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GUIDANCE ON THE DEFINITION OF CRITICAL AND OTHER HYPOTHETICAL EXPOSED GROUPS FOR SOLID RADIOACTIVE WASTE DISPOSAL

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FOREWORD

The BIOMASS Programme on BIOsphere Modelling and ASSessment was launched in Vienna in October 1996, and is sponsored by the International Atomic Energy Agency and a number of other organisations, see below. The Programme is addressing radiological issues associated with accidental and routine releases of radionuclides to the environment, and solid waste management. Three important themes involving environmental assessment modelling are covered:

Theme 1: Radioactive Waste Disposal. The objective is to develop the concept of "Reference Biospheres" into a practical system for application to the assessment of the long-term safety of repositories for radioactive waste. The following Task Groups have been set up to achieve this:

TG1: Principles for the Definition of Critical and Other Exposure Groups.

TG2: Principles for the Application of Data to Assessment Models.

TG3: Consideration of Alternative Assessment Contexts.

TG4: Biosphere System Identification and Justification.

TG5: Biosphere System Descriptions.

TG6: Model Development.

Theme 2: Environmental Releases. BIOMASS provides an international forum for activities aimed at increasing the confidence in methods and models for the assessment of radiation exposure related to environmental releases. Two Working Groups have been set up, concerned with: Dose Reconstruction for previous releases; and Remediation Assessment to evaluate the efficacy of remedial measures.

Theme 3: Biosphere Processes. The aim of this Theme is to improve capabilities for modelling the transfer of radionuclides in particular parts of the biosphere which have been identified as being of potential radiological significance. This topic is being explored using a range of methods including reviews of the literature, model inter-comparison exercises and where possible, model testing against independent sources of data. Three Working Groups have been set up, to examine modelling of: 1) long-term tritium dispersion in the environment; 2) radionuclide uptake by fruits; and 3) radionuclide migration and accumulation in forest ecosystems.

This report has been produced by Task Group 1 of Theme 1 and provides guidance on the definition of critical and other hypothetical exposed groups to be assumed in assessments of solid radioactive waste disposal. It has been produced with valuable contributions from many participants in BIOMASS and has been widely circulated for comment at each stage of drafting. The support provided to this work through the Theme 1 Steering Committee organisations listed below is also gratefully acknowledged.

Agence National pour la Gestion des Déchets Radioactifs (ANDRA), France

BNFL, United Kingdom

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), on behalf of Empresa Nacional de Residuos Radiactivos SA (ENRESA), Spain

Institut de Protection et de Sûreté Nucléaire (IPSN), France

Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (NAGRA), Switzerland

Japan Nuclear Cycle Development Institute (JNC), Japan

United Kingdom Nirex Ltd (Nirex), United Kingdom

The IAEA Scientific Secretary was Mr. C. Torres of the Waste Safety Section, Division of Radiation and Waste Safety.

ABSTRACT

The purpose of this BIOMASS Theme 1 report is to provide guidance on defining hypothetical human behaviour relevant to long-term radiological exposure assessment in the context of solid radioactive waste disposal. The document also reviews existing guidelines related to the definition of critical and other hypothetical exposed groups, and identifies and explores issues that may affect the choice of approach. Consideration is given to the implications of attempting to characterise aspects of future human behaviour that are inherently unpredictable, yet which must be quantified in order to perform radiological safety assessments.

A successful biosphere assessment will be consistent with the underlying objectives of the assessment, the endpoints that are to be evaluated and the characteristics of the release from the geosphere. These issues are themselves influenced by national regulations, the stage of development of the repository programme and the major features of the disposal system represented in the performance assessment. Moreover, the basis on which safety criteria themselves are determined may have a significant impact on the development of consistent and appropriate characterisations of hypothetical exposed groups. It is therefore not possible to identify a single hypothetical group that can clearly be shown to be representative of those individuals in the population expected to incur the highest dose or risk in all circumstances.

Multiple lines of reasoning and investigation will often be appropriate, as part of an iterative performance assessment, in comparing the exposures determined using different approaches with regulatory criteria. However, endless speculation into potential future human activities provides no further assurance regarding the adequacy of the chosen indicator of radiological impact. Approaches are required that use ‘cautious, but reasonable’ assumptions, based on present-day knowledge, to provide satisfactory assurance that the predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today. In seeking to constrain the potential range of ‘critical group’ habits (such as consumption of a specific foodstuff), extremes of individual behaviour that would be overly cautious, and outside the range of what might be found in a broader community from which the critical group is identified, should therefore be avoided.

EXECUTIVE SUMMARY

Introduction and purpose

There is a measure of international consensus regarding general safety principles, including radiological protection objectives, applicable to radioactive waste disposal. Waste disposal practices should provide for the protection of both current and future generations, and long-term safety assessments should provide assurance that future impacts are compatible with those tolerated today. In order to demonstrate compliance with limits and constraints on dose and/or health risk to humans, satisfactory assurance needs to be provided that corresponding levels of exposure will be not be exceeded.

However, assessment timescales beyond even a few tens, or at most hundreds, of years introduce profound uncertainty into any quantitative description of human behaviour. This means that the biosphere(s) adopted for assessing system performance, in which assumed human behaviour is an integral part, can only be considered as providing indicators of the potential radiological impact of the repository. When integrated with understanding arising from assessments of the behaviour of the disposal system as a whole, these indicators are then used as input to decisions regarding the acceptability of long-term system performance. Providing assurance of limited radiological impact over the periods of interest to post-closure performance assessment requires careful justification of assumptions and hypotheses underlying the evaluation of representative radiological exposures. The challenge, therefore, is to describe future human behaviour in such as way that, notwithstanding the speculative nature of various underlying assumptions, results based on these assumptions provide a satisfactory degree of assurance regarding future levels of radiological protection.

The purpose of this BIOMASS Theme 1 report is to provide guidance on defining hypothetical human behaviour relevant to long-term radiological exposure assessment in the context of solid radioactive waste disposal. The document also reviews existing guidelines related to the definition of critical and other hypothetical exposed groups, and identifies and explores issues that may affect the choice of approach. Consideration is given to the implications of attempting to characterise aspects of future human behaviour that are inherently unpredictable, yet which must be quantified in order to perform radiological safety assessments.

Objectives

In addition to the characteristics of the biosphere itself, basic assumptions relating to the type of society (e.g. agrarian or urban), community structures and level of technological development are fundamental to decisions made concerning the characterisation of future human behaviour. Moreover, because human actions have a profound effect on the surface environment, societal assumptions are also very relevant to the identification, description and modelling of relevant biosphere systems. Providing a coherent overall approach to demonstrating compliance with radiation protection principles and objectives requires consideration of the relationship between the philosophy underlying the development of quantitative compliance criteria and that adopted in performing the exposure assessment. Furthermore, within the assessment itself there is a need for consistency between the description of hypothetical exposed groups and the assumptions underlying development of biosphere system descriptions.

However, those aspects of human behaviour that influence the nature and properties of the biosphere, and which therefore represent important factors determining the fate of possible future releases, have not been specifically addressed in this Working Document. As far as the characterisation of hypothetical exposed groups and their environment is concerned, it is assumed that communities with specific systems of biosphere resource utilisation will effectively be pre-defined (consistent, where necessary, with any prior assumptions made concerning the available resources and exposure pathways of interest) as part of the underlying assessment context.

A successful biosphere assessment will be consistent with the underlying objectives of the assessment, the endpoints that are to be evaluated and the characteristics of the release from the geosphere. These issues are themselves influenced by national regulations, the stage of development of the repository programme and the major features of the disposal system represented in the performance assessment. Moreover, the basis on which safety criteria themselves are determined may have a significant impact on the development of consistent and appropriate characterisations of hypothetical exposed groups.

Existing guidance and requirements

The concept of the ‘critical group’ was originally introduced in order to address the problem of setting quantitative limits on present-day and near-future releases of radionuclides to the environment. In such circumstances, the actual doses incurred by members of the public will be variable due to a multitude of variable environmental factors, as well the intrinsic variability associated with differences in age, size, metabolism and habits. The underlying philosophy was to demonstrate compliance with a dose constraint based on estimated exposures for a particular population subgroup. Subsequently, the term ‘critical group’ has become widely used to describe a set of individuals who, because of their location and commonality in their behaviour and habits, are among the most highly exposed due to releases from a nuclear facility. This Working Document reviews several of the ICRP documents providing information on the definition of critical and other exposed groups.

Compared with the detailed interpretation of the critical group concept in the context of routine discharges, the principles for defining human behaviour in relation to long-term assessments for solid radioactive waste disposal have received relatively limited attention. Nevertheless, a generally cautious assessment approach is dictated throughout existing guidance as a means to provide assurance that actual exposures are unlikely to be significantly underestimated. Updated guidance from ICRP, relating specifically to considerations relevant to the disposal of waste in repositories is at an advanced stage of preparation.

In general, society has established more restrictive targets for individual protection where the potential number of individuals exposed to a health hazard is large; conversely, larger individual risk levels may be tolerated if the number of exposed individuals is small. Most national regulatory authorities have proposed radiological protection standards for waste disposal that are consistent with the maximum average individual risk levels currently tolerated for large populations. However, the regulatory guidance for evaluating compliance with such standards also typically requires that they should apply to the calculated exposures, determined using cautious assumptions, for a hypothetical maximally exposed population group of limited size. Thus, an additional margin of assurance appears to have been considered justifiable in developing regulatory guidance relevant to long-term future discharges from solid radioactive disposal facility. However, this should not necessarily be taken to demand the inflexible adoption of a conservative approach to the application of compliance standards, coupled with an overly-cautious assessment approach.

Primary considerations in defining hypothetical exposed groups

Bearing in mind that the basic principle of providing assurance that future impacts are compatible with those tolerated today, an appropriate starting point is to assign future individuals similar habits to those of the present-day populations against whom future projected risk levels will be compared. However, this does not necessarily mean that present-day behaviour at the site, or in the region of interest will necessarily provide a sufficient basis for assessment. For example, if, as a result of climate change and related factors, future releases are likely to take place into an environment that is substantially different from that of today, it would be reasonable to expect that some analysis of alternatives – consistent with possible future environmental conditions - should be included.

For some assessment contexts, therefore, representations of future human behaviour closely resembling present-day patterns of resource exploitation – perhaps even simulating a local community in the vicinity of the site – would be appropriate. Databases on local, regional or national dietary and other habits are also potentially relevant sources of information to an assessment. When justified by the assessment context, and if adequate data exist, it can also be acceptable to use data on historic land-use practices pertinent to the region, or on a wider spatial scale. Furthermore, where the assessment context dictates that future environmental change should be taken into account, it will be appropriate to represent human behaviour on the basis of present-day (or, if available, historical) practices from analogue locations with biosphere conditions similar to the altered biosphere. The convention for present-day releases is that extremes of behaviour do not need to be considered in radiological assessments in order to demonstrate adequate protection of individuals. This implies that emphasis can justifiably be placed on the exploitation of environmental systems representative of maximum reasonable utilisation of the future biosphere (i.e. taking account of resource availability and nutritional needs, etc.) at the location of interest.

The potential number of people exposed to future releases from a repository, and the homogeneity of exposure across such a group, are not necessarily the primary considerations in assessing radiological exposures for direct comparison with regulatory benchmarks when these are expressed solely in terms of individual dose or health risk. However, such factors may play a part in developing the 'multiple lines of reasoning' that are likely to be necessary in providing assurance that future individuals are afforded a level of protection consistent with that tolerated today. Furthermore, where regulatory benchmarks are in units of collective or population dose or risk, some indication of the potential number of people exposed and the numerical distribution of their exposure will need to be considered.

For many assessment contexts, it may be appropriate to compile assumed distributions of future behaviour into a limited set of behavioural groups. For cases where the definition of a 'critical' group is required, the aim should then be to address alternatives for the possible behaviour of a hypothetical 'Reasonably Maximally Exposed Individual' (RMEI), giving due regard to the need for adopting cautious, but reasonable, assumptions. This should not be taken to imply that the RMEI necessarily represents some separate, specific individual; rather, it should be representative of the reasonable behaviour exhibited by members of a maximally exposed group of limited size.

The information necessary to characterise members of exposure groups for the purpose of evaluating radiological exposures, dose and risk can be divided into the following primary classes:

- General description of the hypothetical exposure group(s) (e.g., agrarian, industrial, level of technological development)
- General description of activities leading to radiological exposure
- Physiological factors affecting exposure and radiation dose
- Location
- Modes of exposure
- Rate and duration of exposure

An important consideration in the context of long-term radiological assessment is the extent to which age-dependent variations in exposure and dose may be important. Part of the difficulty in deciding how to address the issue of whether or not to consider different demographic (e.g. age and gender) groups separately arises because radiological safety standards tend to be addressed in terms of annual limits or targets, whereas assessment modelling – particularly at long times into the future – inevitably invokes temporal averaging in the representation of events and processes. Moreover, long-term discharges from waste disposal facilities will tend to give rise to life-long, chronic exposures. Because individuals will spend most of their lives while exposed as adults, taking account of exposures during infancy and childhood may not necessarily change the estimated lifetime doses or health risks, summed over exposure pathways, by very much. However, this remains to be more conclusively demonstrated.

A further consideration (particularly in the context of probabilistic approaches to performance assessment) is the assumed location of the hypothetical exposed group in relation to the contaminated biosphere system. In principle, it is possible to assume that some representative exposed group will always be situated in the region of maximum environmental contamination, whatever the precise geographical location of that region might be. Again, in order to provide adequate assurance of protection, care needs to be taken in matching the level of caution adopted in the assessment calculation to that implicit in the definition of safety criteria.

A cautious, but reasonable, approach to defining behaviour relevant to exposure is to characterise the habits of individuals using information (where available) describing the range of behaviour in analogue communities forming sustainable units of resource exploitation in comparable biosphere systems. As far as the consumption of specific dietary items is concerned, it is often assumed that, provided the sampled population is sufficiently large, the top 5% of a distribution may be taken as representative of a critical consumer group. Using approximately the 95^{th} to 97.5^{th} percentile of the distribution to define a 'critical' consumer group is reckoned to strike a prudent balance between caution and discretion.

Strategies for identifying the 'Critical Group'

One strategy for identifying and describing a 'critical group' is to characterise a number of potentially exposed groups, based on the prior identification of specific patterns of behaviour and seeking to relate these to the ways in which different biosphere resources are typically exploited. The assumed characteristics of candidate critical groups are fixed prior to performing the exposure calculation and the most exposed of these candidate groups then serves as a representative indicator of the maximum potential exposure. This can be identified as the *a priori* approach.

By contrast, the *a posteriori* approach explores a range of potential combinations of exposure pathways, using sampling methods to identify a combination that, while not being unrealistic, corresponds to the maximum potential dose or risk within the biosphere system for the particular geosphere releases postulated. Hence, 'unit' exposures for each pathway and radionuclide are considered first and detailed behavioural characteristics are defined through a process by which the dose from combining these pathways (subject to defined physical and physiological constraints) is maximised using mathematical sampling methods. The specific characteristics of the critical exposure group therefore emerge as a consequence of the procedure. This approach has seldom been used explicitly in the context of total system performance assessments conducted to date.

There are advantages and disadvantages to using either method. An advantage of the *a posteriori* approach is that it may identify pathways (or potential combinations of pathways) that might not otherwise have been addressed via the *a priori* definition of exposed groups. Its primary disadvantage is that there may be difficulties in interpreting the meaning of aggregated risk (or expectation value of exposure) in a probabilistic assessment covering various outcomes. By contrast, an important advantage of the *a priori* approach is that the implications of the results can be more readily understood, because the definition of hypothetical exposed groups is related to prior experience (including, if desired or required, the present-day local community in the vicinity of the discharge), rather than emerging via a mathematical procedure. Its primary disadvantage is that it may overlook potentially relevant exposure pathways.

Neither approach is recommended here to the exclusion of the other. Rather, a combination of the two could be used to establish the final exposed group definition(s). For example, consideration of a wider range of potential pathways (i.e. *a posteriori* approach) might initially be used to eliminate exposure pathways of negligible radiological significance from further consideration. This would then provide guidance for the selection of a small set of fixed (i.e., *a priori*) exposed groups, with reasonable confidence that the identified group(s) were sufficiently representative to provide adequate assurance of the protection of future communities.

Unresolved issues

Various matters relevant to the evaluation of future exposures have not been fully resolved at this time. These include the following:

— The possibility of demonstrating whether a drinking water pathway alone, or 'subsistence farming' behaviour, represent reasonable benchmark cases for use in assessments.

— The need for a coherent approach to assuring the protection of different age groups, taking account of the averaging assumptions implicit in environmental modelling.

— The development of recommendations relevant to the treatment of exposure pathways linked to human intrusion scenarios.

— A direct comparison of the *a priori* and *a posteriori* approaches.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

(1) There is a measure of international consensus regarding general safety principles, including radiological protection objectives, applicable to radioactive waste management practices. However, there is a lack of consensus regarding how best to interpret such objectives (e.g. for regulatory compliance purposes) in the context of radioactive waste disposal, particularly for releases to the environment that might take place in the distant future. The structure of the BIOMASS Theme 1 programme reflects the common interest of parties involved in radioactive waste management in establishing a coherent approach to the development and quantitative application of safety acceptance criteria for waste disposal facilities.

(2) A variety of complementary safety indicators for geological disposal systems could be adopted [IAEA, 1994], several of which relate directly to human exposure. Indeed, the detailed approaches taken in different countries exhibit a range of features. Nevertheless, the application of radiological protection objectives has customarily been interpreted to include at least some form of restriction on the radiation doses and/or risks incurred by people who could be exposed as a result of the migration of radionuclides from a repository following its closure.

(3) Principles established by the International Commission on Radiological Protection (ICRP) form the foundation for regulatory frameworks and quantitative standards adopted in many countries. The ICRP's 'System of Radiological Protection' [ICRP, 1991] for proposed and continuing practices involving the possibility of radiological exposure (including the disposal of solid radioactive waste) requires that:

(a) *No practice involving exposures to radiation should be adopted unless it produces sufficient benefit to the exposed individuals or to society to offset the radiation detriment it causes.*

(b) *In relation to any particular source within a practice, the magnitude of individual doses, the number of people exposed, and the likelihood of incurring exposures where these are not certain to be achieved should all be kept as low as reasonably achievable, economic and social factors being taken into account. This procedure should be constrained by restrictions on the doses to individuals (dose constraints), so as to limit the inequity likely to result from inherent economic and social judgements.*

(c) *The exposure of individuals resulting from the combination of all the relevant practices should be subject to limits, or to some control of risk in the case of potential exposures. These are aimed at ensuring that no individual is exposed to radiation risks that are judged to be unacceptable from these practices in any normal circumstances.*

(4) Quantitative radiological assessment plays a role at each stage in the implementation of the ICRP system. In particular, in order to demonstrate compliance with limits and constraints on individual dose (or risk) for releases of radioactive materials to the environment, satisfactory assurance needs to be provided that corresponding levels of exposure will be not be exceeded. However, uncertainties in characterising behaviour, and hence in estimated exposure, are significantly greater where the assessment encompasses the exposure of hypothetical individuals from future releases rather than actual critical groups within real populations exposed to present-day discharges [Charafoutdinov, Sitnikov and Stroganov, 1998].

(5) Descriptions of biosphere systems (particularly in so far as they are influenced by human activity) and human behaviour relevant to long-term radiological safety assessments will therefore inevitably incorporate a certain amount of hypothesis and/or speculation. In the context of a radioactive waste repository, where releases may take place far into the future, this places exacting demands on the justification of assumptions and hypotheses that underlie the evaluation of radiological exposures.

(6) In making a radiological assessment for hypothetical future exposures, it is necessary to characterise, *quantitatively*, aspects of human behaviour that are relevant to the application of safety acceptance criteria. 'Relevant' behaviour in the context of releases from solid radioactive waste disposal facilities includes that which gives rise to exposure (e.g., via ingestion, inhalation, or direct external irradiation) from environmental contamination that may be present at some future time. In addition, the assessment should also consider the potential impact of the behaviour of human society on the biosphere itself (e.g., agricultural and other resource exploitation or land use practices).

(7) A common approach is to define one or more hypothetical 'exposed groups', the sizes of which may range from a single individual to an entire community. Members of such exposed groups may be characterised in terms of their sharing of one or more common behavioural characteristics (diet, habits, location, etc.), or simply by a similarity in their overall dose or risk. For consistency with terminology used elsewhere in the context of radioactive discharges to the environment (see Section 2.2), the hypothetical exposed group regarded as being indicative of the highest exposures at some time in the future is often identified as the 'critical group'.

(8) Guidance from international agencies and national regulatory bodies (summarised in Annex A and reviewed in Chapter 2, below) has often appealed to reason as the basis for identifying and defining potentially exposed individuals. However, whereas quantitative radiological standards for long-term safety performance exist, no definitive guidance has been provided on what constitutes a 'reasonable' description of hypothetical future human behaviour in the context of demonstrating compliance with such standards. Moreover, it is not helpful to look elsewhere for guidance; although other types of environmental hazard may be similarly persistent, the use of quantitative measures of impact on such timescales (perhaps many thousands of years after the original disposal of the waste) as a basis for decision making is almost unknown outside the field of radioactive waste management.

1.2. BASIS FOR THE DEVELOPMENT OF GUIDANCE

(9) The International Atomic Energy Agency's general safety principles [IAEA, 1995] state that the overall objective of long-term safety assessments for radioactive waste disposal should be to provide assurance that *"the predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today"*. It is not possible to make a precise identification of a particular population group exposed to discharges from a repository at some time in the future. Rather, the aim of the biosphere component of performance assessment for the disposal system should be to develop suitably robust, representative indicators of what the dose or risk incurred by future groups might be, and thereby to provide a sufficient level of assurance that future individuals are afforded a level of protection consistent with that required today.

(10) Indeed, contrary to the situation that often exists in relation to present-day waste discharges, it is not possible to 'validate' calculated radiological impacts as being realistic estimates of actual exposures in the long term. Hence, the biosphere(s) and associated

descriptions of human behaviour adopted for the purposes of performance assessment in relation to waste disposal cannot provide absolute assurance that rigid quantitative criteria will be met for every possible eventuality. Instead, they can at best be seen as ‘measuring instruments’ of potential future radiological impacts, for comparison with present-day standards of protection.

(11) The Reference Biosphere Methodology [BIOMOVS II, 1996; BIOMASS 1998a] is intended as a comprehensive basis for the development of quantitative radiological assessments consistent with general safety principles. The specific guidance developed in this document is intended as one element of this Methodology, to be used in conjunction with other components, summarised in Section 2.1 and Annex B. Hence, the aim is that biosphere systems representative of the future should be populated with hypothetical ‘exposed groups’, consistent with the system description and with the overall context and objectives of the assessment.

1.3. PURPOSE OF THIS REPORT

(12) The purpose of this BIOMASS Theme 1 report is to review methods for defining present-day and hypothetical future exposed groups for solid radioactive waste disposal, and to provide guidance on the application of such methods in assessing radiological exposure. The document reviews existing guidelines related to the definition of critical groups, and identifies and explores issues (e.g., the underlying assessment context, and criteria and compliance standards) that may affect the choice of approach. Consideration is given to the implications of attempting to characterise aspects of future human behaviour that are inherently unpredictable, yet which must be quantified in order to perform radiological safety assessments.

(13) The component of the assessment process addressed here is therefore the justification of future representations of human society as a basis for the estimation of long-term safety performance indicators. This includes consideration of whether and how to define ‘individuals’ or ‘groups’ within the society in order to undertake such calculations. A range of practical problems involved in implementing long-term safety assessments are identified and considered, covering a broad range of issues and concerns that together provide a basis for further developments. Relevant properties of the biosphere that affect human behaviour have also been addressed.

(14) This report does not consider in detail related issues that are essential to providing a coherent overall assessment framework. For example, those aspects of human behaviour that shape the nature and properties of the biosphere, and which thereby represent important factors determining the fate of possible future releases, have not been specifically addressed. Hence, as far as the characterisation of hypothetical exposed groups and their environment is concerned, it is assumed that societies with specific systems of biosphere resource utilisation (e.g., agriculture, hunting and fishing) are pre-defined as part of the underlying assessment basis. Other Task Groups within BIOMASS are considering how best to incorporate the impact of human and societal behaviour in descriptions of the nature and properties of the biosphere [BIOMASS, 1998c].

(15) Furthermore, the guidance developed in this report is not intended to provide the basis for a single, international standard ‘critical’ exposed group for long-term radiological assessment. Rather, the aim within BIOMASS is to explore a number of example Reference Biospheres (and, within them, a range of representative exposed groups) that are intended to

provide the basis for practical and useful indicators of future radiological exposures [BIOMASS, 1998a].

1.4. STRUCTURE OF THIS REPORT

(16) Section 2 summarises the underlying considerations involved in the identification and quantitative definition of hypothetical exposed groups for the long-term radiological assessment of land-based solid radioactive waste disposal. In particular, the details of any safety assessment are recognised as being dependent on the ‘context’ of that assessment [BIOMASS, 1998b]; Section 2.1 therefore provides a brief description of the relevant components of the assessment context. Existing international guidelines can also guide the detailed development of exposed group descriptions; the current situation, in so far as it applies to long-term safety assessments, is summarised in Section 2.2. A summary of relevant lessons learned from a short survey of national regulatory guidance (Annex A) is provided in Section 2.3.

(17) Two complementary approaches to describing hypothetical exposed groups, each aimed at providing a robust and coherent assessment framework, are distinguished in Section 3. The likely advantages and disadvantages associated with each alternative are discussed. The primary guidance arising from this report, based on the preceding analyses, is then elaborated in Section 4. Finally, the implications of these recommendations are briefly summarised in Section 5; areas where further work is required are also identified.

(18) There are also three annexes to the report. Annex A summarises the results of a partial survey of national guidance and regulations related to the definition of hypothetical exposed groups relevant to the long-term radiological assessment of solid radioactive waste disposal. A brief overview of the relationship between the guidance developed in this document and other elements of the Reference Biosphere Methodology is then presented in Annex B. In particular, Annex B highlights the interdependency between the specification of characteristics of biosphere systems representative of the long-term future and the assumed characteristics of the people that are assumed to populate such systems. Annex C is concerned with the development of a conceptual approach to the distribution of radiological impact across a heterogeneously-exposed population and the potential role of such considerations in informing decision making.

2. UNDERLYING CONSIDERATIONS FOR QUANTITATIVE ASSESSMENT

2.1. ASSESSMENT CONTEXT

(19) Radiological safety assessments are not performed in a ‘vacuum’ but, rather, in support of specific stages of a decision making process. It is therefore important that they should be formulated so as to be ‘fit for purpose’. Hence, in developing and applying any guidance relating to the definition of future human behaviour for such assessments, a prime consideration is the overall context within which the assessment is to be performed.

(20) Nevertheless, a common weakness of many performance assessments has been the use of approaches, models and data that are not obviously well matched to the specific question(s) being addressed [BIOMOVS II, 1996]. Clearly, to apply a ‘reference’ set of exposure characteristics resembling, for example, those of coastal communities in Scandinavia to people living in the south-western regions of the USA would be no more appropriate than

applying a northern temperate coastal biosphere to a disposal site in the desert. A successful biosphere assessment needs to be consistent with the underlying objectives of the assessment, the endpoints that are to be evaluated and the characteristics of the release from the geosphere. These issues are themselves influenced by national regulations, the stage of development of the repository programme and the major features of the disposal system represented in the performance assessment. Moreover, the basis on which safety criteria themselves are determined may have a significant impact on the development of consistent and appropriate characterisations of hypothetical exposed groups.

(21) The purpose of the assessment, the basis on which safety criteria are derived and related factors (such as the local climate and other physical features of the biosphere) establish the ‘ground rules’ for model development and data selection. The BIOMASS programme has recognised that a clear definition of the assessment context is essential for the development of an appropriate safety assessment. One aspect of the work within BIOMASS Theme 1 (see Annex B) has therefore been to identify the relevant components of the ‘assessment context’ necessary for the coherent development of a biosphere system model to support safety assessments [BIOMASS, 1998b]. Components of the assessment context, and their relevance to the identification and characterisation of hypothetical exposed groups, are identified as:

(a) Purpose of the assessment

The general purpose of the biosphere component of safety assessment for solid radioactive waste disposal is to determine the radiological significance of potential future releases of radionuclides. However, the level of detail and comprehensiveness required in identifying and justifying the assumed behaviour of hypothetical exposed groups will vary according to the specific aim of an assessment. For example, if simple calculations are required to test initial ideas for disposal concepts, it may be sufficient to base exposure estimates solely on an assumed drinking water pathway. Alternatively, an assessment intended to support a disposal licence application may demand a much wider variety of exposure pathways and approaches in order for radiological impacts to be adequately addressed.

(b) Endpoints of the assessment

If dose or risk to humans is selected as a relevant endpoint, rather than some other indicator of radiological impact (such as concentrations of radionuclides in environmental media), this implies a requirement to characterise human behaviour and exposure pathways. Some aspects of model and data choice concerning human exposure may depend on more detailed considerations related to such endpoints; for example, the impact may need to be evaluated in terms of a lifetime average annual dose or risk, rather than in terms of the annual exposure in any given year. This, in turn, can affect assumptions adopted in relation to potential variations of human behaviour or biosphere characteristics on different timescales, such as that of a human lifetime. In particular, such considerations might have an important impact on the emphasis given to exposures incurred by different demographic groups.

If the endpoint is individual dose or risk, rather than collective dose or some other population-integrated measure of radiological impact, it may be relevant to consider potentially sensitive subgroups of the exposed population. Such groups would be identifiable, for example, according to their use of particular natural resources, or through some other homogeneity criterion.

Although there is increasing interest in assessing the potential significance of radiological impacts of waste disposal practices on non-human biota [see, e.g. IAEA, 1998; Smith et al, 1998], the focus of this report is limited to radiological impacts expressed in terms of dose and risk to humans.

(c) Assessment philosophy

Even where the assessment endpoints are clearly defined, alternative approaches to addressing those endpoints may be possible. A coherent approach needs to be developed for all aspects of the assessment. A particularly important example concerns the degree of conservatism that is deemed to be appropriate in characterising the hypothetical behaviour of future exposed groups and/or individuals. Regulatory guidance on this issue is generally insufficient to define such behaviour for quantitative compliance assessments. However, the background against which quantitative safety standards are set can itself involve tacit assumptions about which groups within the population they are intended to protect. Further discussion of this question is included in Section 2.3, below.

(d) Site context

The general location of a repository, combined with the particular design of the repository system, may have an important influence on the likely pathways for release, the type of biosphere system into which releases may occur, and the extent to which factors such as climate and ecological change can influence the impact of such releases. These, in turn, will affect the choices that need to be made in relation to the representation of human exposure pathways. In particular, it is necessary to ensure that the assumed human behaviour is consistent with the assumed biosphere system into which the release occurs.

(e) Repository system

Except for human intrusion scenarios, features relating to the repository system will have only an indirect influence on the representation of human exposure pathways, predominantly through their influence on the radionuclides that may be released to the biosphere and the corresponding geosphere/biosphere interface.

(f) Source term and geosphere/biosphere interface

In broad terms, the assumed mode and rate of release of radionuclides from the geosphere into the biosphere mainly influence choices made regarding the modelling of radionuclide transport and accumulation in the environment, rather than the representation of exposure pathways. However, detailed considerations relating to the modelling of the geosphere/biosphere interface and dispersion in the biosphere may assume greater importance in situations where the exposed group involves only a small number of individuals, or if homogeneity of exposure (rather than behaviour) is a critical concern in evaluating representative radiological impacts.

Specific modes of release, or particular radionuclides within the source term, may dictate consideration of exposure pathways that would perhaps not otherwise be included in the description of exposed groups. For example, radionuclides released to the biosphere in gaseous form may increase the emphasis given to inhalation of indoor air.

(g) Time frames

An internationally-adopted safety principle is that waste disposal practices should provide for the protection of both current and future generations. The overall time frame to be addressed in demonstrating compliance with this principle may be established as part of the overall assessment context; in some regulatory guidance, however, only limited advice is given. Combined with information regarding the disposal system, site context and source term, the selection of a specific time frame can have a considerable impact on biosphere assessment [BIOMASS, 1998b], notably with respect to the treatment of environmental change, critical radionuclides and the geosphere/biosphere interface [BIOMASS, 1998c]. In relation to radiological exposure calculations, assessment timescales beyond even a few tens, or at most hundreds, of years introduce profound uncertainty into any quantitative description of human behaviour. Assumptions related to human behaviour over longer time frames will therefore be largely speculative.

All these factors will affect the approach taken to representing the biosphere system and exposure pathways.

(h) Societal assumptions

Basic assumptions relating to the type of society (e.g. agrarian or urban), community structures and level of technological development are fundamental to decisions made concerning the characterisation of future human behaviour. In addition, assumptions about the period of long-term institutional control over the disposal facility may influence the timeframes for the assessment and, thereby, affect assumptions underlying the definition of future exposed groups. Moreover, because human actions have a profound effect on the surface environment, societal assumptions are also very relevant to the identification, description and modelling of relevant biosphere systems. As with the overall assessment philosophy, advice relating to the choice of appropriate societal assumptions is not always incorporated in regulatory guidance. This can be deliberately intended to provide scope for the justification of assessment-specific assumptions and methods; nevertheless, it is important to recognise the degree of ambiguity of interpretation that can arise from failing to specify the societal assumptions under which compliance criteria are set.

2.2. EXISTING GUIDELINES FOR CHARACTERISING HUMAN BEHAVIOUR

Development of the critical group concept

(22) The concept of the ‘critical group’ was adopted by ICRP in order to address the problem of setting quantitative limits on present-day or near-future discharges of radionuclides to the environment. In such circumstances, the actual doses incurred by members of the public will be variable due to a host of variable environmental factors, as well the intrinsic variability associated with differences in age, size, metabolism and habits. The underlying philosophy was to demonstrate compliance with a dose constraint based on estimated exposures for a particular population subgroup. This was originally explained as follows [ICRP, 1977]:

> *“With exposure of members of the public it is usually feasible to take account of these sources of variability by the selection of appropriate critical groups within the population provided the critical group is small enough to be relatively homogeneous with respect to age, diet and those aspects of behaviour that affect the doses received. Such a group should be representative of those individuals in the population expected to*

receive the highest dose equivalent, and the Commission believes that it will be reasonable to apply the appropriate dose-equivalent limit for individual members of the public to the weighted mean dose equivalent of this group. Because of the innate variability within an apparently homogeneous group some members of the critical group will in fact receive dose equivalents somewhat higher than the mean. However, because of the maximising assumptions used, the dose equivalent actually received will usually be somewhat lower than the estimated dose equivalent."

(ICRP Publication 26, 1977; paragraph 85).

(23) Subsequently, the term 'critical group' has become widely used to describe a set of individuals who, because of their location and commonality in their behaviour and habits, are among the most highly exposed to releases from a nuclear facility. This approach was underlined in a recent policy statement [ICRP 1998], which notes that the concept "*was introduced into waste management to allow the individual doses delivered by a source to be assessed without the implied need to identify each individual separately*" (paragraph (3)(f) of ICRP Publication 77).

(24) Whereas Publication 26 refers to the identification of a group whose *characteristics* are 'relatively homogeneous', the fundamental inhomogeneity in radiological protection terms is with respect to total dose, not the factors that determine dose. In other words, it is possible for two individuals with different combinations of age, location, metabolism, and habits to be assessed as incurring similar exposures to the same source. Thus, these two, outwardly different individuals could be classed into the same group due to their homogeneity of *exposure*. This point is emphasised in subsequent revisions of the ICRP recommendations [ICRP, 1991] where, in the context of 'normal exposures' from routine operations, it is stated that:

"In practice, almost all public exposure is controlled by the procedures of constrained optimisation and the use of prescriptive limits. It is often convenient to class together individuals who form a homogeneous group with respect to their exposure to a single source. When such a group is typical of those most highly exposed by that source, it is known as the critical group. The dose constraint should be applied to the mean dose in the critical group from the source for which the protection is being optimised..."

(ICRP Publication 60, 1991; paragraph 186).

(25) For situations where it is reasonable to assume that the statistical variation of dose among the exposed population is comparable with that in a given present-day population (e.g. for routine discharges from planned or existing operational facilities), ICRP has developed specific guidance on the application of the critical group approach. In particular, attention has been given (paragraphs 67-69 of ICRP Publication 43, 1985) to interpreting the requirement for homogeneity within the critical group in the context of environmental monitoring [ICRP, 1985a]. This guidance can be summarised as follows:

(a) The dose limits are intended to apply to mean doses in a reasonably homogeneous group. The necessary degree of homogeneity in the critical group depends on the magnitude of the mean dose in the group as a fraction of the relevant source upper bound (or constraint). If that fraction is less than about a tenth, a critical group should be regarded as relatively homogeneous if the distribution of individual doses lies substantially within a total range of a factor of ten, i.e. a factor of about three either side of the mean. At higher fractions, the total range should be less, preferably no more than a factor of three.

(b) In an extreme case (for example when dealing with conditions in the far future, which cannot be characterised in detail), it may be convenient to define the critical group in terms of a single hypothetical individual.

(c) Usually, however, the critical group would not consist of one individual (as this would be statistically unrepresentative), nor would it be so large that it violated the homogeneity criterion.

(d) The size of a critical group will usually be up to a few tens of persons. In a few cases, where large populations are uniformly exposed, the critical group may be much larger.

(e) In habit surveys, it is not necessary to search for the most exposed individual within a critical group in order to base controls on that one person. The results of a habit survey should be regarded as an indicator of an underlying distribution and the value adopted for the mean should not be unduly influenced by the discovery of one or two individuals with extreme habits.

(f) In calculating doses to critical groups, metabolic parameters should be chosen to be typical of the age groups in the normal population rather than extreme values.

Application to solid radioactive waste disposal

(26) The main emphasis in the guidance discussed above concerns application of the critical group concept to situations (principally effluent discharges) where exposures are virtually certain to occur, with a timing, magnitude and location that is predictable with some confidence. By contrast with such so-called 'normal' exposure situations, and because of the substantial uncertainties surrounding the occurrence and possible magnitude of future releases, the situations of concern in the long term following disposal of long-lived solid radioactive wastes are sometimes identified as 'potential' exposures (cf. [ICRP, 1991; 1993]). The precise implications of assessing future radiological impacts from solid waste disposal in the ICRP framework of potential exposures remain to be developed by the Commission. Indeed, compared with the detailed interpretation of the critical group concept that has been developed in the context of normal exposures, the principles for defining human behaviour in relation to the assessment of potential exposures have received relatively limited attention.

(27) The recent ICRP statement of policy on general issues related to waste disposal [ICRP, 1998] addresses the importance of protection of future generations from exposures resulting from present-day practices. In this context, attention is focused on the appropriate assessment quantities, rather than guidance on the means of evaluating them. Whereas it is noted that "*the relationship between dose and detriment [is] uncertain at times in the distant future*" (ICRP Publication 77, 1998; paragraph 23), several quantities are considered potentially relevant in indicating the degree of protection afforded to future generations. These include the total detriment imposed on a defined generation, and the detriment imposed annually, or over a lifetime, on individuals represented by one or more hypothetical critical groups. Specifically, it is suggested that the annual individual effective dose (for normal exposure) and annual individual risk (for potential exposure) incurred by members of the relevant critical groups provide an adequate basis for comparing the limited detriment to future generations with that applied today (ICRP Publication 77, 1998; paragraphs 68–69).

(28) The primary source of existing formal guidance from ICRP on critical groups in the context of solid radioactive waste disposal is Publication 46 [ICRP, 1985b]. These

recommendations have recently been clarified (but not substantially altered) in relation to broader considerations of radioactive waste disposal (including controlled release to the environment) [ICRP, 1998]. The basic proposition embodied in the ICRP principles is summarised as:

> *"The critical group ... may comprise existing persons, or a future group of persons who will be exposed at a higher level than the general population. When an actual group cannot be defined, a hypothetical group or representative individual should be considered who, due to location and time, would receive the greatest dose. The habits and characteristics of the group should be based upon present knowledge using cautious, but reasonable, assumptions."*
>
> (ICRP Publication 46, 1985; paragraph 46)

(29) Updated guidance from ICRP, relating specifically to considerations relevant to the disposal of waste in repositories (rather than the more general policy on waste disposal [ICRP, 1998], which includes effluent discharge) is understood to be at an advanced stage of preparation. It is not anticipated that basic recommendations relating to the identification and definition of potential critical groups will differ substantially from the previous guidance [ICRP, 1985b] to adopt a 'cautious, but realistic' framework. Rather, the new guidance is expected to consider further the likely inferences to be drawn from working on the basis of such an approach. Some of the possible interpretations and implications are considered below.

(30) For example, coherence between assumptions relating to hypothetical exposed groups and the landscapes and environments they inhabit is important, but endless speculation regarding the possible impact of human behaviour on the biosphere is discouraged. Reference to present-day lifestyles is considered, consistent with approaches adopted elsewhere in radiation protection, but more generalised assumptions will tend to be appropriate as the timescales extend into the far future. An emphasis on homogeneity of habits and characteristics (including age) among members of a critical group is not a major concern in relation to long-term exposures, provided that due attention is given to the identification of suitably representative behaviour.

(31) Sometimes, depending on the assessment purpose, it may be appropriate to provide an estimate of the population dose distribution associated with waste disposal. The background to this is explained [ICRP, 1998] as follows:

> *"To the extent that the justification of a practice involves collective dose, the Commission's policy requires an estimate of the total collective dose attributable to the practice, including the waste management and disposal operations."*
>
> (ICRP Publication 77, 1998; paragraph 35)
>
> *"The unlimited aggregation of collective dose over time and space into a single value is unhelpful... The levels of individual dose and time distribution of collective dose may be significant factors in making decisions... The use of blocks of collective dose resulting from individual doses that are very small or occur at very remote times requires consideration."*
>
> (ICRP Publication 77, 1998; paragraphs 20-21)
>
> *"[The Commission] does not recommend that the component of collective dose due to small individual doses should be ignored on the sole ground that the individual doses*

are small. [Nevertheless,] it may sometimes be possible in optimisation to disregard the collective dose from small doses to large numbers of people if the sources are widespread, because it may not be possible to reduce the collective dose with any reasonable deployment of resources."

(ICRP Publication 77, 1998; paragraph 56)

(32) The potential number of people exposed to future releases from a repository, and the homogeneity of exposure across such a group, are not necessarily the primary considerations in assessing radiological exposures for direct comparison with regulatory benchmarks when these are expressed solely in terms of individual dose or individual risk. However, such factors may play a part in developing the 'multiple lines of reasoning' that are likely to be necessary in providing assurance that future individuals are afforded a level of protection consistent with that tolerated today. Furthermore, where regulatory benchmarks are in units of collective or population dose or risk, some indication of the potential number of people exposed and the numerical distribution of their exposure will need to be considered. Additional discussion of this issue, consistent with the principles discussed above, is presented in Annex C.

2.3. CRITERIA AND COMPLIANCE

National guidance on compliance standards for waste disposal

(33) Regulatory approaches adopted in specific countries in respect of the disposal of long-lived solid wastes, together with guidance from relevant advisory bodies, represent attempts to provide practical interpretation of the general guidance on radiological protection principles provided by ICRP and others. In several cases (see e.g. [Burholt and Martín, 1988; JORF, 1991; HSK/KSA, 1993; SSI, 1998a]), however, practical advice with respect to characterising human behaviour relevant to the evaluation of dose and/or health risk has either been very limited or is absent altogether. A brief, partial survey of guidance available in various countries, based on information provided by BIOMASS participants, is presented in Annex A.

(34) There is general consensus in guidance from national regulatory authorities in different countries that radionuclide releases from repositories for solid radioactive wastes should be controlled so as to limit either individual doses or health risks. For long-term releases from repositories it is understood this 'control' is intended to be accomplished via passive, rather than active features of the engineered and natural barriers comprising the repository system. Guidance from the United Kingdom [Environment Agency et al, 1997], Spain [CSN, 1987; Burholt and Martín, 1988], Sweden [SSI, 1998a], the Canadian regulatory authorities [AECB, 1987] and in recommendations developed in relation to the proposed Yucca Mountain facility [NAS, 1995] is formulated in terms of health risk. By contrast, French [JORF, 1991] and some US regulations [USEPA, 1991; USNRC, 1999] are formulated in terms of dose. Swiss regulations [HSK/KSA, 1993] adopt a hybrid position, with a dose limit supplemented by a health risk limit for unlikely events and processes.

(35) Where a quantitative health risk criterion for individuals has been specified, a value of 10^{-6} per year is typically adopted. However, this may be interpreted either as a strict constraint for the facility under consideration or simply as a target; non-compliance with a target may be justified providing that optimisation of the disposal system has been demonstrated. Specifically, in the UK, it is stated that:

"If for the chosen design the risk to a representative member of the potentially exposed group at greatest risk is above the target of 10^{-6} per year, the developer should show

that the design is optimised such that any additional measures which might reasonably be taken to enhance the performance of the chosen design would lead to increases in expenditure, whether in time, trouble or money, disproportionate to the reduction in risk."

(Environment Agency et al, 1997; paragraph 6.25)

(36) The annual individual dose limits (or constraints) for normal releases from waste repositories adopted in different national regulations are in the range 0.01 mSv to 0.25 mSv. Assuming a dose-to-risk conversion factor for members of the public of 0.05 per Sv [ICRP, 1991], the corresponding conditional individual health risk limits are therefore in the range $5\ 10^{-7}$ to $1.3\ 10^{-5}$ per year.

(37) Overall, the above comparisons suggest that an individual health risk target in the region of 10^{-6} per year and a constraint in the region of 10^{-5} per year have, at least to date, been interpreted internationally as providing a suitable basis for regulation. BIOMOVS II [1996] noted that individual annual health risk levels in the range 10^{-6} to 10^{-5} are consistent with risk levels that society currently tolerates for large populations from a range of different hazards. However, higher individual risk exposures from non-radiological hazards, sometimes exceeding 10^{-4} per year [BIOMOVS II, 1996], are often tolerated for populations of limited size.

Coherence considerations

(38) A coherent overall approach to demonstrating compliance with radiation protection goals requires consideration of the relationship between the philosophy underlying the development of quantitative compliance criteria and that adopted in performing the exposure assessment. Furthermore, within the assessment itself there is a need for consistency between the description of hypothetical exposed groups and the assumptions underlying development of biosphere system descriptions.

(39) A generally cautious assessment approach is dictated throughout ICRP guidance as a means to provide assurance that actual exposures are unlikely to be significantly underestimated. Hence, for example, in assessing future doses from normal exposure situations (e.g. in order to establish effluent discharge limits for new practices) it is normal to adopt conservative assumptions in respect of the location of the assumed receptor relative to potential future environmental concentrations. In the context of potential future releases from waste repositories, however, it may be that such an assumption would lead to a significant overestimate of actual radiological risks. An approach is therefore required that strikes a 'reasonable' note of caution without being over-conservative.

(40) As far as published guidance is concerned, ICRP's interpretation of the term 'cautious, but reasonable' as applied to assumptions regarding future human behaviour is restricted to the recommendation that these should be 'realistic' and based on present knowledge [ICRP, 1985b]. Endless speculation regarding future human behaviour is therefore discouraged; nevertheless, this still leaves considerable room for interpretation in terms of what constitutes an adequate indicator of potential radiological impact (see Section 3.1, below).

(41) Most national regulatory authorities have proposed radiological protection standards for waste disposal that are generally consistent with individual health risk levels tolerated for large populations from a range of different types of hazard. In addition, the regulatory guidance typically requires that these standards apply the calculated exposures for a critical group (i.e., a fairly small number of people), although at least one group, HSK/KSA in

Switzerland, does link the risk limit to population size. Although ICRP suggests that both individual and population dose be kept as low as reasonably achievable [ICRP, 1998], the approach adopted in most national regulations could therefore be seen as demanding greater levels of protection than those applied to other sources of risk at the present day, because the limit on individual health risk is being applied to a small group, rather than the general population.

(42) A conservative approach to the application of compliance standards, coupled with an overly-cautious assessment approach, could potentially lead to disproportionate attention and resources being allocated to the control of risks from waste disposal rather than those from other hazards (see also ICRP [1998], paragraph (49)). Nevertheless, evidence from existing regulatory guidance seems to suggest that additional caution has been considered justifiable in the context of solid radioactive waste disposal.

(43) In practice, the choices made will be need to be justified against the specific context within which the assessment is performed (see Annex B). It seems prudent to expect that demonstrating compliance with regulatory targets and/or constraints will typically involve multiple lines of reasoning, exploring a range of alternative exposure scenarios to build confidence in the results as a satisfactory quantitative basis for informing decision making. This does not necessarily mean that strict compliance with quantitative risk criteria needs to be demonstrated for all possible circumstances explored in the assessment. However, any assessment will need to be supported by sufficient justification to provide, for the particular context under consideration, satisfactory assurance that future individuals are afforded a level of protection consistent with that required today.

3. METHODS FOR IDENTIFYING EXPOSED GROUPS FOR SOLID RADIOACTIVE WASTE DISPOSAL ASSESSMENTS

3.1. INFLUENCES ON CHOICE OF APPROACH

(44) The biosphere(s) and associated descriptions of human behaviour adopted for assessing system performance should provide a representative set of indicators of the potential radiological impact of the repository. When integrated with understanding arising from assessments of the behaviour of the disposal system as a whole, such indicators serve as an input to decisions regarding the acceptability of long-term system performance. The challenge, therefore, is to describe future human behaviour in such as way that, notwithstanding the speculative nature of various underlying assumptions, the results provide a sufficient degree of assurance regarding future levels of radiological protection.

(45) Clearly, future human behaviour can be significantly affected by local or regional environmental factors, such as climate, topography and the availability of water and food. Moreover, human actions such as agricultural activity and civil engineering projects could also have a major impact on the environment into which future releases may occur. In the case of drilling and excavation, such actions may affect the timing, nature and extent of releases of radionuclides into the accessible environment. Thus, the desire for a coherent overall assessment dictates that the assumed socio-cultural and technological context is properly understood and defined as a prerequisite for characterising both the biosphere and future human behaviour.

Reference to present-day behaviour

(46) The range of possible future activities and behaviours that might be considered in representing the far future within an assessment is limited only by our imagination. Historical evidence shows that the potential for significant differences in future human behaviour (compared to the present day at any particular location) is large; moreover, such future behaviour is largely unknown and not open to predictive modelling. ICRP Publication 46 [ICRP, 1985b] seeks to provide a check on speculation by cautioning that 'realistic' assessments of radiological exposure, based on present knowledge, are essential if meaningful comparisons are to be made between different options and alternatives. This is especially the case if indicators of future radiological impact are to be meaningfully compared with exposures that are tolerated today.

(47) Bearing in mind that the basic principle of providing assurance that future impacts are compatible with those tolerated today [IAEA, 1995], an appropriate starting point is to assign future individuals similar habits to those of the present-day populations against whom future projected risk levels will be compared. Apart from any other justification, such an approach would certainly help to address any local community concerns regarding the relevance of the assessment to their current location and practices. However, this does not necessarily mean that present-day behaviour at the site, or in the region of interest (e.g. in relation to the way that local environmental resources are presently exploited) will necessarily provide a sufficient basis for assessment. For example, if, as a result of climate change and related factors, future releases are likely to take place into an environment that is substantially different from that of today, it would be reasonable to expect that some analysis of alternatives - consistent with possible future environmental conditions - should be included. Indeed, this approach was suggested by a Swedish working group [SKI/SSI/SKB, 1989].

(48) It is only for present-day releases that a reasonable measure of assurance can be given with respect to predictions of the detailed distributions of exposures among an exposed population (based on a distribution of location, age, habit, metabolism, and environmental factors). For potential exposures in the far future, any distribution of exposures adopted within an assessment can only be regarded as an assumption. Although such distributions could be generated for the far future by, for example, adopting present-day distributions in relation to behaviour, the endpoints of such an assessment would simply be one of many possible dose- or risk-based indicators of future disposal facility performance.

(49) For some assessment contexts, therefore, representations of future human behaviour closely resembling present-day patterns of resource exploitation – perhaps even simulating a local community in the vicinity of the site – would be appropriate. Databases on local, regional or national dietary and other habits are also potentially relevant sources of information to an assessment. When justified by the assessment context, and if adequate data exist, it can also be acceptable to use data on historic land-use practices pertinent to the region, or on a wider spatial scale. Furthermore, where the assessment context dictates that future environmental change should be taken into account, it will be appropriate to represent human behaviour on the basis of present-day (or, if available, historical) practices from analogue locations with biosphere conditions similar to the altered biosphere.

Exposed group or individual behaviour?

(50) The common use of limits or constraints expressed in terms of *individual* dose or risk may be taken to imply that it is necessary to define future *individual* behaviour, rather than future *group* or *societal* behaviour. However, this is not the intent of much of the existing guidance and national regulations. For example, according to ICRP's recommendations in relation to 'normal exposures' [ICRP, 1991], dose constraints should be applied to the mean dose among a collection of individuals forming a homogeneous group with respect to exposure from a given source. The aim of such an approach is to prevent decisions from being unduly influenced by the discovery of perhaps one or two individuals with extreme habits leading to exposure.

(51) For many assessment contexts, then, it would appear both necessary and appropriate to compile assumed distributions of future behaviour into a limited set of behavioural groups. For cases where the definition of a 'critical' group is required, the aim should then be to address alternatives for the possible behaviour of a hypothetical 'Reasonably Maximally Exposed Individual' (RMEI), giving due regard to the need for adopting cautious, *but reasonable*, assumptions [ICRP, 1985b]. This should not be taken to imply that the RMEI necessarily represents some separate, specific individual. Rather, it should be representative of the reasonable behaviour exhibited by members of a maximally exposed group of limited size.

(52) From a practical standpoint, it may be noted that information related to the behaviour of individuals is often used to derive 'average' behaviour, or to provide an estimate of individual behaviour distribution. For example, survey data of individual habits (e.g., consumption of foodstuffs, location, use of local resources) is typically used to establish, quantitatively, the characteristics of a particular group for a safety assessment. The intent of the majority of existing guidance and regulations, including ICRP guidance, is consistent with this practice. This does not mean, however, that behaviour of a single individual from a survey can properly be used *in isolation*. Indeed, whereas the full set of results of a habit survey may be regarded as an indicator of an underlying distribution, the values adopted for assessment purposes

should not be unduly influenced by the discovery of one or two individuals with extreme habits (paragraph (25)).

Physiological characteristics

(53) Typically, in identifying critical groups for normal exposures to routine discharges from nuclear installations, standard 'reference' values of physiological parameters are adopted as part of the assessment basis. In principle, the same level of cautious, but reasonable assurance regarding protection would be provided by using similar generic data in the context of hypothetical exposures within a reference biosphere system assumed for the purposes of long-term assessment. However, a question remains regarding the extent to which different demographic, or other, groups with special physiological characteristics affecting their absorbed dose or health risk, need to be addressed.

(54) According to the guidance given in ICRP Publication 43 [ICRP, 1985a], doses to critical groups may reasonably be expected to address age-dependent variations in metabolism, at least in terms of identifying representative (rather than extreme) exposures. The adoption of a 'cautious' approach in addressing exposures in the long-term future might therefore be anticipated to embrace children and infants as separate hypothetical exposed groups. Although not as large as that for adults, a significant body of biokinetic and dosimetric data for infants and children does exist, making a separate analysis for these subgroups possible. Dose coefficients are generally higher for children than for adults because (i) gut uptake factors are usually greater; and (ii) radionuclides that are retained in the body will tend to deliver a higher absorbed dose (energy per unit mass) to smaller body organs.

(55) Yet, the particular characteristics of exposures resulting from solid radioactive waste disposal on land suggest age-dependent analyses may not be necessary. Long-term discharges from waste disposal facilities will tend to give rise to life-long, chronic exposures. Because individuals will spend most of their lives while exposed as adults, taking account of exposures during infancy and childhood will not necessarily increase the estimated lifetime doses or health risks by very much. For example, draft guidance currently being developed within ICRP[1] suggests it could be assumed that radioactive contamination of the biosphere due to releases from the repository would remain relatively constant over periods considerably longer than the human life span. It is then reasonable to calculate the annual dose/risk averaged over the lifetime of the individuals, which means that it is not necessary to calculate doses to different age groups. In particular, it is suggested that the lifetime average annual dose can then be adequately represented by the annual dose/risk to an adult.

(56) Part of the difficulty in deciding how to address the issue of whether or not to consider different age groups separately arises because radiological safety standards tend to be addressed in terms of annual limits or targets, whereas assessment modelling – particularly at long times into the future – inevitably invokes temporal averaging in the representation of events and processes. For example, rainfall may be represented not simply in terms of a monthly-averaged rate, but as a *long-term* monthly-averaged rate, based on mean values expected for a given climate over several decades. The biosphere system in which exposure occurs will therefore typically be represented within an assessment model such that environmental concentrations of radionuclides are determined only in terms of their long-term average values. This challenges the internal consistency associated with performing separate

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1 This draft guidance is being prepared by Working Group 4 within the ICRP, but has not yet been adopted by the Commission.

'snap-shot' calculations of annual exposure for different age groups, rather than lifetime-average annual exposures.

(57) Furthermore, from a practical standpoint, variations arising from differences in critical group behaviour may be significantly less than underlying uncertainties in dosimetry [Smith et al, 1997]. For example, some aspects of the behaviour of children and infants (e.g. dietary intake of many foodstuffs) would give rise to rather less exposure than for adults, whereas others (e.g. consumption of milk, exposure to dirt) could be responsible for considerably more. It is difficult to be precise, but a range of up to a factor of five difference, or uncertainty, in annual exposures associated with age-dependent behaviour patterns seems reasonable for most exposure pathways. However, uncertainties in the relevant metabolic and biochemical models and parameters relating to internal dosimetry for children and infants in particular are far larger (with certain specific exceptions) than those associated with behaviour.

(58) Nevertheless, for some assessment contexts, reassurance may need to be provided that children and infants, and other potentially sensitive groups, are adequately protected. This could be seen as being consistent with the overall aim of using multiple lines of reasoning to build confidence in quantitative assessments as a satisfactory quantitative basis for informed decision making. It is not clear if such matters are better addressed in establishing radiological protection standards for waste disposal or if they should be explicitly accounted for in the performance assessments themselves. In either case, the aim should be to determine whether or not differences in overall exposure for different demographic groups are small and, if necessary, to account for variabilities with an appropriate margin of caution.

Parameters relevant to the characterisation of human behaviour

(59) Environmental modelling in post-closure performance assessment provides estimates of the concentrations of radionuclides in various components of the biosphere system.[2] The additional information necessary to evaluate radiological exposures, dose and risk can be divided into the following primary classes:

(a) General description of the hypothetical exposed group(s)

This description should be sufficient to form the basis for defining particular patterns of behaviour and should be consistent with underlying assumptions regarding the socioecomic structure of the wider community and the relationship of such communities to their environment. The level of detail required will depend on the specific approach taken in performing the calculation. Nevertheless, relevant information might include, for example: consideration of the environmental resources that are exploited by the community; and the different demographic groups to be considered in the assessment.

[2] It must be remembered, however, that the environmental model should be developed with consideration of the influence the assumed society on the characteristics of the biosphere. Exposed group assumptions and biosphere definition should therefore be developed together to avoid inconsistency.

(b) *General description of activities leading to radiation exposure*

Relevant group- or age-specific activities to be considered include: eating and drinking; washing; type of work (including relevant sub-tasks linked to particular modes of exposure – e.g. those activities that may be associated with enhanced ambient dust levels); recreation; sleeping.

(c) *Physiology*

Important factors contributing to physiological differences, and thereby potentially affecting radiological exposures, include age, sex and metabolic characteristics (breathing rate, exercise, etc). These need to be specified for each hypothetical exposed group. Apart from their influence on dietary intake of different contaminated foodstuffs, such factors will also influence biokinetics (the retention of ingested radionuclides in tissue) and exposure geometries (i.e. tissue masses and their configuration with respect to radiation sources). In certain cases, internal exposures from radioisotopes of elements that are homeostatically controlled in the body (e.g. iodine, chlorine) may be influenced strongly by the assumed abundance of the natural counterpart or other chemically similar elements within the diet.

(d) *Location*

A description of the surroundings in which each activity defined in (b) is assumed to take place. In addition to general location considerations (e.g. agricultural or urban land), further qualification (e.g. indoor/outdoor) may be appropriate in order better to characterise factors such as dust levels or the degree of shielding from external irradiation.

(e) *Mode of exposure*

The principal modes of exposure relevant to radiological exposure assessment are ingestion, inhalation and external irradiation. It is generally considered that doses incurred via other modes of exposure (e.g. adhesion to skin and hair, transcutaneous transfer) will be relatively unimportant [BIOMOVS II, 1996].

(f) *Rate/duration of exposure*

Relevant parameters correspond to the information necessary to quantify annual average exposures from each potential source. These include, for example: ingestion rates of different foodstuffs and (for inhalation and external exposures) occupancy times at different locations.

(60) An example of applying the general guidance in (a) above to the identification of a ‘cautious but reasonable’ critical group, or RMEI (see paragraph (51)) is as follows. If it were assumed that the hypothetical ‘most-exposed individual’ was part of a community sharing resources collected from a wide area, exposures might be reduced through the mixing of local foodstuffs with resources from outside the immediate area of highest contamination. Whereas caution dictates that such causes of exposure ‘dilution’ should not be overstated, it is reasonable to expect that some consideration should be given to the size of the group ‘at risk’ from future discharges.

(61) One justification for considering the likely ‘dilution’ in exposure associated with increasing the size of the group is the desire to provide a reasonable representation of the distribution of future behaviour in relation to the environment. It would be overly cautious to assume, for example, that virtually all the release takes place into an area the size of a family

garden (e.g., an area of rather less than one hectare), and that the area is used as a family garden that provides 100% of the nutritional needs for the family. However, it would probably be considered reasonable to evaluate the exposure arising from that part of the release that affected such an area. Only when reasonable spatial distributions of both the release itself *and* human behaviour are considered can a reasonable estimate of the future impact of the waste disposal facility be provided. This is particularly important in comparing the results of an assessment with regulatory criteria; it is not necessarily reasonable to apply an individual risk limit on the order of individual risk levels tolerated for large numbers of people if the assessment is for a situation in which only a few people can be exposed [BIOMOVS II, 1996]. A conceptual approach that addresses this issue in relation to the use of assessment results to inform decision making is outlined in Annex C.

Accounting for uncertainties

(62) Past ICRP guidance [ICRP, 1993], and that of many national regulatory agencies, has implied that 'potential' radiological exposures (of which the long-term impact of discharges from solid waste disposal often cited is an example – see paragraph (26)) are properly managed through controls on risk, taking account of the likelihood of exposure. Temporal and spatial uncertainties in the concentration profile of contamination emerging from a repository, evaluated using, for example, Monte Carlo simulations for alternative realisations of the performance of the disposal system, are often assumed to provide a suitable basis for determining the exposure probabilities. In each realisation the environmental contamination is described as a function of time; however, its characteristics (e.g. time of peak discharge to the biosphere, region of contamination, dominant radionuclides) may differ from one realisation to the next.

(63) An important consideration in the probabilistic treatment of such uncertainties is the location of the assumed individuals in relation to the contaminated biosphere system (see, for example, the extended discussion in [NAS, 1995] where it is suggested that the location of individuals in the biosphere be generated stochastically for each Monte Carlo realisation). A balance needs to be reached between achieving an appropriate level of caution in the mathematical aggregation of risk contributions from different realisations and the basis on which the quantitative evaluation criteria themselves are defined, especially as the definition of the exposed groups may differ for each realisation [Thorne, 1989]. Although cautious, it is not obvious how to interpret an individual 'risk'[3] that has been calculated on the basis of the average dose experienced via exposure to the *highest* environmental concentrations in *each* future realisation. Consequently, it becomes difficult to determine whether or not the safety goal (that future individuals are afforded a level of protection consistent with risks tolerated today) has been achieved.

(64) The potential complexities of the interaction between exposed group definition and uncertainties in waste system performance are not addressed in detail within this document. They are nevertheless raised here as a key consideration in the appraisal of alternative approaches to identifying exposed groups for use in comparisons against regulatory benchmarks. Both deterministic and probabilistic approaches to defining future human behaviour as a basis for evaluating radiological impact will have their place in comparisons

[3] 'Risk' is used here in the sense of including potential exposures, where probabilities must be assigned to alternate scenarios giving rise to different levels of exposure. This is different than 'health risk', which is often considered to include only the probability that an individual will develop a health effect *from a 'certain' fixed dose*. 'Risk', as it is used here, can include both concepts [Watkins and Kessler, 1998].

against criteria, by helping to develop the required level of assurance to inform decision making.

3.2. PRINCIPAL OPTIONS

(65) Decisions regarding the hypothetical exposed groups relevant to a given assessment context – their numbers, diet and other behaviour – cannot be considered independently of the assessment-specific biosphere system description. The 'process system' represented in the biosphere assessment model will depend on underlying assumptions related to socio-economic and cultural context that determine human interaction with the biosphere. The assumed scale and manner of exploitation of biosphere resources by a hypothetical local community, as guided by the assessment context, is fundamental to any evaluation of potential radiological impact. The overall aim is to achieve a measure of coherence, both within various elements of the calculation of radiological impact and set against the underlying assumptions on which radiological criteria are themselves determined.

(66) Broadly speaking, there are two main alternative strategies for identifying and describing the assumed behaviour of members of hypothetical exposed groups to provide quantitative estimates of human impact due to potential releases in the long-term future. In what follows, these are identified as the *a priori* and the *a posteriori* approaches. Some detailed considerations in relation to the implementation of these two alternative approaches are addressed in Sections 3.2.1 and 3.2.2. In practice, it seems likely that the relative strengths of the different approaches will depend on the context in which the assessment is performed. A comparison of the possible advantages and disadvantages of each method is therefore presented in Section 3.2.3.

3.2.1. 'A priori' identification

(67) In the *a priori* approach, the assumed characteristics and habits of candidate critical groups are fixed prior to performing the exposure calculation, and the most representative of these then serves as a representative indicator of the maximum potential exposure. The *a priori* approach takes as a premise the fact that any definition of human behaviour in the long term is essentially speculative, but that scientifically-informed reason (e.g. in relation to the potential importance of different exposure pathways for different radionuclides) can be used to make sensible judgments regarding the hypotheses appropriate to performing an exposure assessment. It also emphasises the importance of seeking to achieve coherence between assumptions underlying the identification and definition of biosphere systems representative of the long-term future and those involved in describing human behaviour.

Past guidance – 'subsistence' farming

(68) The UK National Radiological Protection Board [NRPB, 1992] and the position paper prepared for IAEA's Advisory Committee on Waste Safety Standards [IAEA, 1996] both suggest that the habits of the critical group should be representative of 'typical' subsistence farmers. This is based on their assumption that subsistence farmers make a (reasonable) maximum use of local environmental resources; for example, exclusive reliance of local water supplies for all uses - including agricultural purposes - will tend to enhance radiological exposures compared with situations where more diverse sources are exploited. The deliberate recycling of materials and nutrients would also be expected to enhance the accumulation of radionuclides in environmental media and thereby maximise exposures. Thus, such farmers might be possibly expected to have the highest exposure risk.

(69) It is not immediately evident, however, that such a group necessarily provides a fully sufficient basis for ensuring consistency of protection with that afforded by today's radiological protection practices, or that it would always be associated with the highest potential risks. Furthermore, there is little information available concerning biosphere systems and human behaviour relating to 'true' subsistence farming methods. Here 'true' subsistence farming refers to farming in which only *local* resources are available to the farmer. This would preclude the use of modern farming practices that make use of many 'imported' resources (e.g., modern farm machinery produced in factories, fuel, fertilizers). 'True' subsistence farming would have to involve, for example, use of farm animals for ploughing or composting practices as the sole source of fertilizer.

(70) Whereas descriptions of human behaviour typical of such communities may be warranted as part of the assessment if, for example, a cautious assessment philosophy is prescribed, it seems advisable to explore alternative possibilities as a contribution to multiple lines of reasoning, particularly when comparisons are being made with regulatory benchmarks. Consideration of a broader range of alternatives would address concerns regarding the relevance of subsistence farming to present-day behaviour in the vicinity of most existing or planned radioactive waste disposal sites – or indeed to candidate analogue biosphere systems representative of the long-term future. A more general approach is therefore required, consistent with underlying assessment assumptions regarding the level of technological development and socioeconomic structures.

Identifying exposed groups based on resource exploitation strategies

(71) For present-day effluent discharges from nuclear installations, potential critical groups are identified by considering the different ways in which members of the local population can be exposed to radioactivity from the local environment. Habit surveys are conducted on the dietary characteristics of the local community and how it exploits local environmental resources.

(72) By analogy, *a priori* descriptions of human behaviour characteristics can be made that relate their use of resources in the biosphere to long-term indicators of radiological impact. Given the convention that extremes of behaviour do not need to be considered in radiological assessments in order to demonstrate adequate protection of individuals, emphasis can justifiably be placed on units of resource exploitation that are sustainable over several generations in environmental systems representative of the future biosphere at the location of interest. For example, for a subgroup composed of wild game hunters and eaters, it should be assumed that the hunting rate is limited so as to avoid permanent depletion of the stocks of available wild game. The identification of different modes of resource exploitation within the local biosphere is a key step in providing a self-consistent basis for describing the interaction between human communities and their environment.

(73) In the *a priori* approach, the primary elements for identifying and defining relevant human habits are units of resource exploitation representatative of particular subgroups within the local community. The way and the efficiency with which resources from the local biosphere system are exploited will depend on basic (i.e. assessment context) assumptions regarding socioeconomic structures, as well as the level of technological development. Relevant data for characterising the relationship of individual members of resource exploitation units to their environment might include:

— a description of the group (e.g. the group of consumers of a particular local foodstuff);
— the number of people associated with a typical unit (e.g. a farmer and his family);

— the area over which resources are exploited by the unit.

Dietary and physiological characteristics of exposed groups

(74) For each type of resource exploitation unit, a group of individuals can be identified (based on available data) who make maximum reasonable usage of the resources available and who would therefore receive the highest exposures from any contamination in that particular environment. A cautious, but reasonable, approach to identifying hypothetical exposed groups would then be to characterise individual habits on the basis of the information describing the actual behaviour of analogue communities forming sustainable units of resource exploitation in comparable biosphere systems. Thus, the analogue communities must be ones that exist today, or existed in the past, for which adequate data characterising a reasonable range of community behaviour are available. Here 'reasonable range' means that data related to the characteristics described in paragraph (59) are available for subgroups within the analogue community that make maximum reasonable use of the local biosphere resources.

(75) If detailed quantitative information on present-day or historical analogue communities is not available, it may be necessary to revert to more general descriptions of behaviour, based on prevailing patterns of resource exploitation in such communities. Thus, for example, an agricultural community could be considered to include a population subgroup that consumes 'above-average' amounts of locally-produced foods. Different emphases would be obtained by focusing on say, beef farming or market gardening as alternative patterns of resource exploitation. Alternatively, a coastal community might include local fishermen, with different groups emphasising different marine pathways, such as fish and crustacea or molluscs.

(76) As far as the consumption of specific dietary items is concerned, it is often assumed that, provided the sample is sufficiently large, the top 5% of a distribution may be taken as representative of a critical consumer group [Hunt et al., 1982, Tscherlovits and Beninson, 1983]. Established databases suggest that the 95th or 97.5th percentiles of consumption rate for many staple foods tend to exceed the mean values by approximately a factor of three. Hence for any given population, the 'safety criterion' (in the context of routine discharges) tends to be set at three times average behaviour [MAFF, 1996; 1997]. Such an approach is also in line with ICRP guidance. Therefore, using approximately the 95th to 97.5th percentile of behaviour to define a 'critical' consumer group, rather than either a higher or lower percentile, is considered to represent a cautious, but reasonable assumption.

(77) Generalised data sources, based on national surveys, can provide a useful source of information, particularly in terms of addressing a diverse range of potential behaviour. However, small communities with specific patterns of behaviour are often not very well represented in national, or even regional, statistics. Care therefore needs to be taken in basing assumed behaviour on such sources, particularly for more unusual habits associated with specific types of biosphere system. Detailed implications of guidance on the definition of critical groups from relevant habit survey data has been explored in various studies relating to present-day discharges [see, for example, Hunt et al., 1982; Robinson and Simmonds, 1992; MAFF, 1996; 1997]. Local habit surveys – if necessary at analogue locations – are particularly relevant where environmental conditions are such that the diets and other habits of local communities are likely to differ significantly from national and regional patterns.

(78) Consideration of the way in which biosphere system resources may be exploited provides a basis for identifying groups of people that are exposed to contaminants via the same environmental pathway(s). Nevertheless, such a group cannot necessarily be considered homogeneous with respect to radiation exposure, because any one individual may, and usually

does exploit more than one resource. Furthermore, their individual physiological characteristics will determine both their degree of exposure and the radiation doses that arise as a consequence.

3.2.2. 'A posteriori' identification

(79) The *a posteriori* approach to identifying exposed groups adopts the premise that it is possible to determine which particular combination of characteristics of human behaviour would cause an individual to be among those incurring a given exposure range (e.g., among the highest exposures) only after each pathway has been assessed quantitatively, having regard to the specific mix of radionuclides present in the discharge to the biosphere at the time of interest. Hence, rather than adopting fixed prior assumptions concerning the characteristics of human behaviour in relation to the local environment, mathematical sampling methods are used to 'explore' various possible contributions to exposure. The aim is to address a comprehensive set of exposure pathways that might potentially be relevant within the assumed biosphere system, selecting a combination that, while not being unrealistic, corresponds to the average exposure, critical group, or maximally exposed individual, as appropriate.

(80) The *a posteriori* methodology applied to identifying the maximally exposed group incorporates the following basic steps:

(a) Identify a general set of potential exposure pathways, accounting for the specifics of the assumed biosphere system(s) and taking account of the overall assessment context. Particular attention needs to be given to basic assumptions regarding socio-economic structures and level of technological development. The identification needs to be performed in conjunction with the biosphere system description(s) in order to ensure that reasonable consistency is achieved between the assumed pathways and the biosphere(s).[4] Tools such as the Interaction Matrix method developed in BIOMOVS II [BIOMOVS II, 1996], can be used to accomplish this.

(b) Develop exposure models to assess the dose (or health risk) arising from 'unit' exposure to each pathway individually (e.g., consumption of unit mass of a given foodstuff, inhalation of unit mass of dust per year, external irradiation from a given source (such as via bathing/swimming) per year), assuming unit concentration of each radionuclide in the media of interest.

(c) Given an assumed release of radionuclides to the biosphere, calculate the total dose or health risk due to unit exposure via each pathway.

(d) Combine the exposures arising from different pathways according to samples taken from distributions of potential behaviour. For example, national food survey statistics (truncated, where necessary, to avoid excessive pessimism by simulating behaviour at the extreme tails of the distribution) would provide relevant distributions of consumption rate for different foodstuffs. Overall exposures would be constrained by setting upper and lower limits to total consumption, in terms of (for example) calorific intake, water intake, trace mineral requirements, fat and protein requirements, consistent

4 While some PA work has implied this is not a requirement, consistency is always to be valued. For example, it would not be consistent to define a biosphere containing land farmed using modern agricultural practices in conjunction with human characteristics representative of hunter-gatherers. In some regulatory regimes, prescriptive guidance may exist regarding specification of human habits relevant to compliance assessments. Convergence of views on the performance and safety of disposal systems is recognised as an important goal, even though different approaches to reaching such a conclusion may be used [IAEA, 1997].

with the underlying biosphere system description and socio-cultural assumptions.[5] For inhalation and external exposure pathways, sampling might be based on the assumed occupancy at different locations, based on the constraint of the total number of hours per year and basic requirements for time spent eating, working, sleeping etc.

(e) Identify the combination of exposure pathways that gives rise to the highest dose or health risk for the assumed release to the biosphere.

(81) The behavioural characteristics of the 'most exposed' group chosen according to this method may vary from one realisation of the future releases from the disposal facility to the next. The group would also be likely to vary temporally within a given realisation. For example, if in one realisation the release from the geosphere into the biosphere is dominated by Tc-99 and occurs at one particular geosphere/biosphere interface (transfer into a river) then the dominant exposure pathway may be consumption of fruit irrigated by river water. If, in another realisation, exposure at the same time were dominated by plutonium species and their daughters (as a result of groundwater being abstracted for irrigation of soil), then the dominant pathway may be inhalation of contaminated dust.

(82) The *a posteriori* approach helps to identify pathways (or potential combinations of pathways) that might not otherwise have been addressed in an *a priori* definition of exposed groups. However, there may be conceptual difficulties in interpreting the meaning of aggregated risk (or expectation value of exposure) over different scenarios.

3.2.3. Comparison of alternative approaches

(83) Neither a strict *a priori* approach, nor rigorous adherence to *a posteriori* reasoning, is considered appropriate for assessment purposes. The range of potential exposure pathways accommodated within the biosphere model needs to be sufficiently broad to provide assurance that no substantive issues are ignored. However, it also needs to be recognised that no calculation, however detailed, will necessarily be able to provide absolute assurance that precise quantitative criteria will be met for every possible eventuality. Some form of intermediate approach is therefore required.

(84) An investigation of the significance of alternative assumptions regarding human behaviour is therefore indicated, but speculation needs to be constrained by seeking to adopt a 'realistic' approach to evaluating potential radiological exposure, based on present-day knowledge of behaviour in analogue biosphere systems. Such considerations, combined with scientific understanding regarding the potential importance of different exposure pathways and the results of iterative assessments based on both approaches, as well as the underlying assessment context, ultimately underpin judgements made in relation to the identification of relevant exposed groups.

(85) As an example of combining both approaches, the behaviour and characteristics of several hypothetical exposed groups could be specified, consistent with the typical patterns of resource exploitation in different biosphere systems. Having evaluated total exposures for each group, the 'most exposed' of the pre-defined groups would then constitute the 'critical' group for comparison with safety criteria. Another example involves restricting the analysis to a limited number of 'significant' pathways, and excluding potential combinations of diets, habits, and exposure pathways that could otherwise be considered 'extreme'. Such an approach would, however, necessarily invoke some *a priori* knowledge or assumptions related

[5] See [Klos, 1998] as an example of how one such constraint on total consumption was treated.

to the significance of specific exposure pathways, either in terms of the radiological importance, or their relevance to decision making.

(86) Both approaches have advantages and disadvantages. The advantages of the *a priori* approach include: consistency in the characterisation of hypothetical exposed groups for all possible realisations involving the biosphere system of interest; and an ability to address explicit patterns of behaviour and/or resource exploitation that can be related to present-day experience (including, if desired or required, the present-day local community in the vicinity of the discharge). The fact that the definition of the exposed groups is related to prior experience rather than being defined by a mathematical procedure means that the implications of the results may perhaps be more readily understood. In terms of coherence in presenting the overall results of a performance assessment, it is also relatively straightforward to aggregate the exposures from different realisations of the future performance of the disposal system for an individual member of a given exposed group at a particular time/location.[6] However, the approach is handicapped by the fact that any prior choice of 'representative' behaviours, although far from random, is essentially arbitrary and cannot be demonstrated to provide a robust estimate of the maximum potential exposure. It will therefore usually be appropriate to make separate calculations over a range of possible groups and exposure circumstances.

(87) The advantages of the *a posteriori* approach lie in the fact that it makes no pre-judgment of the particular combination of exposure pathways leading to the highest exposure. The use of a suitably constrained mathematical sampling technique can serve to identify, with some assurance, group behaviour consistent with the concept of a 'reasonably maximally exposed individual' (RMEI). Reason is preserved by not allowing unrealistic combinations of exposure pathways (e.g. through constraints on dietary intake) and restricting the sampling of potential behaviour within truncated versions of population distributions.

(88) There are also a few disadvantages of the *a posteriori* approach. Because no explicit reference is made to present-day behaviour in analogue environments, care needs to be taken in defining the ranges of possible exposure to reflect those of communities typical of the assumed assessment biosphere system. In addition, problems of consistency may arise if it is desired to aggregate the doses (or risks) to exposed groups identified for the separate pathways from each of the different realisations of the future performance of the disposal system. If the RMEI differs between realisations, which is likely, the aggregate exposure will clearly represent an overestimate of the risk incurred by any specific individual. On the other hand, this disadvantage can be overcome by modifying the procedure of the *a posteriori* methodology defined above (paragraph (80)). Instead of identifying behaviour that maximises total exposure over each pathway *prior* to aggregation (leading to a variety of exposed group characteristics when aggregated), a single set of behavioural characteristics can be identified that maximises the exposure for the aggregated case. A new step would therefore be inserted following step (c), as follows:

(c′) Repeat step (c) for each realisation of the assumed release to the biosphere and then aggregate the *unit* dose or risk estimates across all the realisations. Then proceed with steps (d) and (e) for the aggregated, unit exposures. This modified approach fixes all locations, ages, metabolisms, etc. for the suite of 'individuals' for whom exposures will be calculated for each separate realisation, so that

[6] Here, it is important to remember that the exposure for any single individual (with pre-defined habits, age, location, metabolism, etc.) may vary greatly from realisation to realisation in a probabilistic assessment. Nevertheless, it is possible to identify the single 'maximally exposed group' from the different candidates defined *a priori*, based on the aggregated exposures across all the realizations.

separate individuals can be tracked through all realisations and consistency is maintained for each case. The 'individual' with the highest aggregated dose or health risk is then the RMEI.

(89) Members of the BIOMASS Theme 1 Task Group are not aware of any direct comparison of results obtained under controlled conditions using the two approaches. Neither approach is therefore recommended to the exclusion of the other. Rather, a combination of the two could be used to establish the final exposed group definition(s). For example, consideration of a wider range of potential pathways (i.e. *a posteriori* approach) might initially be used to eliminate exposure pathways of negligible radiological significance from further consideration. This would then provide guidance for the selection of a small set of fixed (i.e., *a priori*) exposed groups, with reasonable confidence that the identified group(s) were sufficiently representative to provide adequate assurance of the protection of future communities.

4. SUMMARY OF MAIN ISSUES AND GUIDANCE

(90) The purpose of this report has been to provide information and guidance to aid the practical identification and characterisation of exposed groups to be considered in assessments of the long-term radiological impact of solid radioactive waste disposal. Particular attention has been paid to issues related to the uncertainties and practicalities associated with quantifying future human behaviour relevant to such an assessment. The report recognises that, because future human behavior is largely unknown, it is necessary to make a range of assumptions and hypotheses, and to demonstrate that the identified groups provide a satisfactory basis for radiological assessment . Within the Reference Biosphere Methodology, the characterisation of exposure pathways and exposure groups to be considered in the assessment are seen as being critically dependent on the overall context within which the assessment is performed.

(91) Because of its common usage in a variety of international guidance and national regulations, the report includes many considerations and guidance related to identifying 'critical groups'. In seeking to constrain the potential range of 'critical group' habits (such as consumption of a specific foodstuff), extremes of individual behaviour that would be overly cautious, and therefore outside the range of what might be found in a broader community from which the critical group is identified, should be avoided. Established databases suggest that, provided the sampled population is sufficiently large, the top 5% of a distribution may be taken as representative of a critical consumer group for a particular foodstuff. Hence, the 95^{th} or 97.5^{th} percentile of consumption rate for staple foods (depending on the source and structure of the actual distribution) is generally thought to represent a suitable upper bound for any given exposure pathway.

(92) Nevertheless, it is not possible to identify a single group that can clearly be shown to be representative of those individuals in the population expected to incur the highest dose or risk in all circumstances. Furthermore, it is not necessarily reasonable to apply an individual risk limit comparable to levels of individual risk that society tolerates for large numbers of people (usually rather low) if the assessment is for a situation in which only a few people can be exposed (in which case society generally tolerates somewhat higher individual risks).

(93) No single method of characterising human behaviour in long-term exposure assessments can be recommended for all circumstances. However, endless speculation into potential future

human activities provides no further assurance regarding the adequacy of the chosen indicator of radiological impact. Approaches are required that use 'cautious, but reasonable' assumptions, based on present-day knowledge, to provide satisfactory assurance that the predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today, or at least that the predictions are appropriate for use in present-day decision making. This involves the characterisation of hypothetical 'exposed groups', and the use of multiple lines of reasoning to compare the results obtained using different approaches with regulatory criteria.

(94) A prime requirement is therefore to identify and describe the assumptions underlying the calculations of radiological exposure. This requires that premises relating to the socioeconomic, cultural and technological context, within which future biosphere systems and human behaviour are identified and characterised, are clearly defined.[7] These factors, combined with scientific understanding regarding the potential importance of different exposure pathways, underpin the identification of relevant exposed groups. The general classes of information required to fully characterise hypothetical exposed groups are as follows:

— *General description of activities leading to radiation exposure* – relevant activities to be considered include: eating and drinking; washing; type of work (including activities linked to biosphere resource exploitatation); recreation; sleeping.

— *Physiological characteristics* – factors contributing to physiological differences include age, sex and metabolic characteristics. Apart from their influence on the potential intake of contaminated materials, such factors will also influence biokinetics and exposure geometries.

— *Location* – a description of the environmental surroundings occupied by members of the exposed group. In addition to general location considerations (e.g. agricultural or urban land), further qualification (e.g. indoor/outdoor) may be appropriate in order better to characterise factors such as dust levels or the degree of shielding from external irradiation.

— *Mode of exposure* – the principal modes of exposure relevant to radiological exposure assessment are ingestion, inhalation and external irradiation.

— *Rate and duration of exposure* – relevant parameters correspond to the information necessary to quantify annual average exposures from each potential source; for example: ingestion rates of different foodstuffs and occupancy times at different locations.

(95) Two approaches have been identified for the definition of specific exposed groups, particularly the critical group: the *a priori* method and the *a posteriori* method. There are advantages and disadvantages to using either method, and it is recommended that a combination of the two should be used. The overall aim should be to achieve a measure of consistency, both within various elements of the calculation of radiological impact and between the calculational approach and methods used to determine acceptance criteria.

(96) Although dose (or risk) constraints or limits are commonly expressed in terms of *individual* dose (or risk), such constraints/limits are usually intended to apply to a representative member of the exposed *group*. In practice, however, information related to the

[7] The establishment of the assumed socio-cultural context is also recognised to be mutually dependent on the future biosystem, in so far as coherence needs to be demonstrated between the two.

behaviour of individuals is often used to derive ‘average’ group behaviour, or to provide an estimate of individual behaviour distribution. For example, survey data of individual habits (e.g., consumption of foodstuffs, location, use of local resources) are typically used to quantify the characteristics of a particular exposed group for a safety assessment. Most existing guidance and regulations, including ICRP guidance, is consistent with this practice.

(97) It is not possible to make definitive recommendations regarding data sources for human behaviour – in general terms, the best use should be made of available data corresponding to identified analogue communities and biosphere systems. Although generalised data, based on national statistics, can provide a useful source of information on a wide range of behaviour patterns, small communities with specific diets or patterns of behaviour are often not adequately represented in national food statistics. Care therefore needs to be taken in basing assumed behaviour on such sources, particularly for more unusual habits. Local habit surveys – if necessary at analogue locations – are particularly relevant where environmental conditions are such that the diets and habits of local communities are likely to differ significantly from national or regional patterns.

(98) The biosphere system in which exposure occurs will usually be represented within an assessment model such that environmental concentrations of radionuclides can only be determined as long-term average values (in view of general uncertainties and small scale variabilities that are difficult to model). This challenges the internal consistency associated with performing separate ‘snap-shot’ calculations of annual exposure for different age groups, rather than lifetime-average annual exposures. For these and other reasons, it may be inappropriate to make separate calculations for the exposure of infants, children and other demographic groups that may be at special risk. Nevertheless, for certain assessment contexts, it will be consistent with the overall aim of providing multiple lines of reasoning to give some reassurance that potentially sensitive groups within the population are adequately protected.

5. FURTHER WORK REQUIREMENTS

(99) The biosphere component of performance assessments has in the past tended to focus on a single outcome, rather than investigating the possible implications of different assumptions and approaches to defining hypothetical exposed groups. As a result, there has been, to date, little systematic analysis of the potential magnitude of differences in results arising from the adoption of different approaches. Modelling 'experiments' to examine this issue are required in order to provide a more objective basis for decision making. The Example Reference Biospheres being developed within BIOMASS should provide a suitable vehicle for conducting such investigations.

(100) As discussed in Annex C, and in BIOMOVS II [1996], there is an implicit relationship in many risk-based standards for health protection between the assumed limits to tolerability and the size of the group exposed. In general terms, if the (hypothetical) exposed group size is small, the accepted risk level may be somewhat higher – within an overall limit to tolerable exposure – than for larger group sizes. It is necessary to ensure that the basis for defining radiological safety goals and criteria for solid radioactive waste disposal is properly described and understood. Only then can radiological assessments properly inform the decision process.

(101) Various other matters relevant to the evaluation of future exposures have not been fully resolved at this time. These include the following:

— The possibility of demonstrating whether a drinking water pathway alone, or 'subsistence farming' behaviour, represent reasonable benchmank cases for use in assessments.

— The need for a coherent approach to assuring the protection of different demographic groups, taking account of the averaging assumptions implicit in environmental modelling.

— The development of recommendations relevant to the treatment of exposure pathways linked to human intrusion scenarios.

(102) It would be helpful to compare the *a priori* and *a posteriori* approaches suggested in this report to provide an indication of the potential quantitative similarities and differences in results that may arise under different assessment conditions. The purpose of such a comparison is not necessarily to recommend one approach in preference over the other, but rather to understand how they can most usefully play a part in informing decision making.

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ANNEX A
GUIDANCE FROM NATIONAL REGULATORY AND ADVISORY BODIES

Regulatory approaches adopted in specific countries in respect of the disposal of long-lived solid wastes, together with guidance from relevant advisory bodies, represent attempts to provide practical interpretation of the general guidance on radiological protection principles provided by ICRP and others. However, in several cases (see e.g. [JORF, 1991; HSK/KSA, 1993; SSI, 1998]), practical advice with respect to characterising human behaviour relevant to the evaluation of dose and/or risk has either been very limited or is absent altogether. In what follows, a survey (based on that originally presented in [BIOMOVS II, 1996]) is made of guidance available in various countries. The survey is not regarded as detailed, nor fully up to date; the purpose is to illustrate how issues have been dealt with in previous guidance.

Canada

Following the general themes underlying guidance from ICRP Publication 46 [ICRP, 1985b], the Atomic Energy Control Board of Canada has stated [AECB, 1987] that:

> *"The individual risk requirements in the long term should be applied to a [hypothetical critical] group of people that is assumed to be located at a time and place where the risks are likely to be the greatest, irrespective of national boundaries.*
>
> *"Definition of the lifestyle of the hypothetical critical group should be based on present human behaviour using conservative, yet reasonable, assumptions."*

The requirement to calculate doses and risks is limited to 10,000 years, although reasoned arguments must be used to show that there are no "*sudden or dramatic*" increases in releases (i.e. rather than dose or risk) beyond that period. This tends to limit the range of environmental conditions that might need to be considered in order to identify the hypothetical critical group. An assessment of the possible impacts on representative 'reference communities' is also required, although 'reference community' is not defined. AECB refers to deterministic and probabilistic calculations of risk but requires a probabilistic approach. For this approach, it is stated that:

> *"... the arithmetic mean value of the [dose] distribution should be calculated and should be taken as representative of the consequences predicted for an exposure scenario."*

Although not strictly part of regulatory guidance, recent analysis [Zach et al., 1996] has assessed the extent to which the diversity of Canadian peoples may require development of uptake models other that those used for the ICRP Reference Man. In addition, an assessment has been made regarding the potential importance of exposure pathways specific to aboriginal peoples or 'northerners', which may differ significantly from those applicable to an 'average' Canadian. The particularly relevant conclusions of the report are:

- Although Canada is racially diverse, differences between racial groups are not larger than those between individuals within a racial group. Furthermore, ICRP Reference Man is an adequate description for all Canadians.
- The additional consumption pathways that are characteristic of present-day populations living in northern Canada (i.e. on the Canadian Shield) are not significantly different from other agricultural pathways and do not therefore require explicit modelling in dose assessments.

Finland

A detailed safety guide [STUK, 1992] extending the general guidance on the safety assessment of low and intermediate waste disposal includes the following description:

> *"The analysis of the radiation dose to an individual of the public shall be based on the average dose to the members of the so called critical group. The critical group stands for members of public, who can be foreseen to receive the highest radiation doses due to their place of residence and way of living. For the analysis of radiation doses in the distant future, a hypothetical critical group shall be defined to represent the people who will be living in the environs of the disposal site. The nutritional habits and way of living can be assumed to be similar to those of people living today."*

No specific definition of critical group is included in general safety requirements for a spent fuel repository. However, a specific safety guide to be prepared later will address the definition in more detail. It expected to refer to a subsistence farming community utilising a relatively shallow well for deriving water for various purposes. Very deep wells would probably not be included in the base concept. The choice of parameters would be left as the task of the party preparing the safety case for independent regulatory review. Reference has also been made in background documentation to the possibility of using international reference biospheres if they are available for future safety cases [private communication from E. Ruokola to S. Vuori].

More recent regulations [STUK, 1998] relating to the geological disposal of spent nuclear fuel, declared as waste, have provided further guidance on long-term safety considerations. No additional guidance is provided in respect of the identification and characterisation of future human behaviour; however, dose constraints are intended to apply to a time period that is "*adequately predictable*" with respect to the assessment of human exposure (at least several thousands of years). The annual dose to the "*most exposed individuals*" is expected to be limited to less than 0.1 mSv, while the average individual dose to "*larger groups of the public*" should remain insignificantly low. It could therefore be inferred that some indication of the potential distribution of dose across the exposed population is required. In the very long term – when the requirement for adequate predictability can longer be sustained – evaluation of radiological impacts is limited to large-scale considerations and comparisons with natural radioactive substances.

France

Radiological protection criteria for deep geological disposal are defined by the French regulatory body [JORF, 1991] in terms of basic objectives as well as recommended scenarios for analysis. Characteristics of man are expressly required to be representative of present-day knowledge in respect of radiation sensitivity, food requirements and scientific knowledge, especially as regards technical and medical progress. It is expected that analysis will address the effects of long-term changes in biosphere systems as a result of climate change.

Spain

There are no official Spanish regulations relating to deep geological disposal. However, the Nuclear Safety Council has made an official statement [CSN, 1987] regarding the acceptance criteria to be applied to final disposal facilities for radioactive wastes in respect of long-term safety performance. The safety criterion is a level of individual risk (of serious damage to the health of a potentially exposed individual) of less than 10^{-6} y^{-1}, or a risk associated with an equivalent dose to members of the critical group of less than 0.1 mSv y^{-1} [Burholt and Martín, 1988].

These criteria have been used as reference points in recent performance assessment exercises conducted on behalf of ENRESA [Pinedo et al, 1998]. No regulatory guidance is provided with respect to the description of behaviour for a potentially exposed individual, although it is assumed that the individual considered in the assessment belongs to the ‘critical group’.

Sweden

In judging the acceptability of low-level waste and intermediate-level waste at intermediate depth, the Swedish regulatory bodies [SKI/SSI, 1994] adopted a premise that is largely consistent with IAEA’s governing principle [IAEA, 1995], noted previously. Namely:

> *“All radiation doses to individuals, regardless of [when they occur] must be lower than the limits considered as acceptable planning levels for other stages in the nuclear fuel cycle.”*

Concerning high-level waste, the Swedish authorities have worked with other Nordic countries in developing a basis for national regulations [NRP/NSA, 1993]. This basis includes limits and constraints on doses and risks (in the case of ‘unlikely disruptive events’) to individuals, with the recognition that:

> *“Because of different diets, living habits and environmental conditions, there is always a ‘tail’ in the individual dose or risk distribution. Sometimes this ‘tail’ may exceed the respective constraint though the average value in the critical group remains below ... Acceptance of the ‘tail’ in [this] distribution is not contrary to [other] present practices and is consistent with the individual protection principle.”*

Guidance from the Swedish Radiation Protection Institute with respect to criteria for the disposal of spent nuclear fuel [SSI, 1995] offered no advice on how to define human behaviour relevant to exposure evaluation, but suggested that best estimates (rather than deliberate over- or underestimates) of ‘critical group’ doses should be made, together with estimated uncertainties.

The most recent regulations on protection of human health and the environment in relation to solid radioactive waste disposal [SSI, 1998a] set an annual risk limit for a “*representative individual in the group exposed to the greatest risk*”. There is no discussion of how the representative individual within such a group is to be identified. Draft guidance supporting the regulations [SSI, 1998b] notes that the size of the hypothetical group from which the individual is chosen is allowed to have a risk range of 100 from highest to lowest. Although there is relevant discussion in this draft document, the precise way in which such guidance might practically be used within the context of an assessment is not provided.

Switzerland

The Swiss regulators provide extensive explanatory comments alongside their statement of radiological protection objectives [HSK/KSA, 1993], highlighting the difficulties of long-term dose predictions. It is recognised that exposure estimates can only be indicators of impact, rather than 'realistic' predictions, and the guidance requires that indicative dose and risk calculations for the maximum potential consequences of releases from the repository should be carried out. It is noted that, for these calculations, reference biospheres and a potentially affected group with 'realistic' living habits will need to be assumed.

The Swiss regulations are one of the few regulations that note there is a relationship between the appropriate risk level and the size of the population exposed to that average risk level. Although they recommend a critical group approach, they note that, if the size of the defined critical group is quite small then they may allow the average risk level to that small group to be somewhat higher than the published target level. On the other hand, if the size of the critical group is fairly large, then they may require the average risk to that large group to be somewhat below the published risk target level.

United Kingdom

In 1992, the National Radiological Protection Board provided detailed advice on radiological protection objectives for the land-based disposal of solid radioactive wastes [NRPB, 1992]. This advice was taken into account by the UK Environment Agencies in their guidance on requirements for the authorisation of such facilities [Environment Agency et al, 1997].

Up to 100 years after repository closure, the NRPB guidance states that institutional control over the site may be assumed to remain in place, so risk calculations are of little relevance. For the purposes of assessment, NRPB suggest that hypothetical critical groups should be assumed to exist, at any given time in the future (beyond approximately 100 years), at the place where the relevant environmental concentrations are highest, and to have habits such that their exposure is representative of the highest exposures that might reasonably be expected. In addressing the question of homogeneity of exposure across the group, NRPB's position is as follows:

> *"... the critical group risk is the risk to an average individual within the hypothetical critical group. It is worth noting at this point that there may be cases where, although the exposure in terms of risk is relatively homogeneous within the group, the exposure in terms of dose, should a dose occur, would be confined to only a very small number of the members of the group."*

In defining hypothetical groups for the timeframe 10^2 to 10^4 years after repository closure, the NRPB recommends that such groups may be selected on the basis of currently observed behaviour, with the group's habits being broadly representative of a type of area, rather than being based on particular extreme habits observed at a particular time in a particular place. In contrast, on the timescale of 10^4 to 10^6 years after closure, the NRPB considers that:

> *"The emphasis of the assessment should ... be changed so that calculations relating to radionuclide transport in the geosphere continue to be 'predictive', but calculations relating to the biosphere and human activity are simplified by calculating the nominal risk to hypothetical 'reference communities' in a 'reference biosphere'. Thus, calculations will provide an **indicator** of the possible risk, based on estimated radionuclide releases into the biosphere, rather than a **prediction** of the risk"*

NRPB characterises reference communities in the following terms:

- Habits should be chosen conservatively, but not excessively so, based on present-day and historical information, and should be internally consistent;
- For simplicity, the community should normally comprise 'typical' subsistence farmers, i.e. perhaps a few families who produce a range of food to feed themselves;
- The community should not exhibit unusual habits, e.g. they should not be extreme consumers of particular foods, and they would not be likely to drill holes to depths of hundreds of metres;
- A small number of 'reference communities' may be appropriate to reflect a range of conditions (e.g. for a coastal disposal site, one coastal community and one inland community, to represent different sea levels, may be selected), with the most highly exposed being considered when making comparisons with risk criteria.

As far as reference biospheres are concerned, NRPB's recommendation is that these (for the UK) should be based broadly on present-day, temperate conditions, and need not necessarily be matched to the environmental conditions assumed for the purposes of geosphere modelling. The argument for basing reference biospheres on present-day conditions is that the differences between types of biosphere conditions and human behaviour are relatively minor by comparison with overall levels of uncertainty in long-term assessments and the difference between releases into terrestrial and marine environments.

The more recent UK regulatory guidance [Environment Agency et al, 1997] adopts the general principle that:

> *"The assessed radiological impact of the disposal facility before withdrawal of control over the facility shall be consistent with the source-related and site-related dose constraints and, after withdrawal of control, with the risk target."*

Dose constraints define an upper bound, below which the developer is expected to optimise the design and operation of the facility with respect to doses received by members of the public. However, for the period after withdrawal of control over the facility, the Environment Agencies consider that conformity with a radiation protection standard cannot be demonstrated or enforced as it can while controls are in place. Hence, for this period, and in recognition of the more limited level of assurance of conformity that can be achieved, the standard is expressed as a target. Furthermore, because of the uncertainties inherent in radiological impact assessments for this period, the Environment Agencies consider that the protection standard is more appropriately expressed in terms of radiological risk rather than dose.

In characterising human behaviour relevant to the evaluation of radiological impacts, the Environment Agencies' guidance states:

> *"The accepted approach for assessing radiological dose or risk to members of the public from a source of radioactive release to the environment involves identifying one or more* ***exposed groups*** *[where exposed group is defined, for a given source, as any group of members of the public within which the exposure to radiation is reasonably homogeneous; where the exposure is not certain to occur, the term* ***potentially exposed group*** *is used]. The identification of such exposed groups should not exclude from consideration any pattern of behaviour which a reasonable person might adopt, whether or not anyone actually engages in such behaviour at a given time. However,*

behaviour which a reasonable person might regard as extreme and which habit surveys have not revealed need not be considered.

*"The exposed group receiving the highest dose from the given source is the **critical group**. ICRP* [ICRP, 1985b] *states that 'the critical group should be representative of those individuals in the population expected to receive the highest dose equivalent; the group should be small enough to be relatively homogeneous with respect to age, diet and those aspects of behaviour that affect the doses received'.*

"For the period after control is withdrawn, exposure of any given group is not certain to occur and an assessment might identify a number of potentially exposed groups. Any given level of exposure is associated with a certain probability that it will be received. The exposed group potentially receiving the highest dose may not be the group at highest risk, because the probability of receiving the dose must also be considered. All groups potentially receiving a significant dose need to be considered to determine which of them is at greatest risk. The Agencies therefore consider that, for this period, the concept of critical group as defined [above], namely the exposed group receiving the highest dose from a given source, is of limited value. Instead, the emphasis is on identifying a range of potentially exposed groups, and on assessing the doses that representative members of these groups could receive, together with the probability of receiving any given dose."

(Environment Agency et al, [1997]; paragraphs 6.5, 6.6, 6.8)

United States of America

Standards governing the geological disposal of high-level waste, for sites other than at the proposed repository at Yucca Mountain, have been promulgated in Federal Regulations [USEPA, 1991]. The Energy Policy Act of 1992 requires site-specific standards to be promulgated by the US Environmental Protection Agency (EPA) for the proposed repository at Yucca Mountain. The Act states that the standards shall prescribe the maximum individual annual effective dose equivalent to individual members of the public from releases to the accessible environment from radioactive materials stored or disposed of in the repository [Wilson et al., 1994].

A study by the National Research Council's National Academy of Sciences (NAS) supports the use of a reference biosphere(s) approach, combined with hypothetical critical groups, and recommends defining key parameters relevant to such assumptions in a formal rulemaking process [NAS, 1995]. However, the NAS report provided two examples of alternative approaches to defining the critical group. The first approach, recommended by the majority of the NAS committee, suggested a rather elaborate probabilistic approach to critical group definition by combining multiple realisations of exposed group habits and locations with multiple realisations of the groundwater contaminant plume location and concentration distribution. A lone NAS committee member suggested a subsistence farmer Reasonably Maximally Exposed Individual (RMEI) approach. EPA was given the task of developing the new standards based on the recommendations of the NAS, and the Nuclear Regulatory Commission (NRC) was tasked with developing regulations implementing the EPA standards.

As of June 1999, EPA had not published standards based on the NAS report. Although 40 CFR Part 191 [USEPA, 1991] no longer applies to Yucca Mountain, some of the performance requirements incorporated there may be relevant to the form a new standard based on individual dose might take for the Yucca Mountain site. In particular, Section 191.15 states that, for undisturbed repository performance, there should be a reasonable expectation that for 10,000 years the annualised committed effective dose equivalent to any member of the public in the accessible environment will not exceed 15 mrem (0.15 mSv) (emphasis added). In addition, radionuclide-specific limits are established for concentration in groundwater, based on the drinking water pathway. 40 CFR Part 191 also sets standards for containment requirements that are based on a limit on collective dose commitment, truncated at 10,000 years. Although the population of relevance here includes all exposed people, the largest contribution to collective dose could well arise locally, so assumptions for local and regional populations are relevant. In this context, it is expected that only very general models of environmental pathways and assumptions regarding population characteristics will be used [USEPA, 1985].

In February 1999, the NRC issued a draft rule (10 CFR Part 63) implementing the NAS recommendations [USNRC, 1999]. The draft rule assumes a pre-defined critical group and reference biosphere, and proposes an annualised, all-pathway limit on effective dose equivalent of 0.25 mSv (25 mrem) to an average member of the critical group. There is no proposed separate specific limit for dose from drinking water. The general characteristics of the reference biosphere are specified in the regulation, and the regulation limits speculation of future events by limiting biosphere change to those features, events and processes that are "*consistent with present knowledge of the conditions in the region surrounding the Yucca Mountain site*". The critical group is defined as a small farming community residing 12 miles (20 km) south (down gradient) of the Yucca Mountain site. The possible behaviour and characteristics of the critical group are limited by the regulation to the current conditions in the area. Additionally, the regulation specifies that the average member of the critical group will be considered to be an adult. The NRC has specifically requested public comment on the appropriateness of such a pre-defined critical group. Depending on the content of the EPA's standard, the NRC implementing regulation may need to be modified to conform to the standard's requirements.

ANNEX B
RELATIONSHIP TO OTHER ELEMENTS OF THE REFERENCE BIOSPHERE METHODOLOGY

Within the Reference Biosphere Methodology [BIOMASS, 1998a], the definition and quantification of exposure pathways to be considered in the assessment are seen as being critically dependent on two main factors: (a) the overall context within which the assessment is performed; and (b) the basic premises of the assessment approach. Guidance on the development of a coherent overall approach to the characterisation of future human actions was previously developed within BIOMOVS II [BIOMOVS II, 1996]; the present report builds on that guidance and extends it to provide recommendations for broad general application with respect to the representation of exposure pathways.

A key objective of BIOMASS Theme 1 is to "*demonstrate a thorough implementation*" of the systematic approach to biosphere modelling and assessment developed in BIOMOVS II *"with the goal of developing practical Reference Biospheres"* for use in performance assessment [BIOMASS, 1996]. Specifically, BIOMASS Theme 1 should complete "the Reference Biosphere Methodology through specification of principles for definition of critical groups..." [BIOMASS, 1996]. The practical applicability of the principles developed here is being tested within BIOMASS through the development of example Reference Biospheres, based on formally-defined, example assessment contexts [BIOMASS, 1998b]. In developing these examples, a measure of consistency needs to be demonstrated, not only with respect to the particular assumptions and hypotheses adopted in describing human behaviour (as addressed in this report) but also between the overall premises relating to human behaviour and those relating to the assumed biosphere system description.

In addition to guidance on the definition of critical and other exposed groups, BIOMASS Theme 1 participants are also currently addressing problems of assessment context [BIOMASS, 1998b], data [BIOMASS, 1999], and biosphere evolution [BIOMASS, 1998c]. BIOMASS Theme 1 is not intended to develop policy; instead, existing policy will be consistently interpreted as far as is possible with the intent of providing practical guidance to the users.

An important general consideration is relative uncertainty in the various components of the biosphere being considered in BIOMASS Theme 1. Perhaps the most important consideration is that the uncertainty in future human behaviour is both very large and generally unquantifiable. No matter how small the uncertainty may be in models for the engineered barrier, geosphere and biosphere, the *irreducible* uncertainty will still be large for any assessment requiring an estimation of dose or risk to humans in the far future. This large, irreducible uncertainty may have some relevance to identifying appropriate levels of detail in the identification and justification of FEPs, the use of data, and the development of models. This is discussed to some extent in BIOMASS [1998b].

BIOMASS [1998b] also emphasises that calculations performed over the very long term are *indicators* of performance rather than *predictors* of performance. If so, then it can be argued the use of stylised approaches (e.g. in the treatment of biosphere FEPs and exposed groups) and the use of data based on expert judgement are adequate to provide indicators of performance. Definitions must be precise and well-justified, but not necessarily detailed.

Assessment Context [BIOMASS, 1998b]

The assessment context answers the questions: what are you trying to assess and why are you trying to assess it? The assessment context is discussed in more detail in Section 2.1.

Aspects of an assessment context that affect definition of the exposed group include:

— the importance of making "bounding" safety arguments that may require, for example, hypothetical behaviour intended to maximise dose or risk (i.e., it is necessary to demonstrate that the hypothetical behaviour is more "extreme" than most people would think has ever occurred in the past or is ever likely to occur in the future), versus;

— the use of approaches that require "realistic" estimations of dose or risk to individuals or populations with behaviours similar to those in existence today (including the need to make assessments for a variety of lifestyles characteristic of particular present or past behaviours in the region of interest); and

— whether it is important to be able to make risk comparisons with other hazards (e.g., does the assessment context require comparing the long-term risks of disposal with other kinds of risks);

— the need to address the concerns of affected groups who need to feel that any assessment has included their particular characteristics that may differ from the general population.

Use of Data [BIOMASS, 1999]

BIOMASS [1999] describes, in brief, areas where the data relating to specific exposure pathways are particularly sparse or where inappropriate information has typically been used. This is an important consideration for the development of *practical* recommendations on the appropriate degree of detail in definition of an exposed group.

Some data may be based on the assumption of particular land use practices. It is important to know this so that any exposed group definitions that require the use of these data assume a set of land use practices that are as consistent as possible with the data.

Biosphere Evolution [BIOMASS, 1998c]

Obviously, any biosphere system chosen that is not representative of current conditions at a particular site will require the use of hypothetical groups in place of real groups currently at the site. BIOMASS [1998c] suggests that, under some circumstances, it may be appropriate to apply characteristics of some other biosphere currently in existence somewhere else in the world to the site. It may be appropriate, for example, to apply the existing biosphere(s) for central or northern Scandinavia to a candidate site in central Europe as a 'stand-in' for what the biosphere may be like during cooler, wetter conditions. In this case, it may be consistent to apply current behaviour in central or northern Scandinavia to the assessment for the pluvial period at the site in central Europe.

ANNEX C
CONCEPTUAL APPROACH TO CONSIDERATION OF DISTRIBUTION OF EXPOSURE ACROSS A POPULATION

Estimated radiation exposure can at best be considered only as an indicator of the long-term safety performance of a solid radioactive waste disposal facility. Nevertheless, general policy on radiological protection for radioactive waste disposal from [ICRP, 1998] supports the widely-adopted regulatory system that the primary considerations in limiting the detriment to future generations should be individual dose and risk.

In reflecting on the potential utility of collective dose to inform decision making, ICRP [1998] implies that it can be appropriate to consider the likely distribution of exposures that could occur in the future. The following quotations illustrate relevant elements of this thinking:

> *"Much of the Commission's emphasis has been on the qualitative specification of the optimisation of protection. This calls for the individual doses,* ***the number of people exposed****, and the likelihood of potential exposures all to be kept as low as reasonably achievable, economic and social factors being taken into account."*
>
> ICRP Publication 77, 1998; paragraph 37 (emphasis added)

> *"In both the justification of a practice and the optimisation of protection, the presentation of collective dose contributed by very wide ranges of individual dose should be separated into blocks of limited ranges of dose and time. The aggregation of these blocks of collective dose into a single value may be misleading, because it deprives the decision maker of the option of taking account of the individual dose and of the distribution of collective dose in time."*
>
> ICRP Publication 77, 1998; paragraph 52

> *"The use of the blocks of collective dose resulting from individual doses that are very small or occur at very remote times requires consideration. The individual doses from a waste disposal operation range from those to the critical group, which may be as much as a few hundred microsieverts in a year, down to nanosieverts in a year in areas remote from the release point."*
>
> ICRP Publication 77, 1998; paragraph 21

> *"The choice of the separate blocks of individual dose and time intervals for the expression of collective dose needs to be flexible, but for blocks other than those that start from zero time or zero dose, it seems likely that each block should extend over no more than one or two orders of magnitude. The environmental models may not be sufficiently detailed to achieve this degree of disaggregation by ranges of individual dose. For example, models that do not provide information on the distribution of the individual consumption of a food stuff will provide only the aggregated collective dose from that foodstuff."*
>
> ICRP Publication 77, 1998; paragraph 59

Such thinking, related to the potential distribution of individual exposures, is also incorporated within the general guidance of at least one set of national regulations on solid waste disposal ([STUK, 1998; HSK/KSA, 1993], see Annex A). It is therefore useful to reflect on how the assumptions adopted as a basis for quantitative calculations for individual dose relate to such a distribution. In presenting this discussion, however, the intent is not to substitute use of the hypothetical critical group concept as the basis of compliance assessments. Rather, it is suggested that consideration of the distribution of potential individual doses in a hypothetical local population can provide additional ‘regulatory insight’ for the purposes of assessing the potential degree of conservatism inherent in a ‘critical group’ approach.

Distribution of Individual Dose

As a general rule, it can be anticipated that there will be a relatively small group who, because of their location in the immediate vicinity of the discharge and/or their habits, would incur greater exposures as a result of future releases than the rest of the population. There may also be a somewhat larger group of people in the locality who would receive larger individual doses than those living further away. Finally, the vast majority of the hypothetical population may be expected to receive very little or no exposure.

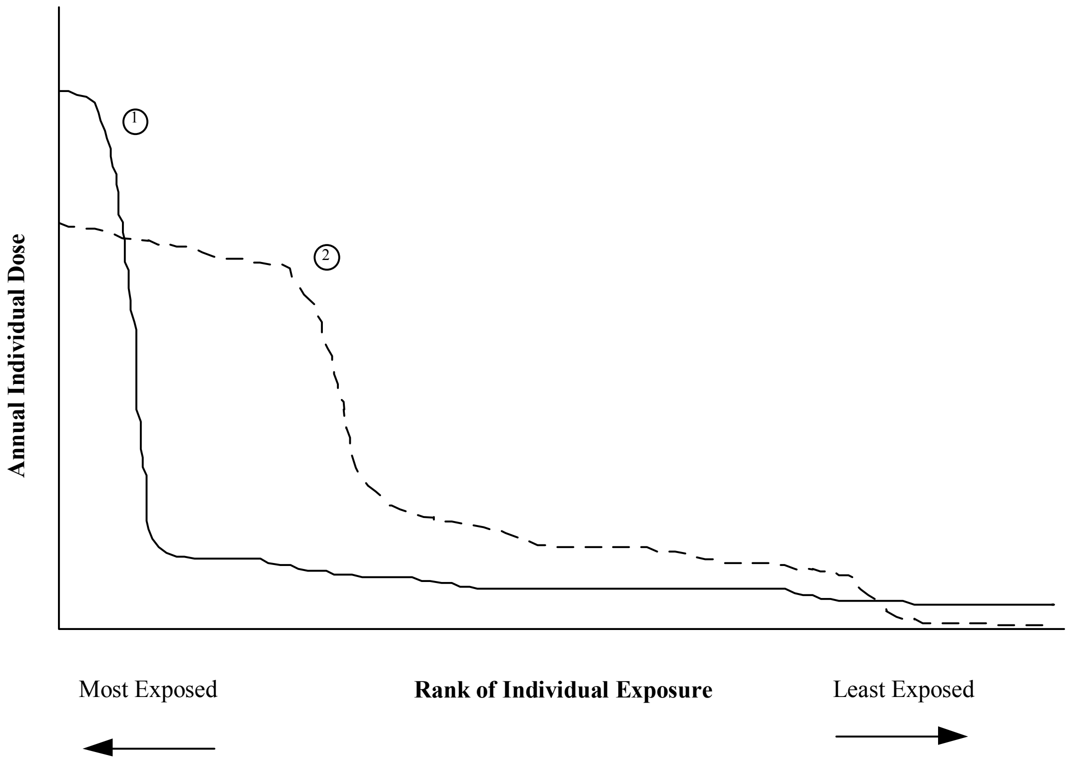

FIG. C1. Conceptual illustration of distribution of dose in exposed populations.

Figure C1 presents a conceptual illustration of two (of many) possibilities for the ‘actual’ distribution of doses in the local population exposed to, expressed in terms of a snapshot of the ‘dose at rank’ at some time in the future. ‘Rank’, in this context, means that individual dose estimates are plotted from left to right in descending order. The shapes of the curves illustrate the distribution of dose rates experienced by those individuals who are most exposed to future releases.

The distribution of dose illustrated by Example 1 in Figure C1 corresponds to a hypothetical situation in which a small, remote community makes significant use of local resources;

moreover, the population happens to be adversely located with respect to the concentration of radionuclides in the environment. Apart from this community, exposures are experienced only at a considerable distance from the point of discharge, where, for example, substantial numbers of people may make use of slightly contaminated river water. The distribution of exposure across the entire population considered is therefore very heterogeneous.

The distribution illustrated by Example 2 is intended to be representative of a situation in which the most exposed individuals live in a small town or village that makes rather less intensive use of local resources. The land area exploited by the community is also assumed to be significantly larger than the immediate vicinity of the point at which discharge of repository-derived radionuclides occurs. Export of a fraction of the resources produced by the community means that the exposures experienced some distance away are slightly higher than would otherwise be encountered by larger population groups. In this case, therefore, a more homogeneous distribution of exposure emerges.

There are three main points of distinction between what is represented in Figure C1 and conventionally defined 'collective' dose. The first is that the information is expressed on a *per capita* basis, whereas collective dose is summed over the exposed population. The second is that the curves display annual doses as a function of population size, whereas collective dose is typically expressed over pre-defined populations of fixed size. The third distinction is that Figure C1 is expressed in terms of annual dose, whereas collective dose is expressed in time-integrated terms.

It is instructive to compare further the 'dose at rank' conceptual presentation in Figure C1 with the use of collective dose in evaluating the significance of discharges associated with solid radioactive waste disposal. Collective dose is traditionally used as an indicator of radiological significance either in comparing between options or in optimising a specific option. Thus, the emphasis is in reducing collective dose until it is As Low As Reasonably Achievable (ALARA). The problem in solid radioactive waste disposal is that collective dose is often not very sensitive to changes within and between options, because it is dominated by very long-lived radionuclides such as I-129 and U-238 that are eventually released from the disposal system and can become widely distributed. Only if collective doses are strongly truncated both in space and time can distinctions within and between options become evident (see discussion in ICRP [1998], summarised above). However, there is no clear guidance on how such truncation should be achieved. Furthermore, if collective dose is partitioned into a multiplicity of quantities by dividing the future both spatially and temporally, it is not clear what relative weights should be assigned to each of these quantities for optimisation purposes.

The presentation associated with Figure C1 builds on the calculation of an average annual individual dose or risk to individuals within the most exposed population, quantities commonly used to assess radiological significance by international organisations and national authorities alike. Results plotted in this format might therefore find a use by decision makers in evaluating safety performance. For example, if, as in the UK, quantitative criteria were expressed in terms of a risk target, it would be possible to determine on the basis of such a presentation how large the population would need to be before the *per capita* risk dropped below the target. Alternatively, it might be possible to make statements such as the following:

— the ten most exposed people have an average *per capita* risk that exceeds the risk target by a factor of three;

— the hundred most exposed people have an average *per capita* risk that is a factor of two lower than the risk target.

By contrast, the use of collective dose limits or constraints is very rare. The only exception to this is the US Environmental Protection Agency's constraint of no more than 1,000 cancer deaths in 10,000 years per 1,000 metric tons equivalent of uranium disposed [USEPA, 1991]. Using a risk factor of 0.06 per Sv, this would translate into a constraint on collective dose of 16,667 person-Sv per 1,000 MTU over the first 10,000 years post-closure.

Although the examples presented in Figure C1 are just two illustrations of the wide range of possibilities that may actually occur, it is instructive to consider how they relate to the hypotheses and assumptions that necessarily underlie an assessment of individual exposure. For example, the point where Curve No.1 meets the Y-axis could be considered representative of a 'maximally exposed individual'. Clearly, if no account is taken of the likelihood that such a person may be present, a calculation based on such maximising assumptions will likely provide an estimate of the upper-bound potential dose incurred at the time of interest. On the other hand, given that any hypothesis will be based largely on speculation regarding future land-use patterns and population distributions, it is difficult to visualise a defensible basis for making a quantitative estimate for the probability of exposure.

Population-Averaged Individual Dose

In order to illustrate more clearly how the 'actual' exposure distributions illustrated Figure C1 might relate to quantitative standards for radiological protection, it is helpful to re-draw the curves in terms of the average individual dose rate for all members of the population as the assumed population size increases. The effect of this is illustrated in Figure C2.

Now, in the case of Curve No.1, it is evident that the average exposure for a very small group of maximally-exposed individuals (in this hypothetical example) is very close to the upper limit of risk tolerability. On the other hand, it is worth bearing in mind that the likelihood of such an exposure scenario is very small, since it depends on the existence of a small community making extensive use of local resources in a region that is adversely located with respect to the release of radionuclides from the repository. Furthermore, when account is taken of a larger population group in calculating the average dose, the result (for this hypothetical example) is within acceptable limits for society as a whole.

By comparison, Curve No.2 suggests that the average exposure experienced by a somewhat larger community, in a less extreme situation with respect to location and exploitation of resources, could be significantly higher than the upper limit on tolerability for large population groups. Whereas the maximum individual dose in the exposed population is significantly lower than for Curve No.1, it is perhaps questionable whether or not the overall situation with respect to radiological exposure is more acceptable.

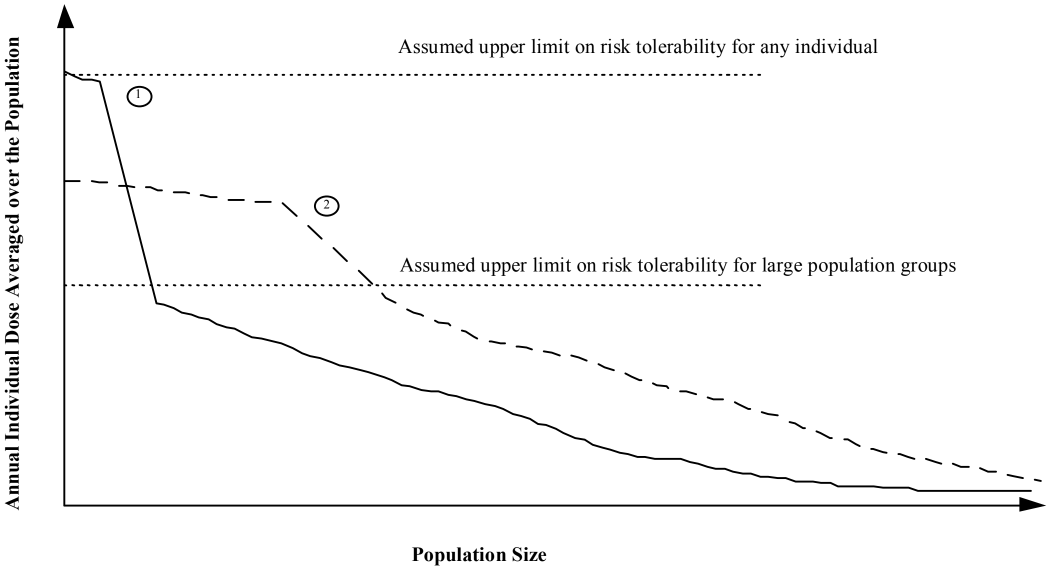

FIG. C2. Illustration of effect of dose averaging in exposed populations.

Given the multiplicity of assumptions involved, it might seem unreasonable to expect that a performance assessment should include an evaluation of the overall distribution of potential individual doses among populations in the vicinity of future releases from a deep repository (as illustrated by the curves in Figures C1 and C2). Conversely, however, it is evident that a single point estimate of potential exposure to a hypothetical maximally exposed individual may not necessarily provide all the information necessary to make judgements regarding compliance. The actual approach taken in any particular case may therefore vary according to the context of the assessment, including the use that is to be made of the results. Moreover, various approaches may well be justified within a single assessment, in order to strengthen the basis for decision making. For example, estimates of potential exposure distributions based on real, present-day local population habits and locations may be of some interest.

Thus, for example, where the site context dictates that substantial heterogeneity of exposure is a possibility, a ‘cautious’ estimate of the dose incurred by the maximally exposed individual might be supported by an ‘equitable’ estimate of the average dose incurred by the regional population. This would allow comparisons to be made with a range of appropriate targets and limits for risk tolerability. Alternatively, where homogeneous exposures are assumed or anticipated for a relatively large population group (particularly if the assumed exposed group is assumed to be homogeneous with respect to risk, rather than dose), an appropriate estimate of the potential size of the exposed population group may be necessary in order to make rational comparisons with acceptance criteria.