NRPB-M279

Consultative Document

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

NRPB-M279

National Radiological Protection Board

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Units

As from 1 April 1978 NRPB adopted the International System of Units (SI). The relationships between the SI units and those previously used are shown in the table below.

Quantity	Unit and symbol	In other SI units	Old unit and symbol	Conversion factor
Exposure	-	$C\ kg^{-1}$	röntgen (R)	$1\ C\ kg^{-1} \sim 3876\ R$
Absorbed dose	gray (Gy)	$J\ kg^{-1}$	rad (rad)	1 Gy = 100 rad
Dose equivalent	sievert (Sv)	$J\ kg^{-1}$	rem (rem)	1 Sv = 100 rem
Activity	becquerel (Bq)	s^{-1}	curie (Ci)	$1\ Bq \sim 2.7\ 10^{-11}\ Ci$

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National Radiological Protection Board
Chilton
Didcot
Oxon OX11 0RQ

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Draft Statement

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

SCOPE

1 The Board has the responsibility 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 1983[1]. The following revised guidance takes into account experience gained in the UK and other countries since the publication of that advice, and allows for the most recent recommendations published by the International Commission on Radiological Protection[2,3], and advice that has been given by other national and international bodies[4-7]. The principles and criteria given below are intended to apply specifically to land-based waste disposal facilities, where human access is from land, but may be applied more generally in judging the acceptability of other disposal options.

PROTECTION OF THE PUBLIC

2 The basic principles recommended by the Board for the protection of the public following the disposal of solid radioactive wastes are as follows.

(i) The radiological risks to members of the public should be as low as reasonably achievable, economic and social factors being taken into account (ALARA) - *optimisation of protection*.

(ii) In order to ensure that individual members of the public are not exposed to unacceptable risks, the radiological risk to a typical member of the critical group, attributable to a single waste disposal facility, shall not exceed the specified constraint - *limitation of individual risk*.

(iii) 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.

3 For the purpose of these objectives, risk is defined as the overall probability that a serious deleterious health effect will occur as a result of exposure to ionising radiation.

ASSESSMENT OF RADIOLOGICAL RISKS

4 Calculations to predict radiological risks in the future should take due account of the uncertainties inherent in such predictions. 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.

5 For times up to about one hundred years after the closure of the site, it may be assumed that some form of institutional control over the site will remain. During this period, the system of dose limitation should be applied. For times greater than one hundred years or so, but less than about ten thousand years into the future, the Board considers that the risk to members of the critical group should be predicted for comparison with the risk constraint. Predictions about the human environment and human behaviour more than ten thousand years or so into the future are unlikely to be valid, and therefore such predictions should be replaced by general assumptions. The Board considers that individuals who might be alive within this time frame will be adequately protected if calculations indicate that suitably chosen, hypothetical reference communities would not be exposed to unacceptable risks.

6 Furthermore, any predictions about the natural environment more than one million years or so into the future are unlikely to be valid, and therefore predictive calculations should not be continued beyond this time. Qualitative arguments should be used, however, to show that the likelihood of any sudden, significant increases in risks after this time is low. The specified risk constraint should therefore apply from the time institutional control of the site is assumed to be lost (a maximum of one hundred years or so after closure) until such time as risk calculations cease to be valid, taken to be one million years or so from the present day.

7 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 such events occurring is ALARA. The total probability of such events occurring as a result of natural events and processes should be below the specified constraint.

8 Calculations to predict radiological risks should include estimates of the uncertainty in these predictions due to incomplete or inadequate knowledge of the system being modelled and the environmental behaviour of radionuclides. In determining compliance with any numerical risk criterion, both the best estimate and a measure of the uncertainty in that estimate should be considered.

OPTIMISATION OF PROTECTION

9 Whilst recommending that all risks should be kept ALARA, the Board recognises the difficulties involved in carrying out detailed optimisation studies for solid waste disposal facilities; in particular, the difficulty in obtaining reliable estimates of the total risk over long timescales, and the extensive resources often required to carry out such studies (especially when this involves study of a number of possible disposal sites). The Board therefore recommends that, if the risk to a typical member of the critical group, attributable to a single waste disposal site, does not exceed the specified design target, then the optimisation requirement should be relaxed for that site. The design target

represents a level of individual risk which is widely regarded as acceptable, and which is rarely taken into account by individuals in making decisions as to their actions.

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

INTRODUCTION

1 In 1983, the Board published guidance[1] on the application of the ICRP system of dose limitation[2] to the disposal of solid radioactive waste. In 1984, the UK authorising departments issued principles to be used in assessing licensing applications for land-based disposal facilities for low and intermediate level waste (LLW and ILW)[3]. ICRP published its first specific advice on principles for solid waste disposal in 1985[4]. IAEA[5] and NEA[6] have also issued recommendations concerning solid waste disposal and its regulation.

2 The basic recommendations on radiological protection have recently been revised by ICRP, and its revised advice will be published in the spring of 1991[7]. The 1990 recommendations will take account of, among other things, the re-assessment of the risks associated with exposure to ionising radiation resulting from epidemiological studies on the Japanese atomic bomb survivors. The publication of revised ICRP recommendations is one of the factors in the Board issuing new advice relating to solid waste disposal.

3 This report summarises the Board's reasons for issuing new advice relating to solid waste disposal, and gives detailed guidance on the interpretation and application of the principles contained in the Board's statement[8].

EXISTING ADVICE

4 In NRPB-GS1[1], the Board recommended that the risk to an individual (of fatal cancer and hereditary effects in his/her descendants) from waste disposal should not exceed 10^{-4} in a year or, in situations where doses are incurred over periods exceeding 10 years, 2 10^{-5} in a year. In 1983, when NRPB-GS1 was published, the ICRP estimate of the risk of fatal cancer in an individual and serious hereditary effects in any of his/her descendants was about 0.02 Sv^{-1} (0.0125 Sv^{-1} for fatal cancer and 0.008 Sv^{-1} for hereditary disease in all generations), and the recommended dose limit for members of the public was 5 mSv in any single year, with a lifetime average of 1 mSv per year. The risk limits proposed by NRPB were, therefore, consistent with the dose limit and objective recommended by ICRP.

5 The authorising departments' principles[3] specify that 'the risk to any member of the public in any one year, from exposure to radiation from all sources other than background and medical exposure, should not be greater then that associated with a dose of 1 mSv', ie a risk of death of about 10^{-5} y^{-1}, using the rounded risk factor for fatal cancer recommended by ICRP at that time, namely 0.01 Sv^{-1}. By considering the possibility of multiple exposures, this limit is used to define a risk 'target' applicable to any single waste disposal site of 10^{-6} y^{-1} (the annual fatal cancer risk

associated with a dose rate of 0.1 mSv y^{-1} under the 1977 ICRP recommendations[2]).

6 ICRP, in its advice on solid waste disposal[4], recommended that 'normal scenarios' for disposal sites (ie gradual degradation of the waste, leading to release of activity into groundwater and subsequent migration through the environment to man) should comply with a dose limit for individual members of the public of 1 mSv y^{-1} from all non-medical artificial exposures, and that a separate risk limit of 10^{-5} y^{-1} (of fatal cancer and serious hereditary effects) should apply to exposures from all 'probabilistic events' at waste disposal sites.

7 In each of the cases quoted above, the limits were specified to apply for all times in the future, ie individuals alive in the future were accorded a level of protection equal to that given to individuals alive now.

8 The revised ICRP recommendations[7] concerning practices giving rise to exposure to ionising radiation may be summarised as follows.

(i) No practice shall be adopted unless it produces a positive net benefit (*justification*). This principle does not apply to waste management in isolation from the practice which produces the waste, but rather to the practice as a whole, and therefore justification is beyond the scope of this report.

(ii) All exposures shall be kept as low as reasonably achievable (ALARA), economic and social factors being taken into account (*optimisation of protection*). In this context, 'exposures' may be taken to mean doses or risks.

(iii) The *dose limits* recommended for individuals by ICRP shall not be exceeded. In cases where doses are not certain to occur ('potential exposure situations'), dose limits may be supplemented by risk limits.

9 The other main features of the new ICRP recommendations which are relevant to this report are as follows.

(i) The estimate of the risk of fatal cancer associated with exposure to ionising radiation, for a typical population of all ages, is now 0.05 Sv^{-1}, and the estimated risk of serious hereditary effects in all generations is now 0.01 Sv^{-1}. The risk of fatal cancer and hereditary effects is therefore 0.06 Sv^{-1}, and the total risk of radiation detriment (including non-fatal cancers) is about 0.07 Sv^{-1}.

(ii) The definition of effective dose (formerly effective dose equivalent) has been changed to incorporate revised tissue weighting factors, which are now based on total radiation detriment and allow for new information on cancer risks in individual tissues (fatal and non-fatal), as well as loss of life expectancy from both fatal cancer and hereditary disease.

(iii) The new recommendations introduce the ideas of dose and risk constraints which, when applied to single sources, are intended primarily to ensure that individuals are not subject to unacceptable doses or risks.

10 The 1990 ICRP recommendations are not discussed in detail in this report; a document will be issued in due course giving the Board's response to the revised advice.

NEED FOR NEW ADVICE

11 The Board now feels that the advice given in GS1[1] requires further clarification, in the light of recent experience in the field of safety assessments for solid waste disposal facilities and the revised ICRP recommendations[7].

12 Differences in the interpretation of existing advice have been particularly apparent in the prediction of exposures in the far future, and in the treatment of uncertainty.

13 It is recognised that considerable resources are being devoted to long-term, site-specific assessments for waste disposal facilities, and that, in view of the large degree of uncertainty inherent in such assessments, and the generally small magnitudes of the risks involved, it is important to consider how resources can best be concentrated on the most relevant areas of research.

14 To date, assessments of disposal sites have tended to be aimed at convincing other experts in the field, and much recent work gives too little thought to the presentational aspects of safety cases for public inquiries and for wider public reassurance. It is necessary to consider what can be done to improve the transparency of assessment methodologies, without detracting from their scientific robustness.

BOARD ADVICE ON OBJECTIVES FOR SOLID WASTE DISPOSAL

Scope

15 The *principles* (qualitative) and *criteria* (quantitative) recommended by the Board are intended to apply to the *post-closure* period for *existing and future disposal** facilities for *all* types of *solid radioactive* wastes (including wastes which arise in liquid or gaseous form, but are converted to solids prior to disposal). The advice is not intended to apply to other activities such as site operation, waste conditioning, storage, and transport, or to liquid or gaseous wastes, nor does it take account of the chemical toxicity of wastes.

16 The advice refers primarily to land-based disposal options, ie options in which access is from land. This includes disposal options in which the waste is placed below the sea bed by means of tunnels from land. However, the general principles contained in the advice may, if necessary, be used to judge the acceptability or otherwise of other waste disposal methods.

**Disposal*, as contrasted with *storage*, implies that there is no intent to retrieve the waste at a later date. This does not necessarily mean that it cannot be retrieved, only that retrieval is not intended.

Risk limits and constraints

17 *Individual risk* is the probability of a specified deleterious health effect occurring in an individual or his/her descendants as a result of exposure to ionising radiation:

$$R_i = \gamma_i \sum_j p_j \cdot E_j$$

where R_i is the risk of effect i, γ_i is the risk (or probability) of the effect per unit effective dose, and p_j is the probability of event j which, if it occurs, gives rise to an effective dose E_j (assuming this is less than about 0.5 Sv). For the purposes of this advice, the precise value of γ (see paragraph 9(i)) is relatively unimportant in the context of the other uncertainties involved. Therefore the Board recommends the use of a general value of γ to represent 'risk', when assessing solid waste disposal facilities where doses are predicted to occur well into the future (more than 100 years or so). Advice will be issued in due course specifiying the recommended value for use in such assessments.

18 A risk *limit* represents the boundary between what, to an individual, is just tolerable and what is unacceptable, if the risks are incurred on a year-by-year basis. It is an individual-related concept, and therefore applies to the total of all artificial sources of radiological risk (excluding medical exposures). Studies on the acceptability and tolerability of risks[9,10] suggest that risks much greater than 10^{-5} y^{-1} verge on the unacceptable.

19 A risk *constraint* is an upper bound on optimisation to prevent unacceptable risks to individuals who are exposed to more than one source. For a single site, the constraint is a fraction of the limit for exposure from all man-made sources. Risk constraints may also be used to limit inequity between the exposures received by different individuals. A practice which would exceed the risk constraint should not be adopted. However, compliance with a constraint does *not* mean that the practice is acceptable; the level of protection must also be demonstrated to be optimum. To allow for the possible exposure of individuals to a number of different sources, the Board recommends a risk constraint, on the exposure of a typical member of the critical group attributable to a single waste disposal facility, of 10^{-5} y^{-1} (one in one hundred thousand per year).

20 A *design target*, below the risk constraint, may be specified to indicate a risk level which is generally regarded as being of little concern. Such a target could be exceeded, provided that the level of protection is optimised, but if the target is met then the requirement for detailed optimisation shall be relaxed. The Board recommends that an appropriate design target for the risk to a typical member of the critical group attributable to a single waste disposal facility is 10^{-6} y^{-1} (one in one million per year).

Calculation of individual risk in future time frames

21 In most cases, the radiological risk to individuals from a waste disposal facility will be assessed by means of predictive models. In view of the timescales over which predictions are likely

to be made, the sophistication of these models should reflect the amount of information available.

22 The principle that future generations should be accorded a level of protection consistent with that provided today appears to have been interpreted too rigidly both by regulators and by those performing assessments. Risk limits have been specified which refer to 'any time in the future', and this has led to assessments being performed which continue to predict risks up to 10^7, 10^8, or even 10^9 years into the future, with an attempt at a constant level of detail throughout. The table gives, for perspective, a chronological table of a number of historical and (predicted) future events. It is clear that assessments which extend into the very far future (beyond about 10^6 years) can have little scientific credence, and even those with timescales of 10^4 to 10^5 years are subject to considerable uncertainty.

23 Some countries (eg Sweden[11] and the USA[12]) have introduced 'cut-off' times for site assessments at 10^4 years, beyond which risk calculations do not need to be performed for licensing purposes. For a deep repository, however, the time until activity first reaches the biosphere may be considerably greater than 10^4 years, and therefore a 'cut-off' at 10^4 years does not seem appropriate.

24 The emphasis of assessments does need to be changed, however, as the timescale of prediction increases, to reflect the scientific basis upon which calculations are made. In considering the various 'components' commonly defined in assessments - the waste form, the near field, the far field, the biosphere and humans - it is apparent that the period over which assumptions remain valid decreases as the physical distance from the waste itself increases. Consequently, attempts to make detailed predictions 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 the reliable prediction of radionuclide transport through the geosphere.

25 The Board recommends that, for calculational purposes, the future should be divided into a number of time frames. The 'boundaries' between time frames given here are orders of magnitude, for convenience; in practice, more convenient times (of similar order) could be selected in particular cases. The following time frames are suggested.

(i) **Closure to 10^2 years**
Institutional control over the site may be assumed to remain in place for 100 years at most after the site is finally sealed. During this time, the system of dose limitation should be applied.

(ii) **10^2-10^3 years**
The biosphere may be expected to remain broadly similar to the present day conditions, although human behaviour could change significantly. Site-specific risk calculations should be performed for comparison with the individual risk constraint. Assumptions about human behaviour should be generally representative of the type of area being studied (see paragraphs 26-32).

(iii) **10^3-10^4 years**

Large-scale biosphere changes are likely, but the geosphere is unlikely to undergo any major alterations. In theory, it might be appropriate to use a 'generic' biosphere and a site-specific geosphere to calculate risks and to compare them with risk criteria. In practice, however, this would introduce additional complexity into the calculational procedure, and it is not felt that this would be warranted. Therefore, it is recommended that this period be combined with the previous time frame, and that site-specific calculations should continue up to about 10^4 years. Explicit consideration should be given to the effects of possible major biosphere changes (eg rivers or lakes drying up, coastal erosion and climatic change).

(iv) **10^4-10^6 years**

Repeated glacial cycling is expected to occur within this time frame, and, whilst it is possible to make general predictions about environmental conditions, the range of possible biosphere conditions and human behaviour is too great to allow reliable predictive modelling. The emphasis of assessment should therefore be changed so that, whereas calculations relating to radionuclide transport in the geosphere continue to be predictive, calculations relating to the biosphere and human activity should be simplified, by calculating the risk to 'reference communities' in a 'reference biosphere'. In the absence of reliable detailed knowledge concerning the environmental conditions, and the types of humans that might exist in this time frame and their habits, it is sufficient to assume that if these 'reference communities' are protected, then this gives reasonable assurance that any individuals actually present will also be protected. The selection of reference communities and biospheres is discussed further in paragraphs 31-34. In effect, the approach described above is equivalent to limiting releases from the geosphere, and therefore an assessment may either:

(a) calculate the risk to members of the reference communities, with the modified assumptions about the biosphere and human behaviour indicated above and in paragraphs 31-34, and compare these risk values with the risk constraint, or

(b) use the reference communities and biospheres to convert the risk constraint into a constraint on (probability-weighted) radionuclide release rates from the geosphere. Results from geosphere transport models may then be compared directly with these constraints. Such constraints would, however, be applicable only to the particular modelling approach used: for example, the location and nature of the geosphere-biosphere interface varies from model to model.

(v) **After 10^6 years**

10^6 years is the approximate lifetime of the human race to date, and the timescale over which stable geological formations can be expected to remain relatively unchanged. The scientific basis for risk calculations in this time frame is therefore highly questionable, and assessments beyond 10^6 years should concentrate on qualitative discussions, such as under what circumstances the flow of nuclides into the environment might change significantly and/or suddenly. It is not appropriate to apply a numerical risk constraint in this time frame, but the requirement that risks should be ALARA remains applicable.

Application of the critical group concept

26 The concept of a *critical group* was developed for the assessment of doses to the public from routine effluent discharges[2]. A critical group is a relatively homogeneous group of people whose location and habits are such that they receive the highest doses as a result of the discharges. The group may be real (in which case their actual habits may be known or predicted), or hypothetical (in which case habits may be assumed, based on observed habits in similar groups). The members of a critical group are therefore representative of those people who receive the highest doses; they do not necessarily live at the point where environmental concentrations (and therefore 'potential doses') are highest.

27 The *critical group dose* is that received by a *typical* member of the critical group. The purpose of the critical group concept and the critical group dose is to ensure that the vast majority of members of the public do not receive unacceptable exposures, whilst, at the same time, ensuring that decisions as to the acceptability or otherwise of a practice are not prejudiced by a very small number of individuals with very unusual habits.

28 When assessing releases from a solid waste disposal facility, the critical group concept cannot be used directly in the form described above because, in most cases, the characteristics of the exposed population are very much more uncertain than in the case of routine discharges. However, the critical group remains a useful concept, and it is appropriate to make use of hypothetical critical groups. For the purposes of solid waste disposal assessments, these are assumed to exist, at any given time in the future, at the place where the relevant environmental concentrations (and therefore the 'potential doses') are highest, and to have habits such that their exposure is representative of the highest exposures which might be expected. 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 critical groups 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 are unlikely to be very different from the present requirements, although the range of foods consumed may change considerably.

29 By analogy with paragraph 27, the *critical group risk* is the risk to a typical individual within the hypothetical critical group. It is worth noting at this point that there may be cases where, although the exposure *risk* is relatively homogeneous within the group, the exposure to *dose*, should a dose occur, would be confined to only a very small number of the members of the group. For example, suppose a hypothetical critical group is defined as including all geotechnical workers in the UK at a given time who routinely examine drilling cores. All members of that group are exposed to approximately the same risk as a result of the possibility that a drilling core might be obtained from close to an undetected waste disposal facility. However, if such a core is obtained, only the member of the group who examines that particular core might receive a dose.

30 For calculations relating to the relatively near future (within 10^4 years), critical groups may be selected on the basis of currently observed behaviour, but a critical group's habits should be broadly representative of a type of area, rather than being based on particular extreme habits observed at a particular time in a particular place. For example, risk calculations for a repository on the Lincolnshire coast might use critical group habits typical of small fishing communities on the north-eastern coast of England, but should not then go further in selecting particular, extreme examples of behaviour observed in particular fishing communities; such detailed assumptions about human behaviour cannot be warranted in view of the uncertainty present.

31 For calculations relating to the far future (beyond 10^4 years), the critical group should represent a 'reference community', located at the point of highest environmental concentrations. The habits of such a community should be chosen conservatively, but not excessively so, based on present-day and historical information, and should be internally consistent. For example, if the reference community comprises subsistence farmers, then they should be 'typical' subsistence farmers (ie perhaps a few families who produce a range of food to feed themselves), rather than those with particular habits, and they would not be likely to drill holes hundreds of metres deep. A small number of such 'reference communities' may be chosen to reflect a range of conditions (eg for a coastal disposal site, one coastal community and one inland community, to represent different sea levels may be selected), with the most pessimistic being considered when making comparisons with the risk constraint.

32 The subject of critical groups, including the application of the concept to various areas of radiological protection, is currently under review at NRPB and elsewhere, and detailed Board advice will be issued in due course.

Reference biospheres

33 The choice of reference biospheres for the far future will be determined to a large extent by the choice of reference communities (see paragraph 31), as these communities are assumed to live at the point where environmental concentrations are highest. For example,

the area of land occupied by an inland reference community will correspond to that required to grow the crops which that community is assumed to eat, and to support the animals which it is assumed to keep. Therefore the area of contaminated land considered in the reference model should not be smaller than this minimum 'subsistence area'; the food eaten by the community is assumed to be taken from this area, and will therefore reflect the average concentration over the area as a whole. If the area of release from the geosphere is larger than the subsistence area, then only the corresponding fraction of the release will enter the relevant section of the biosphere. Similarly, for a coastal reference community, the volume of water with which the release from the geosphere may be assumed to mix 'immediately' (ie the sea area having the highest nuclide concentrations) should be at least large enough to support sufficient fish, etc, for a community which derives the vast majority of its food from that sea area. If the area over which activity is likely to be released from the geosphere is larger than this, or if observed water flows clearly indicate that greater 'immediate' dilution is likely, then the volume of water considered should be correspondingly larger.

34 In general, reference biospheres should be based broadly on present-day (temperate) conditions, as these can be modelled most readily and reliably. Reference biosphere calculations are not intended to be predictive, but simply to convert between radionuclide fluxes, which can be rather unwieldy, and risk, which is the quantity to be limited. Within the context of glacial cycling, temperate conditions are those under which there is the greatest likelihood of communities existing at a specified place. It is also worth noting that, compared to the overall level of uncertainty in long-term radiological assessments, differences between different types of biosphere conditions and human behaviour are of relatively minor importance.

Treatment of uncertainty

35 Uncertainty is the overriding problem in solid waste disposal assessment and regulation. 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 formalisms have to be developed for disposal assessments.

Types of uncertainty

36 Uncertainty may be divided into two categories: that which exists as a result of the inherent unpredictability of random processes (hereafter referred to as *objective* uncertainty), and that which arises from the fact that human knowledge of any complex system will be incomplete (*subjective* uncertainty). Objective uncertainty is intrinsic to the system being studied and is independent of human attempts to interpret the system, whereas subjective uncertainty is intrinsic to the process of trying to measure and model a system on the basis of a finite amount of information. For example, if an unbiased coin is tossed, the result cannot be predicted; whether the coin comes up heads or tails is a random process, and the outcome is objectively uncertain. If the coin is tossed 10 times, the precise number of heads cannot be

predicted, as the objective uncertainty is still there. The subjective uncertainty in this process is very small; if an unbiased coin is tossed 10,000 times, we know to expect 5,000 heads. There is a small amount of subjective uncertainty; the coin could have a slight undetected bias, and there may be a probability of the coin landing on its edge, which may be too difficult to calculate. On this basis, we could put error bars on our estimate of the expected number of heads.

37 The Board's interpretation of the term *risk* is that objective uncertainty is intrinsic to risk, and should be intrinsic to the calculation of risk, whereas subjective uncertainty should be addressed separately in terms of the confidence which can be attached to the risk calculation.

38 The treatment of 'subjective' uncertainty separately and explicitly is not only more consistent with the definition of risk, but it is also more likely to lead to clear, understandable presentation of results.

39 In practice, the distinction between the different types of uncertainty may not always be clear. Where such doubt exists, uncertainty should be regarded as being due to incomplete knowledge (ie subjective), and treated explicitly by means of uncertainty analysis.

Treatment of objective and subjective uncertainty in risk calculations

40 It is recommended, therefore, that risk calculations should be performed in three stages, as follows.

(i) Objective uncertainty as to the future evolution of the site should be addressed by selecting a range of scenarios to represent qualitatively different possibilities. Each of the scenarios should then be assigned a probability, or a degree of belief, to represent the relative likelihood of that scenario (or one similar to it) actually occurring. The set of scenarios should be complete, in the sense that every reasonably plausible evolution of the site should be comparable to one of the scenarios, and therefore the sum of the scenario probabilities should be unity.

(ii) 'Best estimate' calculation - for each scenario, each parameter should be assigned a best estimate value, and a single calculation is performed to give the *best estimate risk* for that scenario. The *weighted best estimate risk* is then the probability-weighted sum of the best estimate risks from all of the scenarios (bearing in mind in this summation whether the critical groups in the different scenarios could be the same people). This gives a single value of the weighted best estimate risk.

(iii) Uncertainty analysis - for each scenario, each parameter whose value is subjectively uncertain should be assigned a probability density function (pdf) to represent the relative likelihood of that parameter having a particular value within a range of possible values. A large number of risk calculations (runs) should be performed, with each

parameter value for each run being sampled from the appropriate pdf. For each run, the (probability-weighted) risks from the different scenarios should be summed where appropriate, bearing in mind that the scenario probabilities may also be uncertain and therefore may need to be sampled from a pdf. Each run thus yields a weighted risk, and the weighted risks from all of the runs are incorporated into a pdf representing the relative probabilities of different values of risk. This pdf therefore represents the uncertainty in the risk as a result of the uncertainty in the parameters used in calculating the risk. Various characteristics of the pdf may be calculated; for example, the 90th percentile of the distribution may be taken to indicate a risk which is unlikely to be exceeded.

41 If the best estimate calculation for any scenario indicates that the dose to a member of the critical group would exceed 0.5 Sv in a year (the approximate lower limit for deterministic effects), then that scenario should not be included in the risk calculation, but should be treated separately (see paragraphs 56-61).

42 Similarly, if, whilst performing the uncertainty analysis, any run is found to produce a critical group dose in excess of 0.5 Sv in a year, then that run should be treated separately. The parameter values used in that run should be documented, so that the specific case can be studied more closely to get a more accurate estimate of the probability of such a dose being received, and treated as discussed in paragraphs 56-61. For the purposes of constructing the pdf of risks, a risk value must be assigned to the run(s) giving rise to a high dose; however, the linear relationship in paragraph 17 is not applicable, and such a value is not easy to determine. If only the percentiles of the distribution are to be used, then the exact risk value assigned to the run in question is not important, provided that the resulting risk is above the highest percentile of interest (the 90th, say). In this case the run should be considered to have produced some nominal high risk value; the obvious choice is simply to assign a 'risk' of 1 y^{-1}. This will have only a marginal effect on the value of the 90th percentile. However, if the mean of the distribution is to be used, then a 'real' risk value will be required, as the risk value used may have a significant effect on the mean.

43 In principle, the best estimate of a parameter value is the *mode* of the pdf, ie the most probable value, and therefore the best estimate risk might be expected to be close to the mode of the distribution obtained from the uncertainty analysis. In practice, an expert who is asked for a best estimate may tend to err on the side of caution, and therefore the best estimate risk could turn out to be significantly higher than the mode.

Compliance with numerical criteria in the face of uncertainty

44 When risk calculations are made, the uncertainty in those calculations will mean that the result is actually a 'fuzzy number', ie its exact value is not known, but a pdf can be constructed to represent the relative likelihood of different values, and a best estimate can be made. In order to compare these

results with a criterion, such as a limit or target, it is necessary to decide which calculated value(s) of risk should be used.

45 The values which are most likely to be important are those of the weighted best estimate and one of the upper percentiles (the 90th, for example). The former may be regarded as representing the most likely risk, while the latter would represent a reasonable level of assurance that unacceptable risks will not be incurred.

46 However, it is worth considering the common case where the weighted best estimate is well below the 90th percentile. If the weighted best estimate is used to determine compliance, the level of assurance that the criterion will actually be met may not be high enough, whereas, if the 90th percentile is used, this may be over-cautious as it could be strongly influenced by a relatively small number of parameter value combinations which give rise to high risks. The problem may be solved by using a weighted sum of the best estimate and one of the upper percentiles (the 90th, say) as the quantity to be compared with criteria. In this way, compliance decisions may be 'balanced' so as to take account both of the 'most likely' risk and the 'worst likely' risk, and of objective and subjective uncertainty.

47 Another possible value is the expectation value or mean of the pdf obtained from the uncertainty analysis. It is common in disposal safety assessments for the mean to fall in the vicinity of the 90th or 95th percentile, and in these cases the mean (remembering that it is a critical group which is being considered) may be assumed to be suitable for comparison with criteria to give a reasonable assurance of safety. Indeed, the mean, which is influenced both by the large number of 'low risk' sets of parameter values and by the small number of 'high risk' combinations, could be seen as representing some form of combination of the best estimate and the upper percentiles. However, the nature of this combination is unclear, and will vary between different assessments. The mean is unhelpful because it is a mathematical construct which has no physical interpretation; it cannot realistically be regarded as an 'expected value' when the range of values is so great that the mean is controlled very strongly by the highest values.

48 In view of the considerations above, the Board recommends that the quantity to be used for comparison with the risk constraint is a weighted sum of the weighted best estimate of risk and the 90th percentile of the pdf of risk obtained from uncertainty analysis. The use of the mean or expectation value of risk is not recommended.

Probabilistic events

49 There has been a common tendency (see, for example, reference 4) to consider 'normal scenarios' (undisturbed groundwater transport under best estimate conditions) within the framework of a dose limit, separate from 'probabilistic events' (such as human intrusion into the waste form, or 'sudden', large-scale environmental change), which are subject to a risk limit. This, in effect, draws an analogy between waste disposal facilities and nuclear power plants, whereby normal scenarios are analogous to

routine discharges and probabilistic events are analogous to reactor accidents.

50 This analogy is not, however, ideal. Whereas routine discharges from power plants can be planned on the basis of relatively reliable, short-term predictive models, and monitored to check the models (with the option of modifying the discharges if necessary), releases from a waste disposal facility in one thousand years must be planned on the basis of much less reliable, long-term predictive models which, because of the timescales involved, cannot be checked directly (furthermore, it would be very difficult for the release to be modified once the site is closed). The analogy can therefore only be applied within the period of institutional control of the site (see paragraph 25).

51 In fact, there is a continuum of possible events which could affect the exposure of man to the waste by causing modifications to some part of the disposal system. Over the timescales of interest, normal scenarios, where no such events occur, can reasonably be argued to be just as probabilistic as any others. The Board therefore recommends that normal scenarios should be treated within the same framework as other scenarios, and should be included in the calculation of risk for comparison with risk constraints.

52 The analogy with nuclear power plants can more usefully be applied if only the treatment of potential accidents is considered. Reactors have multiple safety systems, and a degree of redundancy in these systems is desirable. Accidents which tend to involve the failure of *some* of these systems are subject to safety criteria, which require assessment of the probability of accidents with particular consequences (release categories), and therefore may be interpreted as being broadly equivalent to a site risk constraint). Accidents which tend to involve failure of *most* or *all* of the safety systems would have consequences which are essentially uncontrolled, and such accidents must be shown to have a sufficiently low probability of occurrence.

53 Waste disposal sites, in particular deep geologic repositories, commonly employ a multibarrier system of safety (eg waste form, waste canister, backfill, host-rock and biosphere). By analogy with the above, events which bypass or modify one or two of these barriers (eg drilling a borehole for drinking water into an aquifer carrying a 'plume' of activity, or excavating disposal trenches during redevelopment) should be treated within a risk framework (probability and consequence**), whereas events that bypass most or all of the barriers can only be 'controlled' by limiting the probability of occurrence. Thus, such events may be subject to an analogous system of limitation, but with *probability*, rather than risk or dose, as the relevant quantity.

54 The most useful division to make is to separate those events involving a significant possibility of deterministic effects. In these cases, the definition of risk given in paragraph 17 is not

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**In this formulation of risk, the *probability* is the probability of receiving a dose, and the *consequence* is the probability of a deleterious health effect associated with that dose if it is received. The consequence is not the health effect itself.

applicable, and it is therefore inappropriate to combine risks of stochastic effects with risks of deterministic effects; hence, these situations should be dealt with by means of a system of probability limitation. In practice, doses leading to deterministic effects are only likely to occur in scenarios whereby intermediate or high level waste is brought to the surface by direct human intrusion into a deep repository or by some dramatic environmental event.

Probabilistic events leading to stochastic effects

55 The risk to an individual should be calculated by summing the risks to that individual from all situations which would give rise to doses and dose rates in the stochastic region (ie less than about 0.5 Sv delivered within a year). Care must be taken in deciding the extent to which such summation is justified, ie whether, from a present-day perspective, one future community could be judged to be at significant risk from more than one scenario. Where doubt exists, the risks should be summed.

Probabilistic events leading to deterministic effects

56 The potential consequences of some events, such as human intrusion into a high level waste repository, cannot be reduced significantly; if such an event occurs, the consequences are likely to be 'unacceptable'.

57 Probabilities might be reduced by, for example, avoiding geological areas which contain anything which might foreseeably be regarded as an exploitable natural resource in the future, or by making the repository deeper and/or smaller. Requirements to limit the *consequences* of such improbable events are not desirable; to modify a repository design solely for compliance with such a limit would not be sensible, particularly as such modifications might well detract from the performance of the repository in 'normal' situations.

58 It is therefore proposed that waste disposal sites should be chosen and designed so that the total probability of all events having the potential to lead to doses which would cause deterministic effects should be as low as reasonably achievable, economic and social factors being taken into account.

59 It is further recommended that the total probability of an individual in the critical group receiving a dose which could cause deterministic effects, as a result of any naturally occurring events, should not exceed 10^{-6} y^{-1}. This probability constraint applies for all times up to 10^6 years. The constraint is lower than the risk constraint on the grounds that, in general, events causing immediate death or injury are regarded as worse than those which could result in death or injury in later life. Naturally occurring catastrophic events whose non-radiological consequences on individuals and society would clearly greatly outweigh any radiological consequences (eg a large meteorite impact) may be excluded from the calculated probability.

60 In view of the unpredictability of human behaviour, it is not considered to be practicable or helpful to set a probability constraint for human-induced events which could lead to exposures in the deterministic region.

61 It should be remembered that events which lead to individuals receiving doses which could cause deterministic effects may also result in doses in the stochastic region to another 'critical group', and the associated risks should be considered in the calculation described in paragraph 55. Intervention by a future society to reduce or prevent doses should not be assumed to occur.

Human actions affecting disposal sites: Underlying assumptions

62 In assessing possible human actions which might disrupt a waste disposal site, only inadvertent human actions are considered. In this sense, 'inadvertent' is taken to mean that, although the action itself may be intentional, it is done without knowledge of the location and nature of the disposal facility. 'Deliberate' human intrusion (ie intrusion with knowledge of the location and nature of the waste) is believed to be beyond the scope of what can be reasonably considered in a risk assessment.

63 Any assessment of the probability and consequences of human interference with a disposal facility must make assumptions about the state of future civilisation, and the results of such an assessment will be strongly dependent on those assumptions.

64 A significantly less advanced society than ours is much less likely to have the capability to disrupt a disposal site (particularly a deep one), and its members would in any case be subject to day-to-day risks greater than those in our society. A significantly more advanced society may reasonably be assumed to be capable of protecting itself to some extent; for example, the probability of detecting the site in advance must be regarded as high, and any intrusion which occurs after the nature of the site has been recognised would not be regarded as 'inadvertent'. Therefore, calculations for human disruption of a disposal site should be based on an assumed level of technology approximately equivalent to that existing (or foreseen) at present.

65 This assumption should, perhaps, imply that human intrusion is extremely unlikely, but it may be wise to be more cautious. It is common to assume complete loss of knowledge of the site at the end of institutional control (100 years at most), an assumption that is apparently incompatible with that about the technological state of society, and is undoubtedly very conservative. However, the probability for such a loss of knowledge is virtually impossible to quantify, and therefore it is difficult to see a better way to proceed.

Presentation of results

66 The results of waste disposal safety assessments should be presented in as clear and comprehensible a form as possible, particularly in cases where the assessments will be subject to widespread public scrutiny. It is hoped that implementation of the recommendations given in this document will, in addition to concentrating effort on the most important aspects of assessments, be helpful in achieving this aim.

67 One additional problem in presenting the results of safety assessments is that risk itself is a quantity that seems to be poorly understood by many people, particularly in cases where the risk is the result of a number of possible situations, some of

which are mutually exclusive. In general, the concepts of probability and consequence are likely to be more accessible.

68 Criterion curves, as suggested in reference 4, may be useful in presenting the results of risk assessments. These generally take the form of a plot of the probability that dose *D* will be exceeded *versus D*; thus a risk limit or constraint appears as a diagonal line (see the figure).

69 Such curves could be particularly useful if a quantity other than risk is being considered. For example, if, as suggested in paragraph 25, the risk constraint were to be represented as a constraint on the radionuclide flux out of the geosphere, then a plot could be used (for each nuclide) showing the probability of a nuclide flux *F* being exceeded *versus F*. As in the case of a risk constraint, the (probability-weighted) flux constraint would take the form of a diagonal line on such a plot.

OPTIMISATION OF PROTECTION

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

71 The main radiological input to optimisation studies has generally been the total (integrated) collective dose, as a surrogate for the total health detriment incurred. For optimisation studies relating to solid waste disposal, however, the use of collective dose is far from ideal. Even with relatively short (in solid waste disposal terms) integration times, the post-disposal collective dose to members of the public is so dependent on detailed assumptions about the biosphere and human behaviour that predictions must be treated with extreme caution. With integration times of thousands or millions of years, such values could become meaningless. Thus it is extremely difficult, if not impossible, to obtain realistic predictions, which is a particular problem if the options being considered are very different from one another (eg different types of disposal method or different locations for disposal sites). The use of integrated collective dose in optimisation studies concerning solid waste disposal is therefore not, in general, recommended.

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

73 More generally, the use of multiattribute decision-aiding techniques (such as multiattribute utility analysis) should reduce the need for absolute values of health detriment, and therefore it may not be necessary for a 'predicted' collective dose to be used at all. For the purposes of comparing options, total health detriment may be measured by means of a more reliable surrogate, reflecting the total release into the human environment (which can

be predicted with some confidence) without reflecting specific assumptions about the biosphere and human behaviour (which cannot be predicted). There are a number of possibilities, including calculating the 'virtual collective dose', ie the collective dose which would be delivered to a chosen reference population in a chosen reference model, or the total radionuclide flux across some specified boundary (weighted according to the nature of the nuclides). Even with a more 'well-behaved' surrogate for health detriment, however, the problem of how to weight this measure of detriment against 'real' detriments (eg worker doses) and costs remains.

74 Society's perception of low consequence, high probability events tends to differ fundamentally from that of high consequence, low probability events. Therefore, if individual risks are used in optimisation studies, the probability and consequence components (see paragraph 53) should always be given separate consideration.

SUMMARY OF MAIN CONCLUSIONS

Need for new advice

75 In order to aid in the interpretation of existing advice, and to encourage improvements in the presentation of safety analyses for solid waste disposal facilities, it is considered necessary to update and clarify certain aspects of previously issued advice.

76 The major principles to be applied to radiological protection in the context of solid waste disposal are, as in previous advice, the optimisation of protection and the limitation of individual risk. 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.

Risk constraints and design targets

77 The Board recommends that the individual risk to a typical member of the critical group, attributable to any single disposal site for solid radioactive waste, should not exceed a risk constraint of 10^{-5} y^{-1}. A site which fails to satisfy this constraint should not be licensed, whereas a site which does satisfy this constraint may be licensed, if it is also shown to represent an optimum level of protection. The purpose of the risk constraint is to ensure that an individual who may be exposed to risk from more than one artificial source of radiation (excluding medical exposures) is not subjected to an unacceptable level of risk.

78 The Board further recommends that, if the individual risk to a typical member of the critical group, attributable to any single disposal site for solid radioactive waste, does not exceed a design target of 10^{-6} y^{-1}, then the requirements for optimisation should be relaxed. A site which fails to satisfy this design target may nevertheless be licensed, but it would have to be demonstrated to represent an optimum level of protection.

Calculation of individual risk in future time frames

79 It is recommended that, for the purposes of risk assessment, the future should be divided into time frames, with the emphasis of the assessment changing as the period of prediction increases.

80 Predictive site-specific calculations relating to the accessible environment (biosphere) and human behaviour should not continue beyond 10^4 years into the future. For times greater than 10^4 years, simple reference models of the biosphere and human behaviour should be adopted, in order to calculate the risks to hypothetical reference communities. By showing that these hypothetical communities would be protected, it is intended to provide assurance that any individuals actually present in the far future will be adequately protected.

81 Predictive site-specific calculations relating to the behaviour of geological formations should not continue beyond 10^6 years into the future. For times greater than 10^6 years, predictive calculations are not sufficiently reliable to be warranted, and therefore the treatment of this period in safety cases should be primarily qualitative. The risk constraint and target quoted above do not apply beyond 10^6 years, although the requirement that exposures be kept ALARA remains applicable.

Application of the critical group concept

82 The critical group concept should be modified for use in the context of solid waste disposal. Hypothetical critical groups should be assumed to exist at the time and place where environmental concentrations of radionuclides are predicted to be highest. The habits of these groups should broadly represent the habits of observed present-day critical groups, but should not be based on the most extreme examples.

83 The critical group for times beyond 10^4 years should, in general, be a reference subsistence community with habits broadly typical of those of subsistence communities in the present day. The habits of the community should be consistent with their status, and extreme habits should not be used.

Treatment of uncertainty

84 Where possible, uncertainty should be designated as being objective (inherently unpredictable) or subjective (uncertain due to lack of human knowledge). If doubt exists, uncertainty should be designated as subjective.

85 Objective uncertainty should be treated by means of a series of distinct scenarios, representing qualitatively different possibilities. Best estimate risk calculations should be performed for each scenario, and a weighted best estimate risk obtained as the probability-weighted sum (where summing is appropriate). 'Best estimate' should not be interpreted as 'mean' or 'expectation value'.

86 Subjective uncertainty should be addressed explicitly, by means of uncertainty analysis, giving a probability distribution of possible outcomes (ie risks).

87 The appropriate risk value for comparison with the risk constraint should be a weighted sum of the weighted best estimate of risk and the 90th percentile of the risk distribution obtained from uncertainty analysis.

Probabilistic events

88 All scenarios predicted to give rise to doses below about 0.5 Sv within a year (ie the lower limit for deterministic

effects), including any 'normal scenario', should be considered in the calculation of risk for comparison with the risk constraint.

89 The probability of occurrence of events predicted to cause doses in excess of about 0.5 Sv within a year should at all times be as low as reasonably achievable, economic and social factors being taken into account.

90 The total probability of occurrence for all naturally occurring events predicted to cause doses in excess of about 0.5 Sv within a year should not exceed a probability constraint of 10^{-6} y^{-1}.

Optimisation of protection

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

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

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

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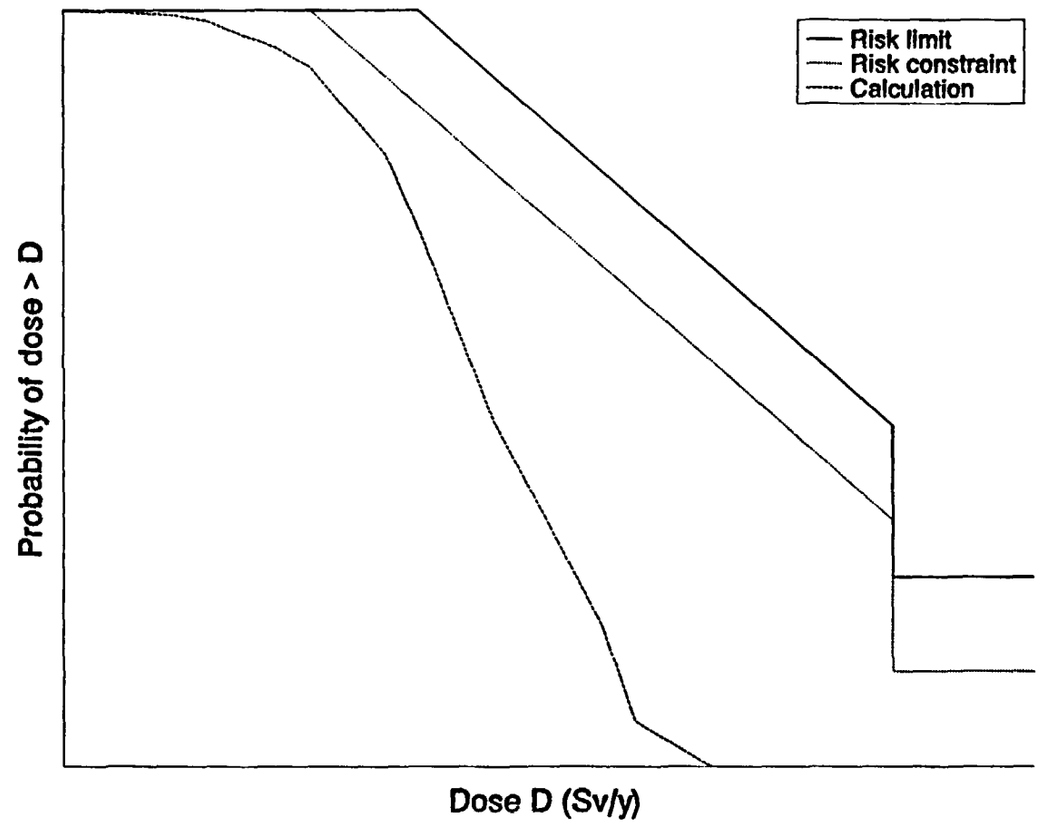
Approximate timescales

Years	Historical	Future	$t_{1/2}$*
10^2	Discovery of radioactivity	'Greenhouse' effects	
10^3	Norman conquest	Large ecological changes, eg lakes fill with weeds	
	Egyptian pyramids		
		Mineral and energy resources exhausted?	^{14}C
10^4	Discovery of agriculture		^{239}Pu
	Last glaciation of northern Europe	Next glaciation	
	Use of fire and tools by humans		
10^5	Emergence of Neanderthal man	Time between major glaciations	^{99}Tc
10^6	Emergence of *Homo sapiens*	Stable geological formations remain relatively unchanged	^{237}Np
10^7	Evolutionary branching between humans and apes	Appearance of new families of species	^{129}I
10^8	Dinosaurs populate the earth	Large-scale movements of continents (thousands of kilometres)	
10^9	Appearance of multi-cellular organisms	Significant probability of 'nearby' supernova, or meteorite impacts	
		Increase in solar intensity sufficient to erase life on earth	^{238}U
	Age of the earth		
		Sun becomes red giant	

*Approximate half-lives of some significant radionuclides in solid waste disposal assessments, for reference.



Criterion curves