temperate conditions, although there may be major local and regional changes over timescales of thousands of years (eg rivers or lakes drying up, coastal erosion and environmental effects associated with climate change). Human behaviour is likely to change greatly over this period, although it could be argued that physiological and hence dietary requirements may remain broadly similar. However, significant natural changes in the UK geosphere on this timescale are unlikely.

As discussed above, there is considerable uncertainty about human habits and lifestyles and the changes in the biosphere. It should be noted that the aim of the assessments is to give an indication of the doses and risks in the future by covering a wide range of possible scenarios. The aim of the assessments is not to predict exactly the doses likely to be received in the future as this is unrealistic. As stated in the IAEA BIOMASS report (IAEA, 2003b):

> 'the biosphere(s) adopted for performance assessment should not be regarded as somehow simulating the actual biosphere that will necessarily be present when a future release to the biosphere occurs. Rather, it is appropriate to consider them as adequately representative of possible outcome for assessment purposes.'

Therefore biospheres based on general human habits and biosphere conditions should be developed – for example, the reference biospheres developed in the BIOMASS project (IAEA, 2003b).

TABLE Timescales considered in post-closure assessments

Years	Historical	Future	Nuclide half-life *
10			^{137}Cs
100	Discovery of radioactivity	'Greenhouse' effects	
1,000	Norman conquest	Large ecological changes, eg lakes fill with weeds	^{226}Ra
	Hadrian's wall built with stone blocks and cement		
	Egyptian pyramids	Mineral and energy resources exhausted?	^{14}C
10,000	Discovery of agriculture		^{239}Pu
	Last glaciation of northern Europe	Next glaciation	
	Use of fire and tools by humans		
100,000	Emergence of Neanderthal man	Time between major glaciations	^{99}Tc
1,000,000	Emergence of *Homo Sapiens*	Stable geological formations remain relatively unchanged	^{237}Np
	Evolutionary branching between humans and apes		
10,000,000		Spontaneous appearance of new families of species	^{129}I
100,000,000	Dinosaurs populated the Earth	Large-scale movements of continents (thousands of kilometres)	
	Uranium ore deposit in Cigar Lake, Canada, formed †		

* Approximate half-lives of some significant radionuclides in solid waste disposal assessments, for reference.
† It still exists despite being in highly permeable sandstone host rock chiefly because of its natural clay buffer (Miller et al, 2000).

The BIOMASS project states that one of the important stages in the development of the reference biospheres is the consideration of human activities and, in particular,

a characteristics of the human population (age distribution, density, economic activities and diet),

b human activities likely to change the biosphere system (eg quarrying, ploughing, soil improvement, damming and dredging),

c human activities leading to potential radiation exposure.

One of the considerations of human activity is the location of the population being considered. Obviously it is not actually possible to predict the location of the exact group of people that will be exposed to the highest doses in the future and hence some assumptions have to be made. In line with the precautionary approach and the principle of protecting future generations to the standards accepted today, the HPA recommends that doses and risks are assessed for a hypothetical representative person in a reference biosphere, calculated in the following way. First, as a result of processes and events acting on the disposal facility there will be a part of the biosphere where the concentrations resulting from the facility are greatest, eg where any radioactivity that has migrated from the disposal site reaches the Earth's surface. It is then conservatively assumed that the hypothetical representative person inhabits this area at the time that the concentration at the surface is at its maximum. It is also assumed that this hypothetical representative person behaves in a similar way to present-day people in that region, hence the characteristics of the hypothetical representative person and consequently the exposure pathways can be established by following the approach recommended by the ICRP for determining the characteristics of the representative person (ICRP, 2006). This is essentially the same as in previous NRPB advice, updated to bring it into line with the new ICRP terminology of the representative person. This may be more conservative than is the case for routine discharge assessments (because there is considerably more uncertainty as to whether such a group is likely to exist at a particular location), but the rationale is that, if people with certain habits do exist at a particular location at some time in the future, then they will not be subject to unacceptable exposure. It is important, however, that hypothetical representative persons should not be assigned habits which are too conservative, particularly as the assumptions about their existence and location are conservative. For example, if individuals do exist at a specific location at some time in the future, their total calorific requirements and fluid intakes are unlikely to be very different from present-day requirements, although the range of food consumed may change considerably.

In addition to assuming that the hypothetical representative person behaves in a similar way to present-day people in that region, account needs to be taken of the impacts of climate change. Thus, for example, the hypothetical representative person may also be defined based on human behaviour and habits within climatically analogous regions of the world.

For inadvertent human intrusion, the HPA recommends that it is assumed that intrusion could occur as soon as active institutional control ceases but that other times of intrusion are also considered to encompass the range of possible results. The characteristics of the hypothetical representative person should be based on present-day characteristics.

For both processes and events and inadvertent human intrusion it is recommended that a number of scenarios with hypothetical representative persons are considered. This will ensure that a sufficient number of significant exposure pathways have been identified to provide adequate assurance of the protection of future communities. Depending on the type of disposal facility being considered and the type of radioactive waste being placed in the facility, these scenarios and hypothetical representative persons may include a farmer living in a temperate climate, a geotechnical worker examining drilling cores and a construction worker excavating a site. Although the biosphere can be assumed to remain broadly temperate, the effect of expected changes to the biosphere, such as climate variation leading to increased irrigation or coastal erosion and inundation, should also be addressed either in separate scenarios or as part of the same scenario.

10.2.2 From around 10,000 years up to around 1,000,000 years

As discussed in the BIOCLIM biosphere modelling report (Texier et al, 2004), global warming may cause onset of the next glaciation to be delayed. However, it is expected that glacial cycles will continue with a period of 10,000 years or so. Hence the range of possible biosphere conditions and that of human behaviour are too great to allow reliable modelling of the biosphere. Obviously, there is the possibility that glaciation will have eroded significant areas of the surface but there is also the possibility that, as a result either of such erosion or of technological developments, humans will no longer live anywhere near the disposal site. Therefore, in line with the principle of protecting future generations to the standards accepted today the HPA recommends that calculations are performed to give an indication of the possible range of exposures using 'reference' assumptions. This involves considering a few reference biospheres. The HPA recommends that doses are calculated for exposures to a hypothetical representative person from a 'reference community'. The reference community should normally comprise 'typical subsistence farmers'. They should not have extreme habits, eg they should not be extreme consumers of particular foods. A small number of reference communities may be appropriate to reflect a range of conditions. In line with the precautionary approach, the reference community for events and processes is conservatively assumed to be located where the highest environmental concentrations are, at the surface of the biosphere. Inadvertent intrusion should also be considered in this period, using present-day characteristics to ensure protection of future generations to the same standard as the current generation.

10.2.3 After 1,000,000 years

This is the approximate age of the human race. It is also the timescale over which stable geological formations can be expected to remain relatively unchanged. The scientific basis for dose and risk calculations beyond 1,000,000 years is therefore highly questionable, and assessments beyond times of, at most, a few million years can only be interpreted in a qualitative manner. In other words, they can be used to provide information on, for example, when the peak flux of radionuclides to the environment may occur and whether it could be significantly higher than the peak flux that occurs before 1,000,000 years. However, the HPA considers that it is inappropriate to apply numerical dose or risk criteria to this timescale. Obviously, it is possible to apply the same 'reference' assumptions used for the previous period but it should be remembered that any values of dose or risk estimated for this period are highly speculative. Demonstration that doses or risks are as low as reasonably achievable on this timescale is limited to a discussion using qualitative arguments.

10.3 Treatment of uncertainty

Treatment of uncertainty is an inevitable consequence of the long timescales that often have to be considered in solid waste disposal assessment. The future is inherently unpredictable, and human knowledge of the environment, and how to model it, is incomplete. It is not possible (even in principle) to model every possible future sequence of events, so formulations have to be developed for disposal assessments. Uncertainty may be divided into several broad categories:

a conceptual uncertainty arising from how well the conceptual model represents the reality of the disposal facility it is meant to describe,

b scenario uncertainty arising from how appropriate and how comprehensive or complete is the choice of scenarios,

c modelling uncertainty arising from how well the mathematical models represent the conceptual understanding,

d parameter uncertainty arising from the uncertainty in the parameter values for use in the models. Parameter uncertainty may be due to natural variability, eg groundwater velocity, or the fact that human knowledge of any complex system will be incomplete, eg the inexact nature of measurement techniques.

It is important that an assessment is clear and transparent and should describe how these uncertainties are addressed.

It is recommended that risk calculations should be performed in stages, with the types of uncertainty that are included in each stage identified clearly. The stages could include the following.

'Central value' calculation For each scenario, each parameter, including the probability of the scenario, is assigned a central value, and a single calculation is performed to give the central dose or risk value for that scenario. The sum of the doses or risks from all of the relevant scenarios (bearing in mind whether, in this summation, the representative groups in the different scenarios could be of the same people) gives a single value of dose or risk that can be compared with the appropriate criterion.

Sensitivity analyses Conceptual and modelling uncertainty could be addressed by using, for example, alternative models, bounding and scoping studies, laboratory and field studies, and natural analogues.

Scenario selection Uncertainty as to the future evolution of the site could be addressed by selecting a range of scenarios to represent qualitatively different possibilities. Each scenario may represent itself as a series of possible futures which have very similar radiological consequences and hence can be treated together as one possible future evolution. Each of the scenarios has a probability associated with it which represents the relative likelihood of that scenario actually occurring. The set of scenarios should be sufficient to encompass every reasonably plausible evolution of the site and therefore the sum of the scenario probabilities should be unity.

Uncertainty analysis To determine the confidence in the results for each scenario. For each scenario, each parameter whose value is uncertain is assigned a probability density function to represent the relative likelihood of that parameter having a particular value within a range of possible values. A large number of calculations (runs) is then performed, with each parameter value being sampled from the appropriate probability density function. Since each run generates a value of dose and its associated risk, a probability density function of the dose or risk from each scenario is generated. Various characteristics of this function may be calculated: for example, the 95th percentile of the distribution may be taken to indicate a risk which is unlikely to be exceeded.

If the central value calculation for any scenario indicates that the dose to the hypothetical representative person would exceed 0.1 Sv in a year (the approximate lower limit for deterministic effects) then the scenario should not be included in the uncertainty analysis but should be treated separately. The parameter values used in that scenario should be documented and a more accurate estimate obtained of the probability of such a dose being received.

The ICRP publishes dose coefficients for external radiation exposure and intakes of radionuclides for use in the calculation of effective dose to a reference person. As discussed by Harrison and Streffer (2007), because the dose coefficients are calculated using defined models and specified radiation and tissue weighting factors, for the purposes of regulatory control, they are used as point values and are not regarded as subject to uncertainty. However, it is recognised that there are uncertainties in all inputs to these calculations, including biokinetic and dosimetric models and risk estimates for stochastic endpoints. Considering doses from intakes of radionuclides, uncertainties vary depending on the element, extent of knowledge of the chemical form involved and the route of intake. Typically, uncertainties are small for some radionuclides, such as isotopes of caesium and iodine, with a range of around two to three, but for other radionuclides, such as isotopes of plutonium, uncertainties can exceed a factor of ten. Knowledge of the magnitude of uncertainties can be a useful input to decisions on the optimisation of protection.

10.4 Compliance with numerical criteria in the face of uncertainty

When risk calculations are made, the uncertainty in those calculations will mean that the ‘result’ is not a single value, but a probability density function can be constructed to represent the relative likelihood of different values, and a central value can be estimated. In order to compare these results with a criterion, such as a constraint, it is necessary to decide which calculated value(s) of risk should be used.

The values which are most likely to be important are those of the central value and one of the upper percentiles (the 95th, for example). The former may be regarded as representing the likely risk, while the latter could represent a reasonable level of assurance that unacceptable risks will not be incurred.

The results of risk calculations undertaken to support an application for authorisation for disposal of solid radioactive waste should provide a reasonable level of assurance that the radiological criteria are not exceeded, taking into account the points made in the previous two paragraphs.

As discussed in Section 10.2.2, for timescales beyond 10,000 years or so it will be difficult to model the biosphere realistically, and at times approaching 1,000,000 years it will become increasingly difficult to model the geosphere. Therefore at long timescales qualitative arguments rather than quantitative calculations are likely to become increasingly important and, correspondingly, the numerical criteria will become less important.

10.5 Optimisation

Optimisation continues to play a key role in radiological protection and should be a continuous, forward-looking, iterative process. The risk constraint for processes and events affecting the disposal facility and the dose guidance range for inadvertent human intrusion directly into near-surface facilities are intended to give an indication of the upper bounds of acceptable risk and dose for these circumstances. However, it is also important that the risks and doses are optimised below these levels. For circumstances where no numerical criteria have been given, ie inadvertent human intrusion directly into geological facilities, optimisation is the key consideration. The main factors in the optimisation process are: the likelihood of exposures; the number of people exposed; and keeping the magnitude of their individual doses as low as reasonably achievable, taking into account economic and social aspects. It should be remembered that it will be necessary to weigh up short-term factors relating to the design, construction and operational periods, such as costs and occupational doses, against long-term factors, such as doses to the public following the closure of the waste disposal facility. Other relevant considerations are the management of non-radiological hazards, potential adverse impacts and the technical feasibility and effectiveness of any mitigating action.

The ICRP comments in its recommendations (ICRP, 2007) that the intention of the optimisation principle is that ‘the level of protection should be the best under the prevailing circumstances, maximising the margin of benefit over harm’. It must be stressed that optimisation does not mean minimisation; optimisation should balance detriment against the resources available. Thus the overall best option may not necessarily be the one with the lowest estimated doses to future generations.

As the best waste management option will always be specific to the exposure situation, the waste and the waste disposal facility, it is not relevant to specify a dose level below which optimisation is no longer required. Nevertheless, if the radiological impact is very small then inappropriate levels of effort could be expended on comprehensive and detailed optimisation studies in order to reduce the risk further. It is important that the level of effort expended on reducing the dose or risk is proportionate to the dose or risk associated with the waste management option.

Society’s perception of low consequence, high probability events tends to differ fundamentally from that of high consequence, low probability events. Therefore when individual risks are used in optimisation studies, the probability and consequences should always be given separate consideration. This also links to the need for transparency in the optimisation process due to its judgemental nature. All the data, parameters, assumptions and values used in the process should be presented. This should ensure that there is traceability in the decision-making process, resulting in an informed decision and giving greater confidence in the optimisation process.

10.5.1 Collective doses

The main radiological input into optimisation studies has generally been the total (integrated) collective dose as a surrogate for the total health detriment incurred. However, this is not always appropriate for waste management options because of the long timescales and uncertainties involved. The post-closure collective dose to members of the public is dependent on detailed assumptions about the biosphere, human behaviour and population size so that such calculations must be treated with extreme caution. An optimisation study requires parameters that enable the decision-maker to differentiate between the different options and the uncertainties in the long-term collective dose mean that this is not a useful discriminator.

In Publication 101 on dose assessments for radiological protection and their optimisation (ICRP, 2006), the ICRP gives some advice on the use of collective doses. In particular, the ICRP makes it clear that under certain circumstances it is inappropriate to use collective doses when optimising: 'When the exposures occur over large populations, large geographical areas, and long periods of time, the total collective dose (ie the summation of all individual exposures in time and space) is not a useful tool for decision aiding because it may aggregate information excessively and could be misleading for selecting protective actions'. The ICRP also states that collective dose is not intended as a tool for epidemiological risk assessment, and it is inappropriate to use it in risk projections. In particular, the calculation of the number of cancer deaths based on collective doses from trivial individual doses should be avoided. The HPA concurs with this view for assessments of solid waste disposal.

In situations where collective doses are useful, the ICRP document advises on a move away from collective doses to 'group' doses, thus taking earlier guidance on disaggregation a step further. Essentially the ICRP recommends that, in broad terms, the concept of collective dose is retained but within the context of a 'dose matrix'. A European Commission report (Smith et al, 2006) examined the guidance on the calculation, presentation and use of collective doses for routine discharges. The report concluded that collective doses to a limited number of population groups over various periods could be determined, and this could go some way to providing the required breakdown of collective dose into different geographical regions and times for a dose matrix. For long periods, however, the report found that the *per-caput* dose rate is similar for all geographical populations and hence there is little to be gained from the dose matrix approach for times far into the future.

For collective doses resulting from discharges during the operational and active institutional control phases the Environment Agency et al (2002) in their document on principles for prospective assessments state that the collective dose should be truncated at 500 years. As one of the co-authors of this document, the HPA * concurs with this truncation time for the calculation of collective dose

* At the time, the NRPB was a co-author of the document.

from controlled discharges. However, for collective doses resulting from the disposed waste in the post-active institutional control phase it is not possible to recommend a specific truncation time. Collective doses and 'group' doses should only be calculated for times where they can serve as a useful discriminator between the different waste management options. This is likely to be of the order of several hundred years post-closure but the exact length of time will be dependent on the disposed waste and type of facility. However, it is inadvisable to consider the very-long-term collective dose to members of the public in view of the large uncertainties. These uncertainties effectively make any comparison meaningless.

11 Conclusions

11.1 Need for new advice

There are two main reasons for revising the advice on radiological protection objectives for the land-based disposal of solid radioactive wastes. First, the previous advice was based on recommendations from the ICRP which have recently been updated (ICRP, 2007). Second, there have been a number of recent policy reviews by the UK Government looking at the options for radioactive waste disposal.

The major principles to be applied to radiological protection in the context of solid waste disposal are, as in the previous advice, application of individual dose and risk constraints and the optimisation of protection. Individuals and populations who might be alive at any time in the future should be accorded a level of protection at least equivalent to that which is accorded to individuals and populations alive now.

11.2 Criteria for operational and active institutional control phases

The operational and active institutional control phases of any disposal facility for radioactive wastes will be subject to the regulatory regime existing at that time. The same radiological protection principles and criteria that apply to facilities using radioactive materials should also apply to those disposing of the waste.

11.3 Criteria for passive control and uncontrolled phases

11.3.1 Processes and events affecting the disposal facility

For all processes and events that lead to exposure of individuals (other than human intrusion directly into a waste disposal facility), the HPA recommends that a risk constraint of 1 in 100,000 per year is applied to the exposure of an individual representative of the more highly exposed individuals in the population, and is applied to the exposure from a single waste disposal facility. This risk constraint is intended to apply at the planning stages of the disposal facility or at the planning stages of any future disposals at an existing disposal facility. In line with the basic philosophy of radiological protection, meeting this risk constraint is not sufficient in itself: optimisation is required to reduce the risk to a value below this risk constraint, economic and social factors being taken into account. Conversely, this risk constraint should not be viewed as a limit but as a factor in the optimisation process.

If there is another disposal facility which might be affected by the same natural processes and events as the disposal facility being proposed then consideration should be given to the combined doses and risks to any relevant group of individuals.

11.3.2 Inadvertent human intrusion into the disposal facility

For inadvertent human intrusion into a near-surface disposal facility the HPA recommends an annual dose guidance range of around 3–20 mSv related to the exposure of an individual representative of the more highly exposed individuals in the population following inadvertent intrusion. Values towards the lower end of this range are applicable to assessed exposures continuing over a period of a year or more (prolonged exposures), excluding the contribution from radon. If the radon contribution is included then the appropriate values could be up to a factor of three higher. Values towards the upper end of the range are applicable to assessed exposures that are only short term (transitory exposures), ie where the dose is received within one year and none is received in subsequent years (the 20 mSv value applies to the total transient dose).

For geological disposal facilities the potential for inadvertent human intrusion has already been reduced by placing the waste at depth. Although the potential for intrusion and resulting doses, including deterministic ones from higher activity waste, cannot be completely eliminated, the principle of optimisation applies, ie to show that all that can reasonably be done has been done. Therefore the HPA considers that it is not useful to specify a dose constraint or dose guidance level. However, it is still important that a few scenarios are used to explore the range of likely probabilities of intrusion and the consequences of intrusion into a geological disposal facility and to demonstrate that protection has been optimised. These scenarios should illustrate the potential impacts of inadvertent human intrusion on the intruder and others affected by the intrusive actions, and not be seen as a definitive statement about the possible evolution of the waste disposal facility and the state of the human society that may come into contact with it.

11.4 Assessment of doses and risks

The level of complexity and effort expended on the assessment of doses and risks should be commensurate with the level of hazard presented by the waste. Assessments of doses to workers and doses to the public from any operational discharges during the operational and active institutional control phases should be performed in the same way as for existing facilities. For future periods, the HPA recommends that for processes and events it should be conservatively assumed that the hypothetical representative person inhabits the area where the concentrations resulting from the disposal facility are greatest. For inadvertent human intrusion, the HPA recommends that it is conservatively assumed that intrusion could occur as soon as active institutional control ceases but that other times of intrusion are also considered to encompass the range of possible results. For periods up to around 10,000 years the biosphere can be assumed to remain broadly similar to that of the present day, eg temperate, although the effect of expected changes such as increased coastal erosion and inundation should also be addressed. Beyond about 10,000 years the HPA recommends that a number of reference biospheres are used in the calculations to give an indication of the possible range of exposures. The results of any of these assessments should be treated in a more qualitative way. Calculations of dose and risk for times greater than a few million years into the future are unlikely to be sufficiently reliable to be warranted. Demonstration that doses or risks are as low as reasonably achievable should rely upon qualitative arguments.

The HPA recommends that where radon is a significant contributor to the estimated doses the assumptions made in the assessments of the doses from radon should be clearly stated.

11.5 Treatment of uncertainty

Where possible, different types of uncertainty (conceptual, modelling and parameter) should be addressed in turn by a series of calculations. The stages that could be included are as follows. Conceptual and modelling uncertainty may be addressed by means of sensitivity analyses, alternative models and comparisons with field studies and natural analogues. Uncertainty as to the future evolution of the site may be addressed by means of a series of distinct scenarios, representing qualitatively different possibilities. Central value risk calculations may be performed for each scenario. Parameter uncertainty may be addressed by uncertainty analysis, giving a probability distribution of possible outcomes (ie risks).

For a facility to be acceptable the results from the assessment should provide a reasonable assurance that the relevant criterion will not be exceeded. It is likely that the parameters of interest will be the central value and an upper percentile of the distribution obtained from uncertainty analysis.

If the central value calculation for any scenario indicates that the dose to the hypothetical representative person would exceed 0.1 Sv in a year (the approximate lower limit for deterministic effects) then the scenario should not be included in the uncertainty analysis but should be treated separately. The parameter values used in that scenario should be documented and a more accurate estimate obtained of the probability of such a dose being received.

11.6 Optimisation of protection

All risks, to individuals and populations, should be kept as low as reasonably achievable, economic and social factors being taken into account. Calculations of collective dose (or societal risk), as an input for optimisation studies, extending far into the future are unlikely to be reliable, and therefore such calculations are not, in general, recommended. When individual risk is used as an input for optimisation studies, separate consideration should be given to the probability and dose elements of risk.

12 Changes from Previous Advice

This section summarises the main changes from the previous advice (NRPB, 1992) and the main changes to the proposed advice (HPA, 2008b) as a result of the consultation.

12.1 Changes from the previous NRPB advice

The main changes from the previous advice (NRPB, 1992) are given below.

a Risk is now given in terms of detriment rather than fatal cancers and serious hereditary effects. Detriment is defined in the ICRP recommendations (ICRP, 2007) as the probability of attributable fatal cancer, weighted probability of attributable non-fatal cancers, weighted probability of severe hereditary effects and length of life lost if the harm occurs. However, the previous ICRP recommendations (ICRP, 1991) gave the value of the risk coefficient of fatal cancer and serious hereditary effects as 0.06 per Sv and the new ICRP recommendations give the value of the detriment-adjusted risk coefficient as 0.06 per Sv (when rounded) so the numerical value of the risk coefficient to be used has not changed.

b The previous advice did not distinguish between near-surface and geological disposal facilities.

c The previous advice was framed in terms of risk only and hence applied a risk constraint to all processes and events including inadvertent human intrusion. This advice gives dose criteria for inadvertent human intrusion.

12.2 Changes from the HPA consultation document

The main changes from the consultation document (HPA, 2008b) are given below.

a The HPA now recommends that a lower dose constraint of 0.15 mSv (annual dose) should apply to exposure to the public from a new disposal facility for radioactive waste during the operational and active institutional control phases.

b Doses from the build-up of radon gas should be included in the estimates of dose and risk for comparison with the criteria. However, the doses and risks estimated for radon should also be presented separately so the contribution of radon gas can be clearly seen and understood.

c A lower guidance level of risk for processes and events of 1 in 1,000,000 per year is no longer specified. However, the need for optimisation below the risk constraint and for the level of effort expended on reducing the dose or risk to be proportionate to the dose or risk associated with the waste management option is stressed.

d The recommendation that the total probability of a person receiving a dose above 0.1 Sv as a result of naturally occurring events should not exceed 1 in 1,000,000 per year is no longer given. The HPA decided that this was not an effective way of preventing deterministic doses as the estimates of the probability of occurrence are not very reliable. The HPA expects that, for the types of waste that are suitable for disposal in near-surface facilities, processes and events affecting the disposal facility are unlikely to give rise to severe deterministic injuries. The advice does recommend that for geological disposal facilities the likelihood of deterministic effects arising should be one of the factors considered in the optimisation study.

e The annual dose criteria for inadvertent intrusion into a near-surface disposal facility are now expressed as a range, from 3–20 mSv, rather than specifying 3 mSv for long-term exposures and 20 mSv for exposures of less than one year.

f Contextual information on the current UK regulatory regime for radiological protection has been removed. This information was included in the consultation document to provide background for the proposed advice but, in the light of the fact that it could change over the expected lifetime of this HPA advice, has been removed.

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Glossary

Authorising departments The agency or department responsible for granting an authorisation (permission) for disposal under Section 13 of the Radioactive Substances Act 1993. In England and Wales this responsibility lies with the Environment Agency, in Scotland with the Scottish Environment Protection Agency (SEPA), and in Northern Ireland with the Northern Ireland Environment Agency, an agency within the Department of the Environment for Northern Ireland.

Becquerel The special name for the SI unit of activity. One becquerel (Bq) is one disintegration per second.

Biosphere Those parts of the environment to which humans normally have access, plus the deep oceans. The biosphere will normally include soils, freshwater bodies, the atmosphere and the marine environment, and also the plant and animal life present in those parts of the environment (either naturally or as a result of human activities). For modelling purposes, the precise location of the boundary between the biosphere and the geosphere will depend on the modelling approach adopted.

Central value The value of a model parameter considered to be most likely to represent the true value for a specified *scenario*. The central value need not be any particular characteristic of the distribution of possible values, but should be determined on the basis of, for example, expert opinion or literature review.

Central value calculation A calculation performed using the *central values* for all parameters for a specified scenario.

Critical group Defined by the ICRP as a group of people representative of those individuals in the population expected to experience the highest individual risk. The group should be relatively homogeneous with respect to age, diet and those aspects of behaviour that affect the risk.

Deterministic effect A radiation-induced health effect for which the severity of the effect is related to the magnitude of the exposure, with an exposure threshold below which no effect occurs.

Detriment Detriment (specifically radiation detriment) is a concept used to quantify the harmful health effects of radiation exposure in different parts of the body. It is defined by the ICRP as a function of several factors, including incidence of radiation-related cancer or heritable defects, lethality of these conditions, quality of life, and years of life lost due to these conditions.

Detriment-adjusted risk The probability of the occurrence of a stochastic effect, modified to allow for the different components of the detriment in order to express the severity of the consequence(s).

Disposal In the context of this document, disposal is the emplacement of waste in a land disposal facility without intent to retrieve it at a later time; retrieval may be possible but, if intended, the appropriate term is *storage*.

Dose constraint A prospective and source-related restriction on the individual dose from a source, which provides a basic level of protection for the most highly exposed individuals from a source and serves as an upper bound on the dose in optimisation of protection for that source. For occupational exposures, the dose constraint is a value of individual dose used to limit the range of options considered in the process of optimisation. For public exposure, the dose constraint is an upper bound on the annual doses that members of the public should receive from the planned operation of any controlled source. Thus the dose constraint places a restriction on the annual dose to an individual from a particular source in order to ensure that when aggregated with doses from all sources, excluding natural background and medical procedures, the dose limit is not exceeded. The Government has set a maximum dose constraint value of 0.3 mSv per year when determining applications for discharge authorisations from a single new source, and a dose constraint value of 0.5 mSv per year for a complete site (which may include several sources with more than one operator).

Dose limit The value of the effective dose or the equivalent dose to individuals from planned exposure situations that shall not be exceeded. For the purposes of discharge authorisations, the UK has (since 1986) applied a dose limit of 1 mSv per year to members of the public from all man-made sources of radioactivity (other than from medical applications).

Effective dose The tissue-weighted sum of the equivalent doses in all specified tissues and organs of the body. This takes account of the relative risks associated with exposure of different organs. It is measured in sievert (Sv). The committed effective dose is the effective dose that will be received by the person over their lifetime as a result of radionuclides taken into the body, eg by ingestion or inhalation.

Emergency exposure situations Unexpected situations that occur during the operation of a practice, requiring urgent action. Emergency exposure situations may arise from practices.

Equivalent dose The radiation-weighted dose in a tissue or organ. This takes account of the different amounts of damage caused by different types of radiation, eg alpha particles and gamma radiation. It is measured in sievert (Sv).

Events Events that have a probability of happening, a specific starting time and a relatively short duration. Examples are flooding and seismic events.

Existing exposure situations Situations that already exist when a decision on control has to be taken, including natural background radiation and some situations involving residues from past practices or accidents.

Geological disposal facility Land-based disposal facility whose depth, taken in the particular geological context, is sufficient to provide a very long delay – tens of thousands of years – before natural features, events and processes would be expected to allow any significant escape of radionuclides from the facility to the accessible environment. In this context, 'deep' can imply horizontal instead of, or as well as, vertical distance as, for example, in the case of a disposal facility sited deep within a mountain.

Geosphere Those parts of the environment below the ground or seabed and beyond the normal range of human access. This may include sub-soils as well as rocks.

Guidance on requirements for authorisation (GRA) A document produced by the authorising departments giving the standards that they will use to judge an application for authorisation for disposal of radioactive waste. The current version of the document was published in 1996 and a revised version will be published in 2009.

Inadvertent human intrusion Intrusion into a disposal facility without full knowledge of the presence and nature of the facility or any other human actions that damage engineered barriers or degrade their functions, such as removing material from a disposal facility cap.

Intervention Any action intended to reduce or avert exposure or the likelihood of exposure to sources that are not part of a controlled practice or that are out of control as a consequence of an accident.

Justification The process of determining whether: (a) a planned activity involving radiation is likely, overall, to be beneficial, ie whether the benefits to individuals and to society from introducing or continuing the activity outweigh the harm (including radiation detriment) resulting from the activity, or (b) a proposed remedial action in an emergency or existing exposure situation is likely, overall, to be beneficial, ie whether the benefits to individuals and to society (including the reduction in radiation detriment) from introducing or continuing the remedial action outweigh its cost and any harm or damage it causes.

Licensing A general term to encompass the different regulatory approval procedures required for the construction and operation of radioactive waste disposal facilities in the UK.

Natural analogue A natural geological system in which processes analogous to those induced by radioactive waste disposal are thought to be operating over long timescales and space scales.

Near-surface disposal facility Land-based disposal facility that is located directly at the surface of the ground, or at depths down to several tens of metres below the surface. For facilities that are constructed at depth they may also be located such that although accessed from land the facility would be under the seabed. Such facilities might be constructed with the intent that they will be covered by clean material to a specified/suitable depth at closure or, in the case of deeper facilities, they might be excavated caverns within the existing rock mass. In addition, it is possible that use of existing structures, that are suitably located and for which a safety case can be made, may be proposed.

Normal exposures Exposure that is expected to occur under the normal operating conditions of a facility or activity, including possible minor mishaps that can be kept under control, ie during normal operation and anticipated operational occurrences.

Operational phase The period during which a disposal facility is receiving waste and is being sealed before closure.

Optimisation of protection (and safety) The process of determining what level of protection and safety makes exposures, and the probability and magnitude of potential exposures, as low as reasonably achievable, economic and social factors being taken into account.

Per caput The average level for a person.

Phased geological disposal option The phased geological disposal option of the Government's Committee on Radioactive Waste Management (CoRWM) involves the incorporation of design features that would enable a disposal facility to stay open and function as a storage facility for several hundred years – though it could be sealed much sooner, even vault by vault as each is filled.

Planned exposure situations Everyday situations involving the planned operation of sources including decommissioning, disposal of radioactive waste and rehabilitation of the previously occupied land. Practices in operation are planned exposure situations.

Post-closure phase The period after a disposal facility has been closed. This includes the active institutional control phase, the passive institutional control phase and the subsequent uncontrolled phase.

Potential exposure Exposure that is not expected to be delivered with certainty but that may result from an accident at a *source* or an event or sequence of events of a probabilistic nature, including equipment failures and operating errors.

Practice Any human activity that introduces additional sources of exposure or additional exposure pathways, or extends exposure to additional people, or modifies the network of exposure pathways from existing sources, so as to increase the exposure or the likelihood of exposure of people or the number of people exposed. Radioactive waste is generated as a result of practices and the management of this waste is therefore only one part of the overall practice.

Processes Processes that have gradual, continuous interactions with the disposal facility. Examples are leaching of the radioactive waste and subsequent migration of radionuclides in the groundwater.

Prolonged exposure Exposure that continues at broadly the same level for periods of the order of decades or longer.

Radiation and tissue weighting factors Dimensionless factors used by the ICRP to reflect the different biological effectiveness of different types of radiation, and the relative contribution of the tissue or organ to the health detriment.

Reference level In emergency or existing controllable exposure situations, this represents the level of dose or risk, above which it is judged to be inappropriate to plan to allow exposures to occur, and below which optimisation of protection should be implemented.

Relative biological effectiveness The ratio of a dose of low linear energy transfer reference radiation to a dose of the radiation considered that gives an identical biological effect.

Representative person Defined by the ICRP as an individual receiving a dose that is representative of the more highly exposed individuals in the population. This term is the equivalent of, and replaces, 'average member of the critical group' described in earlier ICRP publications.

Risk The probability of harm, eg cancer, in a year. It takes into account the probability of receiving a dose in a year and the probability that the dose received will give rise to harm.

Risk constraint A prospective and source-related restriction on the individual risk (in the sense of the probability of detriment due to a potential exposure) from a source, which provides a basic level of protection for the individuals most at risk from a source and serves as an upper bound on the individual risk in optimisation of protection for that source. This risk is a function of the probability of an unintended event causing a dose, and the probability of detriment due to that dose. Risk constraints correspond to dose constraints but refer to potential exposures.

Risk target A concept defined by the authorising departments in their guidance on requirements for authorisation. It is a level of radiological risk from a single disposal facility which provides a numerical standard for assessing the long-term performance of the facility. The numerical value of the risk target is 1 in 1,000,000.

Scenario A defined sequence of possible future conditions at or around a waste disposal site from which the future behaviour of activity from the site may be calculated. A scenario may include a number of events.

Sievert The special name for the SI unit of equivalent dose and effective dose. One sievert (Sv) is one joule per kilogram.

Site For a disposal facility, the piece of land where the facility is, or is intended to be, located. In the context of this document a site may contain more than one disposal facility under common management and is therefore analogous to the ICRP definition of a source.

Source Defined by the ICRP as an entity for which radiological protection can be optimised as an integral whole, such as the X-ray equipment in a hospital, or the releases of radioactive materials from an installation. Sources of radiation, such as radiation generators and sealed radioactive materials, and, more generally, the cause of exposure to radiation or to radionuclides. A source may comprise a number of facilities under common management.

Stochastic effect A radiation-induced health effect for which the probability, but not the severity, of the effect is related to the magnitude of the exposure.

Storage Placement of waste in any facility with the intent to retrieve it at a later time.

Subsidence The gradual sinking or settling of the ground surface through compaction. Sudden events may also occur due to collapse of underground caverns.

Uplift The gradual rising of the ground surface that arises in the warmer period following a period of glaciation. Melting of the ice means that its weight is no longer pressing down on to the ground and therefore it slowly becomes less compacted.

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