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The Concept and Use of Reference Animals and Plants for the purposes of Environmental Protection

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PREFACE

At its meeting in Vienna in May 2003, the Commission decided to set up a Task Group, reporting directly to it, to continue the ICRP's work on issues related to the protection of the environment. The Task Group was tasked to consider end-points of interest for assessing radiation effects in non-human species, to recommend the types of reference organisms to be used by the ICRP, and to define an agreed set for assessing and managing radiation exposure in non-human species.

The membership of the Task Group was as follows:

M. E. Clark, USA
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The Task Group would like to thank the Swedish Radiation Protection Authority and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) for making facilities available for Task Group meetings.

The report was adopted for publication by the Commission in ….

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The Concept and Use of Reference Animals and Plants for the purposes of Environmental Protection

ICRP Publication xx

Approved by the Commission in xx 2005

ABSTRACT

To be added later

1. INTRODUCTION

1.1. Aims

(1) The aims of this report are:

- to select, define, and describe in outline a number of Reference Animals and Plants to be recommended by ICRP;
- to consider issues relating to the dosimetric quantities and units that could be used for such organisms;
- to consider the availability of dose models for the selected Reference Animals and Plants;
- to define end-points for assessing radiation effects in non-human species of relevance to environmental management practices;
- to review the availability of relevant data in order to compile sets of Derived Consideration Levels for the Reference Animals and Plants; and
- to further the development of a common approach to the protection of man and other species.

(2) The report has been produced in order to support the Commission's latest comprehensive review with respect to its revised set of recommendations for radiological protection (ICRP, XXXX; 2006).

1.2. Background

(3) Environmental protection is now a global issue, and an issue that impacts upon human activities in many different ways. All forms of actual or potential threats to the environment are a cause of concern, or of action, or of regulation, and this includes ionising radiation. The Commission therefore set up a Task Group to examine these issues in 2000 and, in its report (ICRP, 2003), it considered (a) that a broader framework for radiation protection of the environment needed to be developed, and (b) that it should be sufficiently flexible to be applied within the context of the many existing and varied approaches to environmental management generally, and to environmental protection in particular. It also considered that such an approach should relate as closely as possible to the current system for human radiological protection, and that these joint objectives could therefore best be met by the development of a limited number of Reference Animals and Plants.

(4) The Commission accepted these conclusions and, in January 2003, decided to set up a second Task Group to continue this work by further considering how to meet expected environmental management needs in relation to environmental protection. Later that year, in October 2003, the Commission went even further and decided to establish a new Committee (Committee 5) on the Protection of the Environment, to commence work in 2005. The work of the second Task Group was therefore slightly modified, and given the more general purpose of laying the foundations for the Commission's future work in this area, and preparing for the work of the new Committee. In pursuit of these objectives, the Task Group has

therefore considered the types of reference animals and plants that could be used by the ICRP in order to meet future environmental management requirements; the types of dose models that could be used; the relevance of existing information on radiation effects for such types of organisms; how such an approach could be used for assessing and managing different levels of radiation exposure in non-human species; and how such an approach could be harmonised with the Commission's existing approach to the protection of human beings.

2. PROTECTING MAN AND THE ENVIRONMENT

2.1. Introduction

(5) The Commission has never made any specific recommendations with regard to the protection of species other than the human being, but in its 1990 Recommendations (ICRP, 1991) it did express the view that:

> '*The Commission believes that the standards of environmental control needed to protect man to the degree currently thought desirable will ensure that other species are not put at risk. Occasionally, individual members of non-human species might be harmed, but not to the extent of endangering whole species or creating imbalance between species. At the present time, the Commission concerns itself with mankind's environment only with regard to the transfer of radionuclides through the environment, since this directly affects the radiological protection of man.*

(6) The Commission still believes that this judgement is likely to be correct in general terms, because the steps taken to protect the public, by reference to dose limits for them, have resulted in strict controls and limitations on the quantities of radionuclides deliberately introduced into the environment. Thus it is probably true that the human habitat has been afforded a fairly high level of protection through the application of the current system of protection. However, there are now other demands upon regulators, in particular the need to comply with the requirements of legislation directly aimed at the protection of wildlife and natural habitats; the need to make environmental impact assessments with respect to the environment generally; and the need to harmonise approaches to industrial regulation, bearing in mind that releases of chemicals from other industries are often based upon their potential impact upon both humans and wildlife. All of these demands are currently being met in a multitude of differing ways. This is partly because of the lack of advice on the subject at international level, and partly because there are no agreed assessment procedures, criteria, guidelines or reference data sets with which to approach these issues in a coherent way. This, in turn, leads to different national approaches being developed, and makes international harmonisation difficult

(7) The Commission therefore recognises that there is a need to explore further the nature of the 'risks' that may apply to other species, how such risks may be quantified, and thus how it can be positively demonstrated that they are, indeed, '*…not put at risk*'. The Commission has therefore decided to develop a combined approach to the protection of humans and other species, and to do so within an overall framework that recognises the different but complementary aims and objectives that this involves. The approach recognises that humans, as well as fauna

and flora, are part of the same overall ecosystem; but whereas the protection of human beings has aims and objectives that may be universally applied, the aims and objectives with respect to the protection of other species will vary considerably, depending on the species involved, and the nature and the circumstances relating to the risks to which they are exposed.

(8) The Commission also recognises that the reduction of the frequency of radiation effects in individual animals or plants does not necessarily imply that the individual animal or plant is the object of protection. But whereas effects upon ecosystems are usually observed at the population or higher levels of organization, information on dose responses to radiation is usually obtained experimentally at the individual level. And because radiation effects at the population level - or higher - are mediated via effects on individuals of that population, it therefore seems appropriate to focus on the individual for the purpose of developing an assessment framework. The Commission also notes that a large number of animals and plants are already afforded protection at the level of the individual in international or national law, and it would be inappropriate to provide advice that could not be used in such legal contexts. The question of whether one should protect individuals or populations from harmful effects of radiation in any particular circumstance, however, is not an issue of direct concern to the Commission.

(9) The decision to develop a framework for the assessment of radiation effects and their consequences in non-human species has not been driven by any particular current concern over environmental radiation hazards. It has been developed both to fill a conceptual gap in radiological protection, and to clarify how the proposed framework can contribute to the attainment of society's wider goals of environmental protection. The Commission's decision to develop an explicit assessment framework should therefore support, and provide transparency to, such decision making processes.

(10) The Commission considers that a framework is needed that can be a practical tool to provide high-level advice and guidance, and thus help regulators and operators demonstrate compliance with existing or forthcoming environmental legislation. It should also be noted that the recommended system is not intended to set regulatory standards. It does not, however, preclude the derivation of such standards after sufficient experience has been gained with the proposed framework; on the contrary, it should provide a basis for such derivation. This framework could therefore serve as a basis from which national and other bodies could develop, as necessary, more applied and specific numerical approaches to the assessment and management of risks to non-human species under different circumstances, and thus with respect to normal situations, accidents and emergencies, and controllable existing exposures. As was the case with the initial adoption of ICRP's Reference Man (ICRP, 1975), further work will be required to develop more fully the concepts and use of reference animals and plants.

2.2. Establishing a Common Approach

(11) The Commission has therefore recognised the need to develop a common approach to, and scientific basis for, the relationships between exposure and dose,

and dose and effect, for all living things. In the case of human radiation protection, this approach has been based on an entity called Reference Man. The Commission has therefore concluded that a parallel approach would be of value for the protection of other species, and that this could best be achieved by the development of a small set of Reference Animal and Plants, plus their relevant databases, for a few types of organisms that are typical of the major environments. In doing so, the Commission recognises that this approach cannot reflect the full range of biological diversity, or provide a general assessment of the effects of radiation on the environment as a whole. However, the Commission considers that this approach could provide the basis for judgments about the probability and severity of the likely effects of radiation on such animals and plants, or on other types of organisms that differ in specific characteristics from the reference types.

(12) It is therefore intended that each reference type would serve as a primary point of comparison for assessing risks to animals and plants with similar life cycles and exposure characteristics. More locally relevant information could be compiled for any other animal or plant, but each such data set could then be related in some way to the reference types. Such a combined set of information should then serve as a basis from which national bodies could develop, as necessary, more applied and specific approaches to the assessment and management of risks to non-human species as national needs and situations arise.

(13) In order to be of practical value, and to assist in their interpretation, the Commission believes that bands of *derived consideration levels* for Reference Animals and Plants could be set out in logarithmic bands of dose rates relative to normal natural background dose rates of the reference organisms. Additions of dose rate that are below the levels of their background dose rates might then be considered to be of low concern, and those that are orders of magnitude greater than background would be of increasingly serious concern because of their known adverse effects on individual organisms. But the need for any managerial action, would be dependent upon, for example, factors that would include the numbers and types of individuals affected, the nature of the effects, the spatial and temporal aspects of contamination, and specific legal requirements.

(14) Another prime purpose of the use of a set of Reference Animals and Plants is to develop a common approach to the protection of man and the environment under all circumstances. As a starting point, the objectives of such a common approach might therefore be along the following lines:

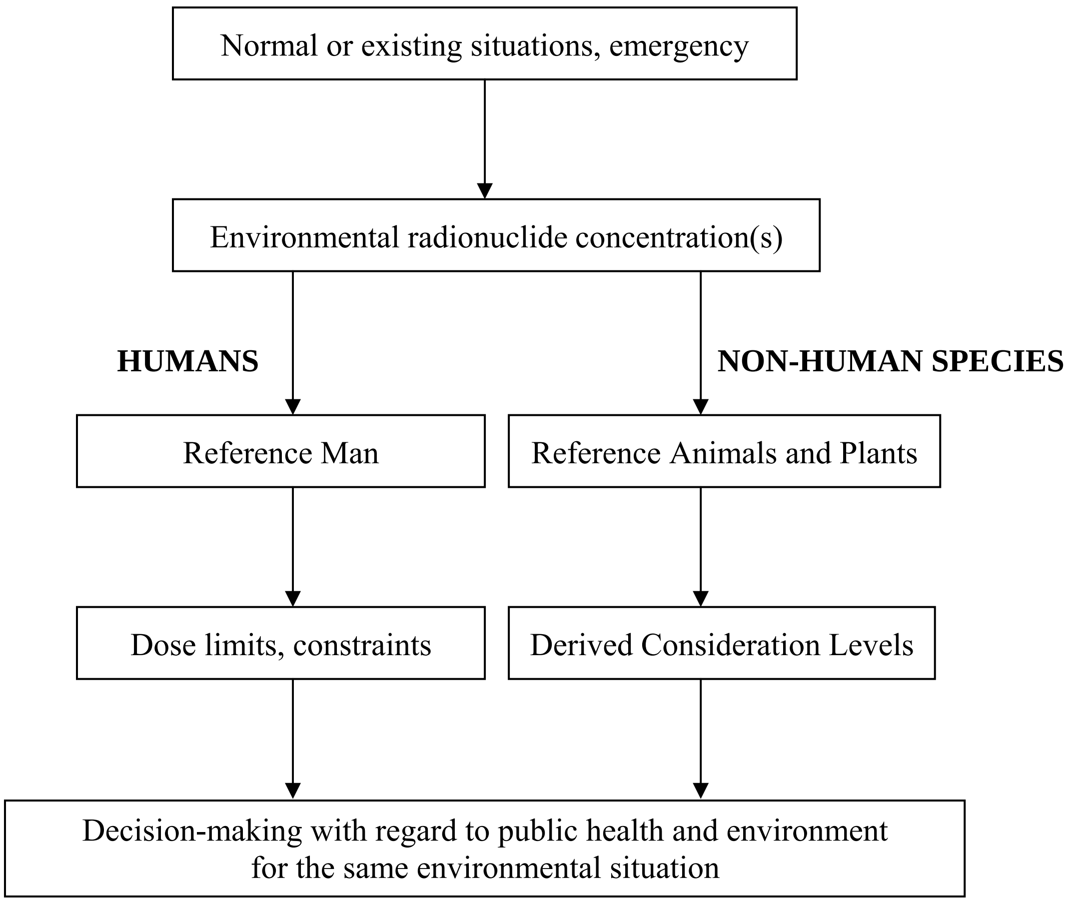
- to **safeguard human health** by preventing the occurrence of deterministic effects; limiting stochastic effects in individuals and optimising the protection of populations; and
- to **safeguard the environment** by reducing the frequency of effects likely to cause early mortality, or reduced reproductive success, in animals and plants to a level where they would have a negligible impact on conservation of species, maintenance of biodiversity, or the health and status of natural habitats or communities.

(15) The achievement of these objectives should, in turn, be centred on a common scientific approach, such as the use of sets of reference dose models, reference dose per unit internal and external exposure values, plus reference data sets of doses and effects for both humans and fauna and flora. Similarly, it is the

intention of the ICRP to develop this approach such that there is a commonality in its basic approach to dosimetric modelling, and the interpretation of radiation effects.

(16) One further advantage of applying the Reference Animals and Plants' approach is that, for any given spatial and temporal distribution of radionuclides, from any source and under any circumstance, one should be able to estimate both the relevant levels of concern with respect to members of the public (based on Reference Man) and the Derived Consideration Levels, with respect to non-human species (based on Reference Animals and Plants). These two systems will be independent of each other, but derived in a complementary manner,and based on the same underlying understanding of the radiation effects on living matter. Also, in a practical sense, they could each be related to the same concentration of a specific radionuclide, within a specific environmental material, at any particular site (Figure 1).

Figure. 1 A common approach for the radiological protection of humans and non-human species (Adapted from Pentreath, 2002a, and ICRP, 2003a)



2.3. Building a common science base

(17) Yet another objective of the use of a set of Reference Animals and Plants is to explore some of the basic concepts of the interaction between radiation and a wide range of biological materials, the results of which would be of value not only in managing the exposures of different species, but might also be of value in

generating new insights into the effects of radiation that could be of help in the management of human exposures. The vast majority of existing data has been derived for the purposes of human radiation protection, even though much of it has been derived from studies on other animals. But it is clearly important that the protection of all species, including man, is based upon the best possible and comprehensive understanding of the interaction of radiation with living material generally, and much can be gained by comparative studies. In order to do so, however, it is essential to develop a common language and basic approach.

(18) Bearing in mind the great variation amongst plants and animals, particularly with regard to their life cycles (including such features as active and dormant periods, sexual and asexual reproduction); their life spans (from days to centuries); and their exposure pathways (where they are in the environment, and what they do), it is clearly also necessary to explore a number of basic issues. These include considerations of the degree of generality (or not) that can be applied to consideration of LET, RBE, and radiation weighting factors across the whole of the animal and plant kingdoms. They also include consideration of the generality of the terminology used, such as chronic and acute dose rates in the context of biota with a life cycle of only days, or for plants that can live for centuries; the relevance (or not) of deterministic and stochastic effects in plants and animals; and, indeed, the extent to which different biological “end points” and their consequences, such as early mortality, reduced reproductive success and so on, are of value in different circumstances.

3. REFERENCE ANIMALS AND PLANTS

3.1. Introduction

(19) The concept of a ‘reference human’ to help manage the many different situations in which human beings would or could be exposed to ionising radiations has long been used and recognized by ICRP, which began its work to define the first reference individual (standard man) in the 1940s and published its first comprehensive report on Reference Man in 1975 (ICRP, 1975). The purpose of Reference Man was to create *points of reference* for the procedure of dose estimations to humans, for the derivation of relevant quantities and units for their interpretation, and for considering the relationships between doses to different parts of the human body and their effects, in the context of human radiological protection. The Commission has recently adopted a report that provides up-dated information on Reference Man (ICRP, 2002).

(20) The ICRP has now proposed a similar system of discrete and clearly defined Reference Animals and Plants for assessing radiation effects in non-human organisms (ICRP, 2003a). The approach is based on the concept developed by Pentreath (1998, 1999, 2002 a,b, 2003, 2004, 2005). This, first of all, envisaged the use of a limited number of fully biologically described animals and plants in order to develop a systematic means of relating exposure to dose, and dose to different categories of effect that could be interpreted in terms of the normal biology of these particular types of animals and plants in environmental situations. The effects considered to be of relevance were those of early mortality, morbidity, reduced reproductive success, or some form of observable cytogenetic damage, irrespective

of whether or not they arose from stochastic or non-stochastic dose effect relationships. And secondly that, in order to consider how best to manage different situations of additional radiation exposure, within the many different contexts of 'environmental protection', as variously defined in existing environmental legislation, such information could then be set out so that dose rates known to cause such categories of effects could be expressed as multiples of the natural background dose rates, for each type of animal or plant, in the form of Derived Consideration Levels.

(21) This approach therefore acknowledges that one cannot provide a general assessment of the effects of radiation on the environment as a whole. The Commission now considers that it should be possible to derive a reasonably complete set of internally related information for a few types of organisms that were typical of the major environments. This can best be achieved by drawing upon existing information, and by selecting organisms that would be amenable to further study in order to gain a better understanding of their responses to radiation. Thus, by using sets of dosimetric models and environmental geometries relating to such reference animals and plants, with clearly defined biological characteristics and life histories, and applying them to distributions of radionuclides in different environments, one should be able to make a judgement about the probability and severity of the likely effects of the radiation exposure on such individuals. One should then, in turn, be able to make a general assessment of the likely consequences either for individuals, or for the relevant population (depending on the environmental management issue being addressed) using these and other environmental data and information, for such types of animals and plants.

(22) The concept is therefore similar to that used for human radiological protection, in that it is intended to act as a foundation for the making of a number of basic calculations, and to serve as a point of reference for drawing comparisons with other – and probably more limited – sets of information on other organisms. Such a basic reference-animals-and-plants approach has been used previously to provide advice at an international level, primarily in order to establish release rate limits to evaluate potential environmental impacts of radionuclides released into the marine environment (Pentreath and Woodhead, 1988). This was applied by the IAEA to redefine annual release rate limits for the purposes of the London Convention (IAEA, 1988). It is also similar to the concept of assessment and measurement endpoints used in ecological risk assessments frameworks (Suter, 1999), and to the approach recently used in the shape of 'reference organisms' (variously described over a range from multi-phylogenetic assemblages, to generalised phylogenetic types, down to individual species) to assess ecological radiation exposures in Arctic and European environmental situations (Brown et al, 2003; Larsson, 2004). The need for such a basic and generalised framework for environmental protection has also been strongly supported by the International Union of Radioecology (Strand et al, 2000).

3.2. Criteria for choosing different types of animals and plants

(23) There are many factors that have had to be considered in the selection, description, definition, and potential application of reference animals and plants, and the Task Group was greatly assisted in their consideration of these issues by being

able to draw upon the many studies, seminars, conferences, and research programmes that have recently been held on this general topic, including the following: symposia on the protection of the environment from ionising radiation in Stockholm, (Amiro et al, 1996), Canada (Anon, 2001), Darwin (IAEA,2003), and Stockholm (IAEA, 2005); two IAEA Reports (IAEA, 1999, 2002); the IUR (Strand and Oughton, 2002); the NEA (2002); and the results of the EPIC and FASSET projects (Brown et al, 2003; Williams, 2004).

(24) It is also evident that limits have to be placed on the level of complexity of the system that could or needs to be developed by the ICRP, both with regard to the dose models that are required and the level of interpretation that needs to be applied with respect to different categories of radiation effect. Limits have also had to be placed on the number of reference animals and plants that could be used in such a system.

(25) Given that the objective is to provide a starting point for the assessment of exposure, radiation dose, and possible dose responses for such an enormous variety of living animals and plants, it is clearly not easy to select a few types for the purposes of creating a small reference set. A number of basic scientific criteria can and have been considered, but perhaps the first to note is that of what the information is likely to be used for, and under what circumstances. These were anticipated to include the following:

- *requirements to meet new or expected environmental legislation*, particularly in relation to wildlife conservation and habitat protection, that may apply to individual animals and plants, their populations, or to specific habitats and communities, and that may need to be applied to existing practices;

- *requirements for 'environmental impact assessments'* in relation to existing or proposed practices that, as well as including the above requirements, may necessitate evaluations to be made with respect to potential impacts on other forms of environmental management, such as those relating to fisheries, agriculture, and so on, and of the consequences of major accidents and emergencies; and

- *requirements to achieve consistency in regulatory approaches* to large industries, particularly with regard to the need to consider, explicitly, not only their potential impact on the general public but also their potential impact on the environment generally.

(26) The feature common to all of these requirements is the need to have a consistent and transparent approach to relating exposure to dose, and then relating dose to what is known about different sorts of effects on different types of animals and plants. But it is appreciated that the application of this type of information will vary substantially at national or regional level.

(27) Bearing these points in mind, the Commission considered that a mixture of animals and plants was needed that reflected both the variety of operational and regulatory requirements, and the need to be pragmatic in terms of developing a flexible framework to accommodate future needs and the acquirement of new knowledge. It would therefore appear that, in relation to the anticipated requirements:

- for the purposes of *new or expected environmental legislation,* particularly with regard to wildlife and habitat conservation, any likely list of candidate types would need to include a number of vertebrate animals, such as a bird and a mammal, and possibly even a reptile or amphibian, and that wetland habitats appeared to be particularly subject to international and national concerns, often with respect to the transboundary movements of wildlife within geographic regions;

- that for evaluations in relation to *environmental impact assessments*, particularly where these interface with other forms of environmental management, any list would necessarily require examples of animals and plants that were relevant to such practices as fisheries, agriculture, and forestry; and

- with regard to *achieving consistency in regulatory approaches*, it was noted that in other forms of pollution control a number of 'toxicity-test' type organisms are already routinely used, and thus some overlap with such types of organisms would be desirable, and that because ecotoxicological studies are also often used in pollution control, it would be important to ensure that the total reference set had a reasonable coverage of the major ecological compartments of terrestrial and aquatic ecosystems.

(28) Notwithstanding such requirements, however, it is also necessary to be pragmatic. It is simply not possible to gain the necessary information about radiation effects on some types of wildlife that are the subject of conservation measures, or are fished or otherwise harvested commercially in aquatic and terrestrial environments. Nor is it possible to gain sufficient information to represent the wide range of potential exposure situations of animals and plants in the environment under planned, existing, or accident and emergency situations. Fortunately, however, quite a lot of information does already exist that is relevant to the above requirements. Various animals that have commercial value, and several agricultural crops and other plants have been studied in some detail. These, in turn, occupy a range of ecological niches, and display a range of different life histories.

(29) Collectively, therefore, in selecting a small but practical set of reference animals and plants, the following criteria were used:

- that there is a reasonable amount of radiobiological information already available on them, including data on probable radiation effects;
- that they are amenable to future research, in order to obtain the necessary missing or imprecise data, particularly with regard to radiation effects;
- that they are considered to be typical representative fauna or flora of particular ecosystems;
- that they are likely to be exposed to radiation from a range of radionuclides in a given situation, both as a result of bioaccumulation and the nature of their surroundings, and because of their overall lifespan, lifecycle and general biology;
- that their life-cycles are likely to be of some relevance for evaluating total dose or dose-rate, and of producing different types of dose-effect responses;
- that their exposure to radiation can be modelled using relatively simple geometries;

- that there is a reasonable chance of being able to identify any effects at the level of the individual organism that could be related to radiation exposure;
- and that they have some form of public or political resonance, so that both decision makers and the general public at large are likely to know what these organisms actually are, in common language.

(30) A final consideration is that of how best to describe the chosen selected reference animals and plants, bearing in mind that it has not been the intention to select particular species, but equally not to generalize to the extent that the characteristics of the selected types are of little biological meaning.

3.3. Achieving an appropriate level of generalization

(31) The taxonomic framework for past and present life on Earth has always been somewhat flexible, and is still the subject of much debate. Nevertheless, virtually all forms of life can be, simply for convenience, divided into either the animal or plant kingdoms, with viruses and similar micro-organisms being grouped separately. Bacteria, too, are often considered as a separate 'kingdom', although they have also been – and sometimes still are – grouped with the plants. The same applies to the fungi. Single-celled organisms have also been considered separately – as the Protista.

(32) The classification of animals and plants is primarily a reflection of their morphological characteristics, plus physiological and biochemical features, and often draws upon what is known or assumed about their evolutionary history. Such approaches are now greatly strengthened by the use of DNA analyses. Animals are grouped into **Phyla**, on the basis that each Phylum has, more or less, the same 'body plan' (such as chordates, or echinoderms, or arthropods) and within each Phylum they are further grouped into **Classes**, then **Orders**, then **Families** (which share 'typical' traits and features), and then ***Genera*** as the number of features they have in common increases; finally, *Genera* are divided into ***species***. There is no absolute definition as to what a species actually is, but it is usually taken as a description of individuals that (it is either known or expected) can only produce fertile offspring as a result of mating with similar individuals. In some cases, even further distinctions are made – into *sub-species*, or into races and varieties. Plants, too, are characterized in relation to features such as anatomy, embryo characteristics, and biochemistry, and are similarly classified except that they are usually grouped into Divisions rather than Phyla. Features that differentiate either animals or plants at the level of Class or Order are often fairly detailed, and may be more a reflection of their evolutionary history than a factor that is relevant to their general biology today. Such groupings are subject to considerable fluctuations and are the subject of academic study and debate. Thus there are no internationally accepted 'rules' on classification above Family (or 'Super Family') level, and this level of generalisation has therefore been suggested as being the most suitable (Pentreath, 2002 b, 2005; Pentreath and Woodhead, 2001).

(33) The total number of living species of animals and plants is not known with any certainty, although the majority of 'large' organisms have probably been the subject of description and classification. Thus probably 99% of birds and 90% of other land vertebrates have already been described (Goto, 1982). It is generally assumed that there are certainly well over a million species of animals, and at least

half that number of plants on Earth at present; although some recent estimates place the former as high as 3 to 4.5 million, and the latter as low as 0.35 million (Sauchanka, 1997). New species of animals and plants have been described in recent decades at the rate of about 10,000 per year, and approximately half of these are insects, the remainder consisting largely of a wide variety of other invertebrate animals (particularly from the marine environment), and plants.

(34) Animals usually have between 12 and 60 pairs (2n) of chromosomes, but there is considerable variation, even within Orders and Families (for example, in the Diptera (flies) 2n varies from 4 to 20; in the Lepidoptera (butterflies and moths) it varies from 14 to 446). The molecular biology of plants is much more variable than that of animals, with more frequent recombination and re-assortment of genes during meiosis. Nuclei, mitochondria, and plastids within plant cells, all have their distinct DNA systems. Polyploidy is common in plants (50% of all flowering plants), usually because a diploid (2n) plant, by irregular division, gives rise to a tetraploid (4n) plant. Then, as a result of pollination, triploid (3n) plants are formed. These are unable to produce gametes compatible with either ‘parent’, and thus the 2n and 4n forms often diverge because of the resultant genetic isolation (Collinson, 1988).

3.4. A definition of Reference Animals and Plants

(35) Because no clear algorithm for the selection of Reference Animals and Plants can be defined, their selection has to be made on best judgement, bearing in mind the need to keep the total number low, to try and cover terrestrial, freshwater and marine environments, and to satisfy the various criteria discussed above.

(36) Based on all of these criteria, therefore, and in an attempt to be consistent with the concept of Reference Man, a Reference Animal or Plant can be described as follows. *A Reference Animal or Plant is a hypothetical entity, with the assumed basic biological characteristics of a particular type of animal or plant, as described to the generality of the taxonomic level of Family, with defined anatomical, physiological, and life-history properties, that can be used for the purposes of relating exposure to radiation dose, and relating dose to different categories of effect, for that type of living organism.*

3.5. The set of Reference Animals and Plants

(37) Working within this definition, and taking into consideration both the needs and the selection criteria, an initial ‘set’ of reference animals and plants has been identified, as set out in Table 1. A deliberate emphasis has been placed on vertebrate animals but, in compiling the overall ‘set’, consideration has also been given to the range of habitats covered (Table 2), the variety of life histories and life spans represented, and the potential for extrapolating the basic ‘Reference’ animal or plant data to other forms of animal or plant, or to place them in other environments. Thus, again bearing in mind that the primary purpose is to use the reference animals and plants to relate exposure to dose, and dose to effect, it should be possible to adapt the basic data in relation to, for example, the marine flatfish to that of a similar fish in an estuarine situation, or to adapt the freshwater salmonid fish (trout) data to those of a marine ‘round’ fish, and so on. Equally, however, a balance has had to be struck between keeping the descriptions and numerical information as simple as

possible, proportionate to the amount of radiobiological information currently available, and the purposes to which the data will be put.

Table 1. Subjective assessment of the types of Reference Animals and Plants against some key criteria used in their selection (+low; ++medium; +++high affinity).

	Legislation relating to wildlife protection	Use in toxicity testing	Human resource	Data on radionuclide accumulation	Data on radiation effects	Amenable to further study	Public resonance
Deer	+		++	+	+	+	+++
Rat	+	+++		++	+++	+++	+
Duck	+++		+	+	+	+++	+++
Frog	++		+	+	+	++	++
Trout	++	+++	+++	+	+++	+++	+++
Flat fish		+	+++	+++	++	++	+
Bee	+	+	++	++	+	+++	++
Crab		+	+++	+++	+	++	++
Earthworm		+++		++	+	+++	++
Pine tree	+		+++	++	+++	+++	+++
Grass		+	+++	++	+++	+++	++
Seaweed			+	+++	+	++	++

(38) The set is essentially one of ‘wild’ animals and plants rather than domesticated ones. With regard to farm animals, primarily large mammals that live essentially in a human environment, it was considered that the use of the human animal itself was probably sufficient for such managed environmental or ecological situation. The inclusion of the deer in the list was however considered to provide some link, because such animals are farmed in some countries.

Table 2. General types of selected reference animals and plants in relation to their ecological spread.

Organism	**Terrestrial**	**Freshwater**	**Marine**
[Reference Man]	[X]		
Deer	X		
Rat	X		
Duck	X	X	
Frog	X	X	
Trout		X	X
Flat Fish			X
Bee	X		
Crab		X	X

Earthworm	X		
Pine Tree	X		
Grass	X	X	
Brown Seaweed			X

(39) The following descriptions are intended simply as brief introductions to the twelve types of Reference Animals and Plants that have been selected.

3.5.1. The Reference Deer

(40) Large herbivorous mammals occur over most of the temperate regions of the world, and extend into the arctic and tropical regions. Of these, some of the most ubiquitous are members of the deer Family (Cervidae). Deer occur throughout Europe, Asia, Africa, and the Americas, and various native species have been introduced into other countries, including throughout the southern hemisphere, for various reasons. Deer are therefore well studied and have been raised in various forms of captivity. The reference deer is taken to be a medium sized woodland deer.

3.5.2. The Reference Rat

(41) There is probably more information on the effects of radiation on rodents than on any other mammal, with the exception of the human being. Rats and mice (Muridae) have been used extensively in laboratory experiments for a vast range of studies, particularly in relation to human medicine, including a large number in relation to the metabolism of radionuclides, and on the effects of radiation from both internal and external sources. In the environment they are fairly ubiquitous, with a worldwide distribution. Although generally regarded as a human pest, some species are rare, threatened, and thus legally protected in some countries. The reference rat is assumed to be nocturnal, feeding at night and resting during the day in a burrow.

3.5.3. The Reference Duck

(42) Ducks (Anatidae) occur in rural and urban areas, and a number of species have been domesticated in various parts of the world and hence bred in captivity and used as a human food source. Wild ducks are also taken for food in some countries, but many species are increasingly protected, and ‘wildfowl’ generally are regarded as vital components of wetland ecosystems; and wetlands are, in turn, variously protected to provide habitats for wildfowl, either in relation to breeding or in relation to feeding and resting areas for migratory species. Ducks, in general, can thus be viewed as birds that are ‘typical’ of wetland areas, and their exposure to radiation throughout their life histories could arise, externally, from radionuclides on soil or in fresh, estuarine, or sea water, and internally from the ingestion of a wide range of aquatic animals, and from both aquatic and terrestrial plant materials. The reference duck is assumed to have the characteristics of a typical ‘dabbling’ duck. (These are the most ubiquitous, being found in urban and rural areas.)

3.5.4. The Reference Frog

(43) Frogs and toads are also typical of wetland areas in many parts of the world. Some species are extremely rare and many are now protected. Wild frogs and toads are taken for human food in a number of countries, and some species are

farmed as a food source. They have been used extensively as teaching aids. With a typical life cycle involving an aquatic egg, a tadpole stage, and then a terrestrial adult, frogs are likely to encounter a wide range of potential exposure situations in both freshwater and terrestrial environments. The reference frog is taken to be a member of the Family Ranidae, living in a temperate region around fresh water, spending its non-breeding time out of water, and hibernating over the winter period in mud.

3.5.5. The Reference Trout

(44) Salmon and trout (Salmonidae) are regarded as biological indicators of good water quality and are the subject of much environmental and fisheries legislation. They have also been the subject of many laboratory studies on fish physiology, and on radionuclide metabolism and radiation effects, as well as being used to investigate the accumulation and effects of many other environmental contaminants. They are used in toxicity tests for a range of pollutants. Trout, in particular, are also widely farmed throughout the world, and salmon are now farmed in many countries. Salmonid fish live in both marine and fresh waters. They lay their eggs on the bottom of streams and the adults live in the water column. The reference salmonid is taken to be a 'trout' rather than a 'salmon' in order to avoid the complication of migratory effects of the salmon from fresh water to the marine environment. It is therefore assumed to live its life in the same body of water, spawning in a stream that runs into that water.

3.5.6. The Reference Flatfish

(45) Teleost (bony) flatfish species are the basis of commercial inshore fisheries in many parts of the world, and a number of species are farmed commercially. They have been the subject of many laboratory studies, and extensively studied with regard to their accumulation of radionuclides and the effects of radiation. In contrast to salmonid fish, teleost flatfish produce eggs that float in the water column. The larvae remain in the water column for several weeks and thus, together with the eggs, form part of the plankton. The larvae metamorphose and settle on the sea bed, both juveniles and adults living predominantly in or on the bottom sediments. They inhabit both marine and brackish waters. The reference flatfish is taken to be a member of the Pleuronectid Family, although whether or not it is 'right-eyed' is of no particular relevance. It is a shallow-water, bottom feeding fish

3.5.7. The Reference Bee

(46) There are probably more species of insects on the planet than of all other forms of life put together. They play a vital role in the ecology of terrestrial ecosystems, as predators and prey, parasites and scavengers, and as pollinators of flowering plants. A few species are directly harmful to man, by way of carrying diseases, although immense indirect damage can also be done to crops and building structures by other species. Equally, however, many species are essential for crop pollination, and hence in human food production. Many species are also legally protected, either because of their own 'value' (such as butterflies) or because they provide a vital role in maintaining the ecology of other 'valued' animal or plant species. The most studied, and easily reared, insects are the bees. Although the majority of bees are solitary and relatively short lived, the best studied are the social bees, particularly the honeybees. The reference bee is therefore assumed to be a typical social (Family Apidea) bee.

3.5.8. The Reference Crab

(47) Crabs, and lobsters, are amongst the few types of invertebrate animals that grow to a sufficiently large size (up to 20kg in weight and with ‘leg spans’ of over 3m) to warrant the need for more complex geometries to estimate dose rates from internal and external sources. They also have comparatively long life spans. Crab larvae form part of the plankton, and their size and feeding patterns are very similar to other types of crustaceans that spend their entire life cycle as part of the plankton. Although the majority of crabs are marine species, there are many that inhabit brackish waters, and fresh waters, and some are essentially terrestrial. Crabs are widely taken for human food in coastal waters all over the world, and many species are farmed commercially. Their biology has therefore been well studied, and they have been the subject of many radiobiological studies and radiochemical analyses. The reference crab is taken to be a temperate water crab with a reasonably large adult size; it is essentially a crab of the Cancrid Super-Family.

3.5.9. The Reference Earthworm

(48) Earthworms make a large contribution to the total weight or biomass of soils, particularly in temperate regions. They play a vital part in the breakdown of dead plant and animal material in soil and forest litter, and thus in soil fertility, as well as in the maintenance of soil structure and aeration. They also provide a food source for a large variety of mammals and birds. They have been extensively used in the toxicity testing of inorganic and organic chemicals, particularly insecticides, fungicides, herbicides, and heavy metals. Some species grow and reproduce well in organic wastes and have been used to feed both fish and livestock. They have also been used in the amelioration of contaminated land, in land reclamation (such as mine wastes), and as indicators of environmental contamination. The reference earthworm is taken to be a member of the Lumbricid Family, living in the temperate zone.

3.5.10. The Reference Pine Tree

Pine trees (Pinaceae) occur naturally across the whole of the Northern hemisphere, from the Arctic Circle to just south of the Equator, in a wide variety of environments. They have also now been introduced into many southern hemisphere countries worldwide. They have been extensively used by man for building materials, for fuel, and for resin. They have also been well studied with regard to their physiology and general biology, and are easily cultivated. There is also a large amount of information on them with regard to exposure to radiation and its effects.

3.5.11. The Reference Wild Grass

(49) Grasses (Graminaea) of one form or another are the predominant plants throughout much of the terrestrial environment. They occur naturally in a wide variety of forms, including reeds and bamboos, as well as the more familiar cereal crops and the dominant plants of natural pasture land. They serve as food for a wide range of herbivorous mammals, including (as herbage) domesticated forms of cattle, sheep, and horses. They are also the basic food crop for humans all over the world. Their biology has therefore been well studied, including their accumulation of a wide range of chemicals. The ‘Reference Wild Grass’ is taken to be a ‘barley type’ grass.

3.5.12. The Reference Brown Seaweed

(50) Seaweeds are the principal macroscopic plants of the marine environment, occurring in coastal waters all over the world. Some species are commercially harvested for human food, for fertilizer or for use as cattle food, and some are harvested for the extraction of alginates and gums. Seaweeds have also been used extensively to examine the adsorption, or absorption, of a wide range of chemicals, particularly metals, in marine or brackish water environments. Their chemical compositions have therefore been well studied, and they have also been used extensively as indicators of the dispersion of radionuclides in the aquatic environments. And, because some species are eaten by humans, these have been extensively monitored in the vicinities of coastal nuclear sites. The reference brown seaweed is taken to be a Cyclosporean brown intertidal seaweed, living in such a position that it is covered by seawater for 75% of the time. It has a simple life cycle, in that the adult plant is a diploid sporophyte that has male and female conceptacles on the same thalli (monoecious).

3.5.13. Dimensions of Reference Animals and Plants

(51) Possible dimensions of Reference Animals and Plants are shown in Table 3, as represented by solid ellipsoids for primary phantom dose modelling.

Table 3: Possible dimensions of Reference Animals and Plants.

Organism	Major axis of ellipsoid (cm)	Minor axis of ellipsoid (cm)	Second minor axis of ellipsoid (cm)
Adult Deer	130	60	60
Rat pup	2	0.6	0.5
Rat	20	6	5
Duck egg	6	4	4
Duck	30	10	8
Frog egg	1	1	1
Tadpole	1.5	0.75	0.75
Frog	8	3	2.5
Trout egg	0.25	0.25	0.25
Trout	50	8	6
Flatfish egg	0.02	0.02	0.02
Flatfish	40	25	2.5
Bee larva	1.5	0.75	0.75
Bee	2	0.75	0.75
Bee colony (natural)	60	30	30
Crab egg	0.03	0.03	0.03
Crab larva	0.03	0.03	0.03
Crab	20	12	6
Earthworm egg	0.5	0.5	0.5
Earthworm (elongated)	10	1	1
Pine tree trunk	3500	150	150
Grass spike	5	1	1
Brown Seaweed	50	0-5	0.5

3.6. Summary

(52) These twelve animal and plant types - as adults, eggs, or larvae, as appropriate – therefore occupy a range of environmental situations and thus potential exposure to radionuclides from different sources. They range considerably in size but, as a basic step, each could be simplified into simple shapes for the basis of making primary phantoms for the purposes of estimating doses received under different circumstances. The range of sizes that might be expected is indicated in Table 3, and aspects of dosimetry are discussed in the next section.

4. RADIATION DOSIMETRY FOR ANIMALS AND PLANTS

4.1. Introduction

(53) Although many different approaches have been used to estimate the doses received by animals and plants, from both internal and external sources, they have many features in common. A number of international panels and meetings have addressed various aspects of dosimetry, particularly with respect to aquatic organisms (IAEA, 1976, 1979, 1988; NCRP, 1991). All of the approaches used have had to strike a balance between the complexity of the modelling that is theoretically possible, and the practical availability of relevant data to apply to them. There are two issues here: one is the vast range of shapes and sizes that occur throughout the animal and plant kingdoms; the second is the fact that radionuclide concentrations in animals and plants display all of the variations amongst tissues and organs that occur in human beings, but there are few internally consistent data sets for any one particular type of animal or plant. Thus an extreme simplification has often been made, and that is the reduction of the whole organism to a simple shape.

(54) Empirical expressions, involving energy-dependent parameters, have been developed to describe absorbed dose distributions about point sources of α, β, and γ rays (Loevinger et al, 1956; Berger, 1968; 1971; Harley and Pasternack, 1972). These expressions have then been integrated over defined source distributions to give estimates of the dose rates at specified points within the targets, from which average dose rates can be calculated (Brownell et al, 1968; Ellett and Humes, 1971). The targets used have been described as solid spheres or cylinders (IAEA, 1976) or solid ellipsoids (Pentreath and Woodhead, 1988; IAEA, 1988; NCRP, 1991), and estimates made of dose rates from external and internal sources. Much more detailed models were developed by Woodhead (1970, 1979) to describe the special cases of exposures of the embryos of developing fish eggs.

(55) For the marine environment, several generalised faunal types (fish, crustaceans, and molluscs) have already been used to produce a set of dose rate per unit concentration values for 104 radionuclides, and these have been normalised to unit ambient water concentrations to estimate dose rates from both external and

internal sources by applying tabulated values of concentration factors and kd values (IAEA, 1985(NB now updated)) to the calculated dose coefficients (Pentreath and Woodhead, 1988). These values (*dose rate per unit water concentration values*) were applied by the IAEA (1988) to oceanographic models of radionuclide dispersion in order to assess the environmental impact of the deep-sea disposal of low-level radioactive wastes.

(56) More recently, Amiro (1997) has produced sets of '*radiological dose conversion factors*' for screening potential ecological impacts with respect to radionuclides in soil, water, and air. And generalised dose models, for a similar purpose, have been produced by the USDOE (2002).

4.2. Current approaches to dosimetry

(57) With regard to the use of a solid ellipsoid, the majority of studies have estimated the proportion of radiation absorbed within the volume of the ellipsoid by using formulae that describe the distribution of radiation doses around point sources within it, and then integrating the resulting doses over all hypothetical point sources and point receptors. This can be done analytically for simple cases, but for more complex cases, and for greater convenience, it is preferable to use numerical models. Such models can now be run relatively easily. The approach developed by Copplestone et al (2001) is particularly useful; it uses polynomial functions that are derived from the point-isotropic specific absorbed fractions (the fraction of energy absorbed per gram of absorbing medium at a distance *r* cm from a point source of γ ray photons of energy *E* MeV). Such data for protons were calculated and published by Berger (1968) to provide a continuous interpolation for each discrete photon energy. Pairs of co-ordinates, both of which lie within the specified ellipsoid, are selected using a random number generator, the distances between them calculated, and these steps iterated a few thousand times, averaging throughout the mass of the ellipsoid, in order to obtain estimates of ($\boldsymbol{F_E}$), the fraction of energy emitted within the volume that is also absorbed within it.

(58) Tabulated dose distributions around point sources for β particles have also been produced by Berger (1971), but although the same computational method could be used as for γ ray photons, the process is computationally inefficient because of the decay schemes and range of energies of β particles in such radionuclides. Copplestone et al (2001) therefore derived a method that estimates β-particle absorbed fractions by selecting three co-ordinates at random within the defined ellipsoid, generating a vector through them defined by randomly selected angles, calculating a distance along the vector to the surface of the ellipsoid and thus, again within a few thousand iterations, deriving point estimates of $\boldsymbol{F_E}$.

(59) With regard to α particles, because their range in living tissue is small, it is assumed that the absorbed fraction is unity for the sizes of organisms considered; relatively simple equations can therefore be used to estimate dose distributions for internally incorporated radionuclides (eg Harley & Pasternack, 1972). Doses from external α particles are generally taken to be zero, but it should be noted that, for smaller entities (such as benthic eggs or larvae) this aspect needs to be addressed explicitly (Woodhead, 1979)

(60) Copplestone et al (2001) used this numeric approach to calculate a set of '*dose (rate) per unit concentration factors*', where the unit concentration factors

refer either to the concentration of the radionuclide externally in different media (uniformly distributed) or internally. A set of values for 9 radionuclides was derived, for a number of ‘reference organism’ solid ellipsoid geometries. And essentially the same method has since been used by Vives i Batlle et al (2004) for an even greater range of aquatic biota, and for 43 radionuclides, both natural and artificial, including various sets of daughter nuclides.

(61) Recent advances have also been made with regard to dosimetry using Monte Carlo methods. These have been used to estimate dose rates for 25 radionuclides (individually, for radionuclides with half lives > 1 day) in a range of Northern latitude animals and plants, expressed as ‘*dose conversion factors*’ as part of the EPIC programme (Brown et al, 2003). Similarly, as part of the FASSET programme, sets of ‘*dose-rate conversion coefficients*’ for β and γ emitters have been calculated for 37 radionuclides for cylinder and ellipsoid ‘phantoms’ over a range of 0.2 g to 550 kg, taken to represent a range of generalised terrestrial animal and plant types (Taranenko et al, 2004). In both cases, the dose rate conversion coefficients for external sources of photon exposure have been expressed either as dose-rate *per unit concentration* of a radionuclide uniformly distributed in the upper 10 cm or 50 cm of soil, or *per unit area* of a radionuclide in the region of the soil surface. The air kerma at different heights above the ground for various phantoms were also calculated using Monte Carlo simulations.

(62) Thus various methods are now available to estimate dose rates to a wide range of animal and plant types, in a wide variety of environmental geometries, for all radionuclides at the ‘whole-body’ level. Current limitations are to the application of this approach due to the lack of available data, rather than in the models themselves. Nevertheless, all of these ‘whole-body’ approaches necessarily make simplifications with regard to the distribution of radionuclides; these are usually assumed to be evenly distributed, both internally within the organism, and externally. Again, this is as much a reflection on the lack of available data as it is of dosimetric expertise, and yet the distribution of some radionuclide radionuclides that are known to be significant contributors to the total dose rates are known to vary considerably in concentration from one organ to another. Some information is available, and the influence of differential radionuclide distributions within ellipsoids has been examined in a general way by Pentreath and Woodhead (1988) using examples of one order of magnitude internal discrimination, or preferential accumulation, relative to the whole body accumulation for β emitting radionuclides. But if clear relationships between dose rates and specific biological effects are to be better understood, then it is clearly necessary to have more precise information about the dose rates received by the relevant organs or tissues. And although most dosimetric models have been developed for ‘adults’, other stages in the life cycle (which not only have different geometries but may exist in an entirely different part of the environment) also need to be studied in more detail.

(63) There is clearly a need for greater consistency and clarity in the use of the terms used to relate exposure to dose in these various exercises. The allowance for differences in relation to radiation quality is also an important factor in this discussion. This, however, also depends upon what is known about radiation effects for different plants and animals, as discussed in the next section.

(64) Finally, one also has to consider the data bases relevant to estimating the internal exposure of animals and plants relative to the concentrations in the ambient

environment. Such data often take the form of so-called *concentration factors* for aquatic organisms, and as *transfer factors* for terrestrial biota. There are many summaries and tabulations of such data, including those relevant to the selected list of Reference Animals and Plants. In the majority of cases, however, the data have been derived with respect to estimating the dose to humans following consumption of the relevant biota, and therefore often only refer to the 'edible parts', which are not necessarily those of greatest interest in terms of the relationships between dose and effect for the organisms themselves. Nevertheless, such data bases can be examined more closely, and are probably sufficient to enable initial estimations of dose per unit environmental concentration for a large number of radionuclides to be made.

5. THE EFFECTS OF RADIATION ON ANIMALS AND PLANTS

5.1. Introduction

(65) At the sub-cellular level, there is now a considerable body of knowledge relating to the mechanisms by which radiation damage is caused (ICRP, 2003c). This has been achieved primarily by way of examining the fine structure of energy deposition from radiation tracks in the DNA molecule, largely as a result of the further development of Monte-Carlo track structure codes. It is therefore now generally recognised that double and single strand breaks in the DNA sugar-phosphate backbone, plus a variety of damaged DNA bases, can combine together in clusters so that a substantial fraction of the total damage is closely spaced. These effects arise from a combination of events induced by the main tracks and secondary electrons, plus secondary reactive radical species. There is also evidence that both the frequency and complexity of clustered damage depends upon the linear energy transfer (LET) of the radiation. In this respect it is also interesting to note that such damage, being complex and clustered, is somewhat different from the damage that may arise from oxidative attack by reactive chemical radicals, which is usually randomly distributed and relatively simple.

(66) Furthermore, it would also appear that it is the error-prone repair of chemically complex DNA double strand lesions that best explain cellular radiobiological responses such as the induction of chromosome aberrations, gene mutation, and cell killing. And DNA damage-response and repair processes are now also considered to be major determinants of dose, dose rate, and radiation quality effects in cells. Most of this information has been channelled into an understanding of the effects of radiation on humans, particularly with regard to the induction of stochastic effects in different organs and tissues.

(67) This basic understanding of the effects of radiation at a sub-cellular level is extremely important, but it also needs to be linked to the effects that are observed in tissues, organs, and of course the whole organism. There is a large data base on the effects of radiation on plants and animals and all of it, or limited sections of it, have been regularly reviewed from one standpoint or another over the last decade or so (IAEA, 1992; UNSCEAR, 1996; Whicker and Hinton, 1996; Pentreath, 1996; Copplestone et al, 2001; Real, et al, 2004). The data reviewed have been derived in different ways and for different purposes. Some studies have examined the relative effects of high dose rates on different types of animals and plants, presumably in the context of evaluating the impact of nuclear weapons. Many studies have been

carried out on mammals in order to provide information of relevance to human radiological protection. And some studies have been carried out to study the effects of radiation on specific biological end points, such as mutation rates in insects.

(68) Experiments have therefore been carried out at high dose rates over short periods of time, and at lower dose rates over extended periods of time. Some experiments have been carried out by irradiating animals and plants under external 'field' conditions; others have been carried out under carefully controlled indoor laboratory conditions. Some have involved small groups of individuals; others have simultaneously exposed breeding 'populations'. Some studies have used carefully calibrated external sources of radiation; others have involved the use of external or internal exposure to radionuclides in the laboratory, where the actual doses received are not always well described. Some have attempted to relate selected biological effects to ambient radionuclide concentrations, or ambient dose rates, in environmental locations that have been contaminated in various ways, although such 'epidemiological' type studies are few. Thus the range of individual species studied has varied enormously, as have the modes of exposure, the dose rates, and the selection of biological effects recorded. It is therefore not surprising that the majority of reviews conclude with broad estimates of dose-effect relationships, and that such ranges demonstrate considerable uncertainty and overlap.

5.2. General data availability on chronic effects of radiation

(69) With an increasing awareness of the need to develop a more systematic approach to this subject, several recent reviews have examined the available data base of radiation effects with respect to different biological end points across various animal and plant groups. A number of different approaches can and have been used to organize the data. Particularly valuable has been the FASSET Radiation Effects Database (FRED), developed as part of that project (Larsson, 2004; Real et al, 2004). This consists of about 25000 entries, arranged according to four 'effects' categories across 16 wildlife groups, with an additional differentiation between acute and chronic exposures.

(70) Experimental data are usually reported with experimental dose rates averaged over periods of hours, days, or years. Summaries of the data are therefore often arbitrarily organised into such bands of dose rates. With regard to mammals, effects pertaining to early mortality, mutation, and reduced reproductive success have been recorded for different species within dose rates ranging from 0.1 to 1 mGy h^{-1} (Real et al, 2004). For other vertebrates, the data base is poor with regard to birds, reptiles, and amphibians, but there is a substantial amount of information relating to both freshwater and marine species of fish, primarily relating to reproductive success but also with respect to humoral immune responses in developing embryos. These types of effects, for which the information is by no means consistent, have been reported at dose rates estimated as low as 8.3 to 83 μGy h^{-1}, but similar effects have not been detected at 9 mGy h^{-1}. Various effects on adults relating to reproductive success have been reported in the range of 0.1 to 1 mGy h^{-1}, but with little consistency at dose rates of less than 0.2 mGy h^{-1}. At higher dose rates, a wide range of effects have been seen and categorised in all vertebrates, and it is therefore difficult to draw conclusions about any real differences in radiosensitivity between mammals and other vertebrates (Real et al, 2004).

(71) A large data base exists on the radiation sensitivity of terrestrial plants, in relation to both chronic and acute exposures, and these arise predominantly from studies in Russia. The data base has again been reviewed recently by Real et al (2004). The data have been derived both from controlled experiments and from the accidents in the Eastern Urals and at Chernobyl. Many of the data relate to morbidity, with detrimental effects in pine tree species occurring at dose rates of the order of 2.4 mGy day^{-1}, and at dose rates about 2 to 10 times higher for deciduous trees. Prolonged exposures of only 0.5 mGy day^{-1} have been considered to result in increased radiosensitivity due to unrepaired damage. Conifers are considered to die as a result of dose rates of 120 to 240 mGy day^{-1} after a period of 2 to 3 years. Cereal plants have also been the subjects of many studies, particularly with regard to mutation rates over a very wide range of dose rates.

(72) Conclusions drawn with respect to the not inconsiderable data base available on the chronic effects of radiation on animals and plants are therefore often as much affected by the way the data are collated and analysed, as they are to inform upon specific questions. Thus the data have often been summarised not only in relation to different groupings of animals and plants, but also in terms of different bandings of dose rates, which include many different types of effects in many different species within a phylogenetic group. It is probable that such summaries have sometimes been influenced by a belief that dose rate 'guidelines' have been recommended by the IAEA. This is not the case. Various conclusions were drawn by members of an IAEA panel, on the status of the available scientific information, which was published in an IAEA Technical Reports Series (IAEA, 1992), but these did not constitute official IAEA guidance. Dose rate limits for biota have not been adopted in the IAEA Safety Standards; indeed, the IAEA has continued to develop its approach to the subject considerably since then (Linsley, 2002; Robinson, 2002; Gonzalez, 2003). More generally, however, such summaries of the existing data have found it difficult to draw up a clear picture of the relationships between dose and effect for different types of animals and plants within the context of their normal, environmental, life histories.

(73) Reviewers have also, explicitly and understandably, usually omitted the large amount of data that have been derived from laboratory studies of mammals for the purposes of improving the radiological protection of humans, particularly with regard to stochastic effects. As a consequence, none of this data base has been examined with respect to the potential risk and consequences of stochastic risks for the same species in the wild. Such an evaluation needs to be done, for it is the best biologically understood radiation effect. All of these reviews also draw attention to the very large and difficult-to-summarise data bases with regard to RBE in different plants and animals.

6. ISSUES RELATING TO THE USE OF DEFINITIONS, TERMS, QUANTITIES AND UNITS

6.1. Introduction

(74) Existing practice and recent reviews display a broad range of terms, definitions, and modifying factors with regard to discussions of both the estimation

of radiation dose rates and the effects of radiation. With regard to the latter, because the effects of ionising radiation are influenced by the dose, the dose rate, and the quality of the radiation, it has long been recognised that a set of unambiguous definitions of the relevant basic quantities is essential in order to provide a sound system for the radiation protection of human beings. Several terms have been used specifically for human radiation protection, and these are kept under constant review. But for the protection of other species, only the quantities describing the basic physical factors of radiation absorption exist, although various attempts and suggestions have been made to provide greater flexibility, and to allow for the known but limited information available in relation to radiation quality.

6.2. Recent concepts and terminologies with respect to animals and plants

(75) In contrast to the situation with human radiation protection, there is at present no formal or universally accepted approach for making allowance of such factors as LET or RBE in the description of absorbed dose by any other animal, or any plant, and hence of use in evaluations of environmental radiation protection. The need for such an approach has been widely recognized, for several different reasons. Firstly, it is known that the RBE phenomenon exists in animals other than man; indeed, much of the RBE information used in human radiation protection has been gained from animal studies and thus it seems reasonable that allowance should be made for it in the assessment of the relationship between dose and effects for those same animals. Secondly, it is known that many animals and plants have very high levels of naturally occurring alpha-emitting nuclides in their tissues, and thus the use of weighting factors would be useful in attempting to normalise comparative radiation background dose rates. And thirdly, many environmental protection problems relate to concerns over the actual or potential presence of alpha-emitting nuclides, and thus the fear that their potential effects on wildlife could be underestimated if such RBE factors were not taken into account.

(76) Because of these difficulties, there have been various attempts in recent years either to address them, or at least to highlight them. Thus UNSCEAR (1996) suggested that a weighting factor of 5 be used for internal α-emitters, for all living things other than man; this suggestion was made in the belief that deterministic effects would be of the greatest significance.

(77) Subsequently, Pentreath (1999), in proposing the setting up of a set of reference fauna and flora, considered that some method of expressing radiation exposure in terms other than Gy was essential, both in order to describe background dose rates adequately, and to estimate additional dose rates equitably amongst different radionuclides. Two approaches were suggested. One was simply to refer to high and low LET components of the dose rate separately, which was considered to be clumsy; the other was that something along the lines of an equivalent dose be derived, analogous to its use in radiological protection of humans, and that this might be called the *dose equivalent for fauna and flora* (DEFF). The deliberate inclusion of the phrase "dose equivalent" in this definition was intended to help distinguish it from "equivalent dose" used in human radiological protection. The DEFF was defined as the product of Gy and a 'qualifying factor' (*qf*). The starting place for the latter was seen to be, as it had been for the rem, the hard factual information relating to linear energy transfer of radiation in water. It was considered that this would provide values of 1 and 20 for beta/gamma and alpha radiations

respectively, and could be used until more reliable or relevant information became available with respect to particular types of effects in different types of organisms.

(78) Developing this approach further, it was also considered that the use of the DEFF term for specific types of fauna and flora ($DEFF_F$) would need to be set out in such a way that the relationships between any qualifying factor and absorbed dose could accommodate a range of different values, not only in relation to the type of radiation (particularly for alpha radiation) but also for the specific types of reference organisms and effects upon them that might eventually be used in an international system (Pentreath and Woodhead, 2001). As a general starting point, they considered that some form of radiation weighting factor might be derived as the quotient of the accepted maximum and minimum values of the linear energy transfer in water for α-particles, with energies up to 10 MeV, and the maximum and minimum LET values for electrons with energies in the range of 0.01 to 2 MeV. But as this approach yielded values substantially larger than observed RBE ranges for low dose rates of high-LET radiation, it was suggested that actual RBE values relating to the chosen types of fauna and flora should be used to compile a set of ($DEFF_F$) values. And, in order to be generally conservative in those cases where there was no experimental data relevant to such types of fauna and flora, it was thought that a provisional value of about 40 might be adopted, based on the very large range of data available in the existing literature, until the subject had been examined in more detail.

(79) In the meantime, Trivedi and Gentner (2000) had suggested a somewhat different approach: that of deriving a weighting factor in order to arrive at an *equivalent dose for protection of non-human biota*. Starting from the existing ICRP approach to human radiation protection, they suggested the term *ecodosimetry weighting factor*, (e_R), for all non-human biota to fill a role equivalent to that occupied by w_R in human radiation protection. Thus they considered that (e_R) should not reflect values for stochastic effects at low doses, because they considered that not all non-human species develop cancer or receive doses that they considered low. Furthermore, they considered that although the value for e_R should take account of various RBE values for effects from environmental levels of doses, it should not be limited to these inputs.

(80) In looking at the considerable range of α-emitter RBE values for endpoints involving reproductive and haemopoietic systems, Trivedi and Gentner (2000) concluded that, in a number of situations where very high RBE values had been reported, uniform distribution of the radionuclides are typically assumed, which may not reflect the 'real' dose to the critical target. They therefore proposed that RBE values from experiments with fission neutrons, where dosimetry is not an issue, might be used to guide selection of e_R for α-emitters. They also evaluated reported values for RBE for alpha-emitters and determined that the most "realistic" values ranged between 2 and 12. This was interpreted to indicate that the suitable RBE values for alpha-emitters in biota generally are between 5 and 10. Kocher and Trbalka (2002) also expressed the view that an appropriate value probably lies in the range of 5 to 10.

(81) Yet another suggestion came from an IAEA working group on "Quantities, units and compliance" (IAEA, 2000). They suggested that the term *(radiation) weighted absorbed dose (rate)* be used generally for protection of the environment to fulfil the purpose served by equivalent dose in the system of radiation protection

for man. This group defined 'w_r' as the "radiation weighting factor appropriate to the organism, effects endpoint and dose rate".

(82) And at about the same time, Environment Canada (2000) had proposed a *radiation weighting factor* for assessing the effects of alpha emitters generally in the environment under Canada's *Priority Substances List 2* (PSL2) based on a paper by Thompson et al. (2003). While acknowledging that the majority of studies reported RBE values <10, these authors selected studies that they deemed to have "ecologically significant endpoints and at environmentally relevant doses and dose rates". The geometric mean RBE from the selected subset was 40. Their value was described as a recommended *RBE weighting factor for the ecological assessment of ecologically significant alpha-emitting radionuclides*.

(83) The CNSC's Advisory Committee on Radiological Protection subsequently provided a detailed critique of the recent studies that have yielded RBE values for alpha radiation significantly greater than 20 (ACRP, 2002) and recommended that a radiation weighting factor in the range of 5 to 20 for alpha particles, relative to low-LET radiations, would be appropriate for protecting all biota against 'ecologically relevant deleterious effects'. The ACRP also concluded that studies that imply higher RBE's for some endpoints in animals all have serious problems, either with α dosimetry or with poor statistics. Chambers (2003) has also commented on the methodological flaws in the studies that purport to support high values of RBE for alpha emitters.

(84) This debate over what values may or may not apply in different circumstances will no doubt continue. What is clear, however, is that the issue of the development of one or more factors to modify the quantity of absorbed dose in animals and plants needs to be addressed, and addressed logically. The issue, therefore, is not simply about the numerical derivation of a particular value, but about the concepts and assumptions relating to the need and function of one or more qualifying or weighting factors. Until these issues are resolved, there is no basis upon which any common numerical value can be based.

(85) The principal areas that need to be considered appear to include the need for some basic assumptions with regard to the importance of LET with respect to all forms of biological tissues; the need to allow for the fact that the RBE response can be demonstrated in a wide range of biota; the relevance of the biological endpoints used in RBE studies with respect to the many different objectives of environmental management and protection, and in particular to the categories of effects relating to Reference Animals and Plants; the extent of data available on RBEs relating to each one of the ICRP set of Reference Animals and Plants; and the extent to which it is possible to generalise or extrapolate amongst these data (e.g., amongst mammals in general, or vertebrates, or invertebrates, or plants). This report cannot address all of these issues, but a key one is clearly that relating to the concept of RBE. This subject has recently been the subject of an exhaustive review in the context of human radiation protection (ICRP, 2003b) but the following points need to be noted here.

(86) The radiation weighting factors for protection of human beings are primarily based on the need to reduce the risk of stochastic effects, and therefore have a pronounced emphasis on the response to radiation at low doses. In other words, the RBE values used to guide decisions on radiation weighting factors are the low-dose maximum RBE (RBE_M) values. There are two approaches to the

determination of RBE_M (ICRP, 2003b). A low dose method, that determines RBE_M as the quotient of the initial slopes of the reference and test radiations; and a high dose method, which has been applied to determining RBE_M for neutrons, that divides this value by the dose and dose-rate effectiveness factor (DDREF) selected for use with human low-LET acute exposure risk coefficients. The high dose method therefore implicitly argues that low dose-derived RBE values for stochastic effects in humans should be divided by a factor of at least two when applied to high doses.

(87) Factors that are known to effect the determination of RBE values include the effect of selected dose range; the effect of dose rate; the effect of endpoint selected for assessment; the effect of errors in dosimetry; and the effect of choice of the reference radiation. Indeed, there is probably no such readily identifiable entity as *the* RBE for a particular type of radiation that can be generally applied. Instead, there are a number of RBE values, which differ appreciably. It should also be noted that the RBE is only one type of input to the selection of radiation weighting factors, and the limitations of the concept must be borne in mind, particularly with regard to consideration of the levels of effect assessed and the dose range within which the selected levels of effect occur.

(88) Chambers et al (2004) have identified 66 relevant measurements of alpha RBE, and assigned these to one of three broad categories: population relevant deterministic endpoints such as cell mortality, oocyte mortality and sperm mortality; other deterministic endpoints such as haemopoiesis, spermhead abnormality and lens opacity; and stochastic endpoints such as chromosomal aberration, double-strand breaks and mutation.

(89) Another issue is that of making allowance for the non-homogeneous distribution of internal nuclides. At a practical level, this will to some extent depend on the size of the organisms and the dosimetric models that are applied to them. It will also depend upon the type of biological effect observed and its relationship to dose. As yet, it is impossible to draw any conclusions, except that it is an issue that may need to be addressed for some types of animals and plants.

6.3. Discussion

(90) The system for radiation protection of human beings is based on dose, and upper boundaries on what constitute acceptable degrees of risk from radiation-induced stochastic effects are provided by the system of dose limitation. Exposures are generally received as a series of highly fractionated, acute, but low doses. And although the dose limit is specified on a per annum basis, it is assumed that, whatever the dose rate, the exposure should have an effect no greater than if delivered in a protracted (i.e. chronic exposure) manner (UNSCEAR 2000).

(91) Radiation quality factors have been derived for the application of dose assessments for humans, for which stochastic effects are primarily important. However, it is not clear to what extent such effects are of relevance with respect to animals and plants, and even if they were, their significance would probably be considered under different categories of biological endpoints of interest. The absorbed dose therefore remains the key quantity for exposure assessment of biota, although this could usefully be further evaluated in terms of high and low LET.

(92) Looking to the future, the assessment of *probability of causation* (for exposed persons who have developed cancer) may be a more informative model with respect to how an RBE might be used in the protection of non-human biota. Such values are computed for intermediate or high-dose exposures that cause risks of a magnitude comparable to the background risk (ICRP 2003b). Thus neither the values of RBE_M nor the weighting factor conventions w_R and Q(L) are applicable; instead, other dose information needs to be applied. Such considerations may be germane to non-human biota.

(93) For the purpose of pollution control, the above protection objectives may require the explicit demonstration of the avoidance or minimisation of harm to the environment, or the ability to deal with an environment that is already deemed to have been harmed. And, for the purpose of nature conservation, the above protection objectives may, in turn, require assessments to be made of the likelihood of harm to individuals of particular species, or to potential or actual effects on populations of one or more species, or to the sustainability of the ecosystem

7. ASSESSING EFFECTS IN TERMS OF DERIVED CONSIDERATION LEVELS

7.1. Introduction

(94) In the meantime, however, some form of practical means is required in order to make judgements based on our current knowledge of the effects of radiation on different types of animals and plants. Thus although there is a reasonable amount of information relating to various types of radiation effects, these are almost entirely with respect to relatively high dose rates and total doses. And because such effects are primarily of a non-stochastic nature (with the exception of data derived from small mammalian studies) it is difficult, in the absence of any form of 'sliding scale' against which to apply some form of 'risk related' criteria, to make assessments or judgements at lower dose rates. A different approach is therefore required.

7.2. Derived Consideration Levels

(95) It has therefore been suggested that the only other useful comparator might be that of the natural background radiation dose rate normally experienced by such animals and plants (Pentreath, 1999, 2002a). Additional doses that were but fractions, or small multiples, of the normal background dose rates might therefore be unlikely to be the cause of any environmental managerial concern, particularly when considered against those multiples of background dose rates that were known to have specific effects. Dose rates that were very much higher, and in the region of known or expected effects, would however need to be considered further, alongside other environmental information, within any particular environmental management framework. Thus, collectively, all of the derived information relevant to each type of animal and plant could be simplified into multiples of their background radiation dose rates in the form of Derived Consideration Levels. Such data could then be considered alongside other information (such as the size of the area affected, the fraction of a population exposed, and the actual animals and plants concerned) in

order to satisfy the legal framework within which any management action was being taken.

(96) A useful first step, therefore, would be the compilation of data with regard to both the natural radiation background dose rates, and what is known about specific categories of radiation effects for the Reference Animals and Plants. With respect to the former, the following information is of relevance. In the aquatic environment, dose rates are expected to be about 1 to 10 μGy day^{-1} for adult benthic fish (IAEA, 1976; Copplestone et al, 2001; Brown et al, 2004); within a range of 2 to 14 μGy day^{-1} for adult benthic crustaceans (crab) and molluscs (marine snail) (IAEA, 1976; Brown et al, 2004); and about 2 to 12 μGy day^{-1} for macrophytes (seaweeds), based on northern latitude data (Brown et al, 2003). Broadly similar values have also recently been calculated for European waters generally (Brown et al 2004), but for a different set of natural radionuclides, and for less precisely defined biota. For the freshwater environment, pelagic fish are considered to have background dose rates of about 0.5 to 18 μGy day^{-1} (Brown et al 2004).

(97) With regard to the terrestrial environment, external dose rates of about 2 μGy day^{-1} have been calculated for earthworms within the soil, and 0.6 μGy day^{-1} and 0.8 μGy day^{-1} for deer and mice respectively on the soil (Gomez-Ros et al, 2004). Internal dose rates vary very considerably from one organ to another, and from one type of animal to another, making it difficult to draw any clear picture of total average body dose rates. Nevertheless it has been estimated that dose rates from ^{210}Po in some tissues in some mammals could be in the range of 40 to 80 μGy day^{-1} and as high as 0.2 to 7 mGy day^{-1} to the lungs of small mammals living in the soil from radon (Gomez-Ros et al, 2004). Terrestrial plants have a total dose rate of about 2 to 20 μGy day^{-1} (Copplestone et al, 2001).

(98) Secondly, it is necessary to compile data sets of what is known about the effects of radiation, across a range of dose rates, with respect to different types of biological damage. For some of the Reference Animals and Plants, relatively good data sets exist. There are large data bases relating to rodents, across a reasonable spectrum of dose rates, but such data need to be evaluated carefully because of the selection of certain strains of rodents in experiments designed to obtain data of a specific nature, particularly with regard to carcinogenesis, for human radiological protection. There are also various data sets covering several orders of magnitude of dose rates for several types of fish. And, for the Reference Pine (as summarised by Copplestone et al, 2001; Real et al, 2004) it is known that dose rates in the range of about 2 to 25 mGy day^{-1} can have effects such as reduced trunk growth in mature trees, and morphological alterations in pine needles. Such dose rates can eventually lead to mortality in some trees. Decreased stem growth in saplings, and reduced photosynthetic capacity, and thus reduced growth, has been observed at dose rates in the range of 24 to 120 mGy day^{-1}, and reduced seed production and germination at dose rates of 240 to 480 mGy day^{-1}. For other fauna and flora, however, the data bases are largely confined to effects observed at these very high dose rates and over relatively short periods of time. Nevertheless, various data are available on all of the types of Reference Animals and Plants selected.

(99) The question naturally arises as to whether or not it is reasonable, or useful, to try and draw generalisations from the existing data. At this stage, the most sensible approach would appear to be that of keeping the data sets separate, for each Reference Animal and Plant, for the following reasons. Firstly, it is clearly unsafe to generalise without considering individually the quality and quantity of the data

across these different types of animals and plants. Secondly, there is as yet no general theoretical basis for doing so, and the experimental information is extremely varied. Thirdly, it is not clear as to what level of taxonomic division it would make sense to attempt to do so. And fourthly, the basic purpose of the Reference Animal and Plant approach is to assemble information that can be used for different environmental management purposes. These may specifically relate to one particular animal or plant type (such as large terrestrial mammals, or waterfowl) or to mixtures of types relevant to particular habitat types (such as wetlands, estuaries, or forests) for which particular combinations of animal and plant data would be required. All of which, naturally, leads to further consideration of how such information on a limited set of fauna and flora might be used.

7.3. Creating a Reference Set

The ICRP set of Reference Animals and Plants will therefore initially consist of an extended biological description for each of the twelve types, plus the following data sets for each type:

(a) the dimensions of each primary or secondary model used to represent each type at one or more stages of its life cycle (as, for example, in Table 3);
(b) a set of ‘dose per unit concentration’ values (μGy day^{-1} per Bq kg^{-1}) for internal and external exposures, for all of the principal naturally-occurring radionuclides;
(c) a set of ‘dose per unit concentration’ values (μGy day^{-1} per Bq kg^{-1}) for internal and external exposures, for all of the principal artificially-occurring radionuclides;
(d) a set of ‘reference’ internal naturally-occurring radionuclide concentrations (Bq kg^{-1});
(e) a set of ‘reference’ external naturally-occurring radionuclides (Bq kg^{-1}) for seawater, fresh water, and soil;
(f) a set of ‘reference’ background dose rates (μGy day^{-1}) for each type, using the data in (a),(b),(d) and (e) to create the baseline of the Derived Consideration Levels (DCLs);
(g) a set of guideline ‘transfer factors’ and ‘concentration factors’ for the set of artificial radionuclides;
(h) and a set of information, set out logarithmically, summarising what is currently known about the effects of radiation on that type of animal or plant (these are the bands within the DCLs).

7.4. Potential applications

(100) The need to make evaluations of the impact of radiation on the environment, either now or in the future, may arise for reasons that stem from any or all of the various environmental management requirements discussed in Section 3.2, but particularly in relation to pollution control and nature conservation, or under the general guise of what might be termed an environmental impact assessment.

(101) Such needs may also include any of a number of objectives**,** each of which might need to be expressed, and deemed ‘acceptable’ or otherwise, in different ways. These might include *assurance* of the public or their politicians, at national or international level, of the likely environmental impact of any actual or proposed

practices, and demonstration of the ability to deal with any consequences in the event of accidents or emergencies. They might also relate to *compliance* with the spirit or the letter of trans-national general pollution or wildlife-protection obligations; to compliance with national pollution control licensing requirements for particular industrial practices, sites or areas; or to compliance with the requirements of specific national wildlife and habitat protection legislation.

(102) For the purpose of pollution control, the above protection objectives may require the explicit demonstration of the avoidance or minimisation of harm to the environment, or the ability to deal with the environment that is already deemed to have been harmed. And, for the purpose of nature conservation, the above protection objectives may, in turn, require assessments to be made of the likelihood of harm to individuals of particular species, or to potential or actual effects on populations of one or more species.

(103) In order to make an evaluation of the effects of radiation on the environment itself with respect to any particular situation or practice, there are clearly several factors to consider, including the radionuclides of interest, their sources, their previous inventories, their rates of introduction, and their environmental distribution and fate. This basic information is also required in order to protect the general public. Many numerical models therefore already exist that can be applied to different practices, situations, and ecosystems. However, for environmental protection, other information is necessary, such as the potential exposure to radiation of the fauna and flora within the area of radionuclide distribution; plus the likely consequences for them, in terms of radiation effects. Of these two, addressing the former should not be too difficult, the nature of the problem having much in common with the environmental information needed for human radiation protection. The latter, however, is more difficult, and the term ‘consequences’ is far more open-ended than it is for human protection; many other factors therefore need to be considered, not least the original objectives of the assessment.

(104) Common to all of the protection objectives, however, is the process of having to *assess* the situation and then, if necessary, consider the various options for *managing* whatever situations may arise. This is particularly important when attempting to understand the purpose of the environmental evaluation, because each component may need to make use of completely different approaches and interpretations. But what should be common to both assessment and management is the basic scientific understanding, plus the means of expressing and using the relevant scientific information. This has been the basis of success for the radiological protection of humans, and therefore needs to be carefully considered with respect to protection of the environment generally.

(105) In order to make an evaluation of the effects of radiation on the environment itself with respect to any particular situation or practice, there are clearly several factors to consider, including the radionuclides of interest, their sources, their rates of introduction, and their environmental distribution and fate. This basic information is also required in order to protect the general public. Many numerical models therefore already exist that can be applied to different practices, situations, and ecosystems. However, for environmental protection, other information is necessary, such as the potential exposure to radiation of the fauna and flora within the area of radionuclide distribution; plus the likely consequences for them, in terms of radiation effects. Of these two, addressing the former should not

be too difficult, the nature of the problem having much in common with the environmental information needed for human radiation protection. The latter, however, is more difficult, and the term 'consequences' is far more open-ended than it is for human protection; many other factors therefore need to be considered, not least the original objectives of the assessment.

(106) It also has to be recognised that, in many cases, much more specific data on local animals and plants may already be available with respect to specific sites; or that data are often required for organisms that are more relevant in other respects, such as their ecological importance at a local level. But the data sets will always be limited because of the sheer impracticality of ever deriving some of the required information – such as that relating to radiation effects. Such organisms might therefore be regarded as *secondary reference animals and plants*, provided that they could be shown to relate in some way (for example by using the same sort of dosimetry models) to one or more of the ICRP set of Reference Animals and Plants. There are, therefore, a number of issues relating to our ability to extrapolate from limited data bases and frameworks in order to deliver environmental protection in a wider and practical sense.

(107) It is not currently possible to provide recommendations as to how to perform extrapolations that have general applicability, and thus each case has to be carefully considered on its own merits. Due to the relative paucity of information, the main cases for extrapolations, and challenges for methodological development, include the following. There are clearly issues with regard to extrapolating from high acute doses and dose rates (several Gy at about10 to 100 Gy h^{-1}) of low LET γ- and X-rays to lower doses accumulated at lower dose rates (about 1 to 100 μGy h^{-1}). In the radiobiological and radioecological literature, the qualifiers "low-level", "chronic", "higher", "acute" and so on are often used without any definition. But a radiation exposure lasting several days may be effectively "chronic" for a short-lived organism, and yet effectively "acute" for a long-lived organism. Unfortunately, there are very few data that relate directly to the chronic, low-level irradiation conditions of relevance for animals and plants in the wild i.e. exposures at dose rates of 100 - 1000 μGy day^{-1} over the life span of the organisms, and the response endpoints most commonly assessed after acute, high dose, irradiation are not those that are relevant in such situations.

(108) Another issue is that of extrapolation from one organism to another. Although the information is limited, there is clear evidence that there are substantial variations in the radiosensitivity of organisms, both within and between taxonomic groups. This differential sensitivity also extends to different stages of the life cycle for any given organism. Extrapolation should become easier the more closely related organisms are, and the more similar the effects' endpoints considered for the relevant stage in the life cycle (Strand et al, 2003; Garnier–Laplace et al., 2004).

(109) And finally there is the issue of extrapolation from effects in the individual organism to possible impacts at the population and community levels. This will also, in many cases, involve the extrapolation from laboratory conditions (where most experimental information originates) to field conditions (where populations interact with the physical environment as well as with other organisms). Interactions at community and ecosystem level can be particularly complex (Brechignac, 2003; Doi, 2004; Hinton and Brechignac, 2004). Nevertheless, it is necessary to start

somewhere, and by developing an understanding of the effects of radiation on a limited number of animals and plants, at the individual level, and exploring both the consequences of such effects at *their* population levels, and amongst different populations, a broader understanding will develop against which these wider issues can be assessed.

(110) The use of the above set will therefore clearly depend upon the 'questions' that are asked, but these may be, just as an example, along some of the following lines. In a comparative, theoretical, exercise the environmental distribution of radionuclides in one or more environmental situations (e.g., seawater) would be applied using the data sets for the relevant Reference Animals and Plants in order to calculate the expected 'additional' dose rates. The results could then be compared with the relevant data sets in the bands of Derived Consideration Levels to consider what management action would or would not be warranted. Dose rates that were fractions or small multiples of the background values would be unlikely to be of concern; dose rates that were in the range known to cause particular effects in individuals of that type of animal or plant would prompt further consideration, such as the area over which such dose rates were likely to obtain, for how long, what fraction of the local population might be exposed, and so on, depending on what information was being sought, by whom, and why.

(111) In a 'normal' situation, one might first of all wish to calculate the actual external or internal background dose rates for one or more of the selected types of Reference Animals and Plants by making use of locally derived radionuclide information, but using the same modelling approach. Thus the relevant data sets would be used to make such calculations. The extent to which the calculated background dose rate differed from the ICRP reference set would be noted. Then the actual 'additional' dose rate from the practice could be calculated, again using the data sets, and a judgement or evaluation made, as in the first example.

(112) Where, again in for example a 'normal' situation, animals or plants very close to any of the twelve types of Reference Animal or Plant do not exist, or are not the features of interest, then locally derived information might need to be derived for any of the purposes set out above, but particularly with regard to calculating the 'additional' dose. But comparisons could still be drawn with the ICRP reference set (as is the case for calculating human exposures where necessary) and it is likely that the data sets used in the Derived Consideration Levels would still be of value in assessing the likely effects and consequences, if any. And in all such cases, it is expected that other types of assessments, using non-Reference Animal and Plant types, will still find it useful to use the ICRP set to draw comparisons. Thus other types of organisms may be considered to be similar to one or more of them, or lying somewhere in between two or more types of Reference Animal or Plant. In all cases, however, the basis for the calculations and decisions will be transparent and auditable, and amenable to amendment and expansions as further or improved scientific information becomes available.

(113) The consequences of any expected radiation effects may need to be evaluated with respect to individual animals and plants, depending on the legal framework within which action is being considered, but undoubtedly the major requirement will often be the need to make evaluations at the population or ecosystem level. Radiation effects on higher levels of biological organisation (e.g., populations and ecosystems) occur only if individual organisms are affected, and radiation effects' data have generally been obtained for individuals rather than for

higher levels of organisation. In the natural environment the situation can become very complex because of the interactions between each individual and its surrounding ecosystem. The effects can also be modified by the presence of other environmental stressors, or by combined effects related to the presence of other pollutants, and by interactions between different trophic levels. Because radiation effects at the population level – or higher – are mediated via effects on individuals of that population, it therefore seems appropriate to focus on radiation effects on the individual for the purpose of developing a framework of radiological assessment that can be generally applied to environmental issues. This approach is consistent with many of the existing assessment methods for non-radiological environmental contaminants. It is also essential in order to consider how effects such as reduced reproductive success can be interpreted in the context of the normal biology of different types of plants and animals. Even the concept of what constitutes a 'population' will differ amongst the various 'types' of Reference Animals and Plants.

8. SUMMARY AND CONCLUSIONS

(114) The criteria for selecting a small set of Reference Animals and Plants stem from the operational needs of different approaches to environmental protection, as required under different legislative and environmental management regimes, plus the reality of our current limited amount of relevant data, and the prospect of improving upon such a data base in the near future. Nevertheless, it is possible to select about a dozen types of animals and plants that are typical of the major environmental sectors of interest, for which there is a sufficient amount of data available to at least begin the process, and to develop it to a useful and operational stage fairly quickly.

(115) There are certainly sufficient approaches to modelling dose rates at the whole body level, although certain further refinements are required, particularly for the larger animals and plants. More problematic is the lack of a clear means of expressing dose rates across different bands of LET radiation, and across all of the different phylogenetic groups. The data relevant to different categories of biological effects is also somewhat limited, but greater use could be made of the data that do exist.

(116) Collectively, therefore, it has been possible to select, define, and describe in outline a number of Reference Animals and Plants that could be used by the ICRP. With regard to the availability of dose models, a number of suitable modelling approaches already exist, but these would still need to be tailored to the specific types of Reference Animals and Plants selected. Various issues relating to the dosimetric quantities and units that could be used for such organisms have been discussed, and it is evident that doses to biota can only safely be described at present in terms of Gy, although this could be expressed in terms of high and low LET components. A clear priority for the future is to examine further how best to relate dose, and internal distribution of dose for the larger organisms, to the relevant radiation effects across different forms of animals and plants. In parallel, however, it will also be necessary to examine the extent to which the large data base on mammals with respect to stochastic processes and effects (which has been derived largely under laboratory conditions to aid human radiation protection), can be applied to the same and other types of mammals in the wild, and its relevance to the same categories of effects. The large data base on RBE values also needs to be more

rigorously evaluated to see to what extent, if at all, generalisations can be made across different phyla, and between animals and plants.

(117) The end-points for assessing radiation effects in non-human species of relevance to environmental management practices would appear to be those which can be categorised as early mortality; morbidity (particularly with regard to plants); reduced reproductive success; and various forms of cytogenetic damage. Bands of dose rates, relative to the natural background dose rates of different types of animals and plants (Derived Consideration Levels) could then be compiled in order to aid environmental management decision making, although the availability of relevant data is currently very varied, and is of differing accuracy and precision. But, nevertheless, there are sufficient data to begin the process of developing system for assessing the protection of non-human species and guidance for management decisions concerning protection of the environment that is based on the same principles, and uses the same basic scientific understanding, as the approach used for the protection of human beings.

REFERENCES

ACRP (2002) Protection of Non-Human Biota From Ionizing Radiation, Advisory Committee on Radiation Protection of the Canadian Nuclear Safety Commission, INFO-0730.

Amiro, B.D, Avadhanula, R., Johansson, G., Larsson, C-M., Luning, M (1996) *International Symposium on Ionising Radiation*, Stockholm, Vol 1&2, SSI and AECB

Amiro, B.D. (1997) Radiological dose conversion factors for generic non-human biota used for screening potential ecological impacts. J. Environ. Radioactivity **35**, 37-51

Anon (2001) Environmental Protection Approaches for Nuclear Facilities; 2nd International Symposium on Ionising Radiation, Ottawa, Canada

Berger, M.J. (1968) Energy deposition in water by photons from point isotropic sources. J. Nucl. Med. **9**, 15-25

Berger, M.J. (1971) Distribution of absorbed dose around point sources of electrons and β particles in water and other media. J. Nucl. Med. **12**, 5-23

Brechignac, F. (2003) Protection of the environment: how to position radioprotection in an ecological risk assessment perspective. Sci.Total Environ. 307, 35-54.

Brown, J. Thorring, H.and Hosseini, A. (2003) *The "EPIC" Impact Assessment Framework*, Statens Stralevern, 175pp.

Brown, J., Jones, S.R., Saxen, R., Thorring, H. and Vives I Batlle, J. (2004) Radiation doses to aquatic organisms from natural radionuclides. J. Radiol. Prot. 24, A63-A77.

Brownell, G.L., Ellet, W.H., Reddy, A.R. (1968) Absorbed fractions for photon dosimetry .J Nucl.Med. 9, 27-39

Chambers et al. (2003)…[Norman G].IRPA 11 Paper 1095

Collinson, A S (1988) *Introduction to World Vegetation* 2nd Ed, Unwin Hyman, London, 325pp.

Copplestone, D., Beilby, S., Jones, S.R., Patton, D., Daniel, P. and Gize, I. (2001) *Impact Assessment of Ionising Radiation on Wildlife* R&D Publication 128, Environment Agency, Bristol, UK

Doi, M. (2004) Model ecosystem approach to estimate community level effects of radiation. In *The scientific basis for radiological protection of the environment* F. Brechignac and B.J.Howard (Eds) IRSN Series. Paris, in press.

Environment Canada (2001) Environment Canada/Health Canada, Priority Substance List Assessment Report; Releases of Radionuclides from Nuclear Facilities (Impact on Non-Human Biota).

Ellet, W.H. and Humes, R.M. (1971) Absorbed fractions for small volumes containing photon-emitting activity. J Nucl. Med., **12**, 25-32.

Garnier-Laplace, J., Denison, F., Gilbin, R., Della-Vedova, C., Adam, C.,Simon, O., and Beaugelin,K. (2004) Bioavailability in ecological risk assessment for radionuclides. In *The scientific basis for radiological protection of the environment* F. Brechignac and B.J.Howard (Eds) IRSN Series. Paris, in press.

Goto, H E (1982) *Animal Taxonomy* Arnold, London, 60pp.

Gomez-Ros, J.M., Prohl, G. and Taranenko, V. (2004) Estimation of internal and external exposures of terrestrial reference organisms to natural radionuclides in the environment. J. Radiol. Prot. 24, A79-A88.

Gonzalez, A. J. (2003) The development of IAEA policy on the radiological protection of the environment. In: Proceedings of the 3rd International Symposium on the Protection of the Environment from Ionising Radiation, Darwin, Australia, 22-26 July 2002,IAEA, Vienna (203) 3-7.

Harley, N.H. and Pasternack, B.S. (1972) Alpha absorption measurements applied to lung dose from radon daughters. Health Physics, **23**, 771-782

Hinton, T. and Brechignac, F. (2004) *The scientific basis for radiological protection of the environment* F. Brechignac and B.J.Howard (Eds) IRSN Series. Paris, in press.

IAEA (1976) Effects of Ionising Radiation on Aquatic Organisms and Ecosystems. Technical Reports Series No. 172. IAEA, Vienna.

IAEA (1979) Methodology for assessing impacts of radioactivity on aquatic organisms. Technical Reports Series No. 190. IAEA, Vienna.

IAEA (1985) Sediment KDs and concentration factors for radionuclides in the marine environment .Technical Reports Series No. 247. IAEA, Vienna. NB Now updated

IAEA (1988) Assessing the Impact of Deep Sea Disposal of Low Level Radioactive Waste on Living Marine Resources. Technical Reports Series No. 288. IAEA, Vienna.

IAEA (1992) Effects of Ionizing Radiation on Plants and Animals at Levels Implied by Current Radiation Protection Standards. Technical Reports Series No. 332. IAEA, Vienna.

IAEA (1995) The Principles of Radioactive Waste Management IAEA Safety Series No 111 F. IAEA, Vienna.

IAEA (1999) Protection of the environment from the effects of ionizing radiation, IAEA-TECDOC-1091. IAEA, Vienna.

IAEA (2000) Working Group on “Quantities, units and compliance”…..

IAEA (2002) Ethical considerations in protecting the environment from the effects of ionising radiation, IAEA TECDOC-1270, IAEA, Vienna

IAEA (2003) 3rd International Symposium on the Protection of the Environment from Ionising Radiation (Darwin symposium). Proceedings of the 3rd International Symposium on the Protection of the Environment from Ionising Radiation, Darwin, Australia, 22-26 July 2002,IAEA, Vienna (203).

IAEA (2005) International Conference on the Protection of the Environment from the Effects of Ionizing Radiation, 6–10 October 2003, Stockholm, Sweden. IAEA, Vienna.

ICRP (1975) Reference Man: Anatomical, Physiological and Metabolic Characteristics. ICRP Publication 23.

ICRP (1989) RBE for Deterministic Effects. ICRP Publication 58. Annals of the ICRP 20, 4.

ICRP (1991) 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Annals of the ICRP 21 (1-3).

ICRP (2002) Basic Anatomical and Physiological Data for Use in Radiological Protection: Reference Values. ICRP Publication 89. Annals of the ICRP 32, 3-4.

ICRP (2003a) A Framework for Assessing the Impact of Ionising Radiation on Non-Human Species. ICRP Publication 91, Annals of the ICRP 33, 3.

ICRP (2003b) Relative Biological Effectiveness (RBE), Quality Factor (Q), and Radiation Weighting Factor (w_R). ICRP Publication 92, Annals of the ICRP 33, 4.

Kocher, D.C. and Trabalka, J.R. (2000) On the application of a radiation weighting factor for alpha particles in protection of non-human biota. Health Physics 79, 407-411.

Larsson, C-M. (2004) The FASSET Framework for assessment of environmental impact of ionising radiation in European ecosystems – an overview. J. Radiol. Prot. 24, A1-A12.

Linsley (2002) The development of the IAEA policy on the radiological protection of the environment In: *Radiological Protection of the Environment*. NEA, OECD Paris (2002) 21-27.

Loevinger, R., Japha. E.M. and Brownwell, G.L.(1956). Discrete radioisotope sources. In Hine, G.J. and Brownwell, G.L. (Eds) *Radiation Dosimetry* Academic Press,NY, 693-799.

NEA (2002) *Radiological Protection of the Environment*. NEA, OECD Paris (2002)

NCRP (1991) *Effects of Ionising Radiation on Aquatic Organisms*, NCRP Rept **109**, NCRP Bethesda, 115pp

Pentreath R.J. (1996) Effects of ionizing radiation on aquatic organisms and ecosystems. In: Protection of the Natural Environment, Stockholm, Swedish Radiation Protection Institute, 1996, pp124-135.

Pentreath R.J. (1998) Radiological protection criteria for the natural environment. Radiat Prot Dosim. 1998; 75:175-179.

Pentreath R.J. (1999) A system for radiological protection of the environment: some initial thoughts and ideas. J. Radiol. Prot. 19, 117-128.

Pentreath R.J. (2002a) Radiation protection of people and the environment: developing a common approach J. Radiol. Prot. 22, 1-12.

Pentreath R J (2002b) Concepts, methods and models to assess environmental impact. In: *Radiological Protection of the Environment*. NEA, OECD Paris (2002) 121-130.

Pentreath R.J. (2003) Evaluating the effects of ionising radiation upon the environment In: Proceedings of the 3rd International Symposium on the Protection of the Environment from Ionising Radiation, Darwin, Australia, 22-26 July 2002,IAEA, Vienna (203) 204-212.

Pentreath R J (2004) Ethics, genetics and dynamics: an emerging systematic approach to radiation protection of the environment. J. Environ. Radioactivity 74, 19-30.

Pentreath R J (2005) The Concept and Use of Reference Animals and Plants. In International Conference on the Protection of the Environment from the Effects of Ionizing Radiation, 6–10 October 2003, Stockholm, Sweden. IAEA, Vienna (in press).

Pentreath R.J. and Woodhead D.S. (1988) Towards the development of criteria for the protection of marine fauna in relation to the disposal of radioactive wastes into the sea Radiation Protection in Nuclear Energy (IAEA, Vienna) Vol.2 213-243.

Pentreath R.J. and Woodhead D.S. (2001) A system for protecting the environment from ionising radiation: selecting reference fauna and flora, and the possible dose models and environmental geometries that could be applied to them. Sci. Total Environ. 277 33-43

Real, A., Sundell-Bergman, S., Knowles, J.F., Woodhead, D.S. and Zinger, I. (2004) Effects of ionising radiation exposure on plants, fish and mammals: relevant data for environmental protection. J. Radiol. Prot. 24, A139-A155.

Robinson, C.A. (2002) Outcomes of the IAEA programme on the radiological protection of the environment. In: *Radiological Protection of the Environment*. NEA, OECD Paris (2002) 85-88.

Sauchanka, U K (1997) *The Genosphere: The Genetic System of the Biosphere*, Parthenon, NY, 134pp.

Sparrow et al. (1967) Sparrow, A.H., A.G. Underbrink and R.C. Sparrow. Chromosomes and cellular radiosensitivity. I. The relationship of D_0 to chromosome volume and complexity in seventy-nine different organisms. Radiat. Res. 32: 915-945.

Strand, P., Brown, J. E., Avila, R. and Isopje, M. (2003) ….In (IAEA Stockholm conference, in press)

Strand P., Brown J.E., Woodhead D.S. and Larsson C.-M. (2000). Delivering a system and framework for the protection of the environment from ionising radiation 10th Int. Congress IRPA 14-19 May 2000, Hiroshima, Japan, 2000; P-2a-116, 5 pp.

Strand and Oughton (2002) Radiation Protection in the 21st Century: Ethical, Philosophical and Environmental Issues. NRPA/AUN: Osteras, Norway

Suter II G.W. (1999) Developing conceptual models for complex ecological risk assessments. Hum. Ecolog. Risk Assess. 5 (2): 375-396.

Taranenko, V., Prohl, G., and Gomez-Ros, J.M. (2004) Adsorbed dose rate conversion coefficients for reference terrestrial biota for external photon and internal exposures. J. Radiol. Prot. 24, A35-A62.

Thompson P.A. , Macdonald, C.R. and Harrison, F. (2003). Recommended RBE weighting factor for the ecological assessment of alpha-emitting radionuclides. In Proceedings of the 3rd International Symposium on the Protection of the Environment from Ionising Radiation, Darwin, Australia, 22-26 July 2002,IAEA, Vienna (203) 93-100.

Trivedi A. and Gentner N.E. (2000). Ecodosimetry weighting factor (er) for non-human biota 10th Int. Congress IRPA 14-19 May 2000, Hiroshima, Japan, 2000; P-2a-114, 8pp

UNSCEAR (1986) Sources and Effects of Ionizing Radiation. United Nations Scientific Committee on the Effects of Atomic Radiation. UNSCEAR 1996 Report to the General Assembly, with Scientific Annexes. United Nations, New York.

UNSCEAR (1996) Sources and Effects of Ionizing Radiation. United Nations Scientific Committee on the Effects of Atomic Radiation. UNSCEAR 1996 Report to the General Assembly with Scientific Annex, United Nations, New York.

UNSCEAR Report (2000) Sources and Effects of Ionizing Radiation. United Nations Scientific Committee on the Effects of Atomic Radiation. UNSCEAR 2000 Report to the General Assembly with Scientific Annexes, United Nations, New York.

USDOE (2002) A graded approach for evaluating radiation doses to aquatic and terrestrial biota, DOE-STD-1132-2002, Washington, DC, USA.

Vives i Batlle, J., Jones, S.R. and Gomez-Ros, J.M. (2004) A method for calculation of dose per unit concentration values for aquatic biota. J. Radiol. Prot. 24, A13-A34.

Whicker, F.W. and Hinton, T.G. (1996) Effects of ionising radiation on terrestrial ecosystems. In Protection of the Natural Environment, Stockholm, Swedish Radiation Protection Institute, 1996, pp109-123.

Williams, C. (2004) Framework for Assessment of environmental impact (FASSET) of ionising radiation in European ecosystems. Special issue J Radiol. Prot. 24 (4A), 1-177.

Woodhead, D.S. (1970) Assessment of the radiation dose to developing fish embryos due to the accumulation of radioactivity by the egg. Radiat. Res. 43, 582-597.

Woodhead, D.S. (1979) Methods of dosimetry for aquatic organisms. In IAEA Tec Rept Ser 190, 43-96.