ICRP **DRAFT FOR CONSULTATION**

ICRP ref 4817-0544-3078

Annals of the ICRP

ICRP PUBLICATION XXX

Environmental Protection: Transfer parameters for Reference Animals and Plants

Editor

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PUBLISHED FOR
The International Commission on Radiological Protection
by
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Executive Summary

The Commission has based its approach to environmentasl protection upon using the concept of a limited set of Reference Animals and Plants as a basis for relating exposure to dose, and dose to radiation effects, for different types of animals and plants in an internally consistent manner. The results of this approach has, so far, resulted in the derivation of a set of Dose Conversion Factors for the Reference Animals and Plants, which enables dose rates to be calculated when the concentrations of radionuclides within and without these organisms have been established by direct measurement. The resultant dose rates can then be compared with evaluations of the effects of dose rates on the different Reference Animals and Plants. These data have been compiled in such a way that Derived Consideration Reference Levels can then be established, each of which constitutes a band of dose rates for each Reference Animal and Plant within which there is likely to be some chance of deleterious effects occurring in individuals of that type of animal or plant. Site specific data on Representative Organisms can then be compared with such values and used as a basis for decision making.

In many cases, however, direct measurements of the radionuclide concentrations within and without animals and plants are not available. Resort has then to be made to modelling techniques. These, in turn, require data to enable the concentrations of radionuclides within animals and plants to be estimated relative to the concentrations in the ambient soil, water, or air, as appropriate. This report therefore examines these issues, and how they may best be approached given the relative paucity of data available and the unstructured manner in which they have been acquired over many decades of observation and experimentation. An enormous data base has been brought together and used to provide the most up to date data available.

1. INTRODUCTION

1.1 Aims

(1) The Commission's radiation protection framework has recently been expanded to encompass the objective of protecting the environment, having defined its aims as being those of preventing or reducing the frequency of deleterious radiation effects to a level where they would have a negligible impact on the maintenance of biological diversity, the conservation of species, or the health and status of natural habitats, communities, and ecosystems (ICRP, 2007).

(2) In order to achieve this objective, the Commission has decided to use a system of discrete and clearly defined Reference Animals and Plants for assessing radiation effects to non-human organisms, based on the concept developed by Pentreath (1998, 1999, 2002, 2004, 2005, 2009). This approach, most recently and comprehensively elaborated in ICRP (2008), involves the use of a limited number of different types of animals and plants as a basis for systematically relating exposure to dose, and then dose (or dose rate) to different types of effect, for a number of organisms that are characteristic of different types of natural environments. Thus a Reference Animal and Plant is defined as:

> *'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 dose, and dose to effects, for that type of living organism.'*

(3) The Commission acknowledged that a mixture of animals and plants was needed to reflect the variety of global operational and regulatory environmental protection requirements, as well as the need to be pragmatic in terms of developing a flexible framework to accommodate future needs and the acquisition of new knowledge. Several criteria were therefore used to select a limited set of organism types that might be considered as typical of the terrestrial, freshwater, and marine environments. The conceptual approach based on this set of Reference Animals and Plants, together with their dosimetric models, data sets, and knowedge about the effects of radiation on these, or similar types, of animals and plants, together with an assessment of their relevance to wider environmental protection objectives, therefore forms the scientific basis underpinning the Commission's current environmental protection system.

(5) Central to the framework developed was the intended use of these Reference Animals and Plants to serve, quite literally, as points of reference against which other data sets of information could be compared (Pentreath, 2005). The Commission has already used this concept to develop numeric models to derive simplistic estimates of dose rate relative to external and internal concentrations of radionuclides for the different types of Reference Animals and Plants. It has also reviewed data on the effects of

ionising radiation on such plants and animals, and provided a set of Derived Consideration Reference Levels as a means of providing a common basis upon which decisions relating to such effects could be made (ICRP, 2008).

(6) In many cases the extent to which animals and plants are exposed to radiation can be measured directly; but for planning and other theoreticl exercises it can not, and such exposures therefore need to be estimated. And central to the derivation of such estimates of exposure is the need to model the transfer of radionuclides in a robust manner. What is missing, therefore, is a set of reference data values that could be used to estimate the extent to which such types of organismes would be exposed to external and internal exposure in relation to different release rate scenarios in the aquatic and terrestrial environments. This report is intentended to fill this gap. And a useful starting point is therefore consideration of appropriate transfer parameters (especially those used in commonly applied assessment approaches) and how such values might be used in models of environmental radionuclide transfer.

1.2 Background

(7) Although many transport processes are common to a large number of radionuclides, the quantitative importance of such processes is often dictated by the unique properties of the particular radionuclide in question. By way of introduction, therefore, a broad overview of some of the key processes influencing the environmental behaviour and fate of radionuclides is given below, and these are schematically set out in Figure 1.1.

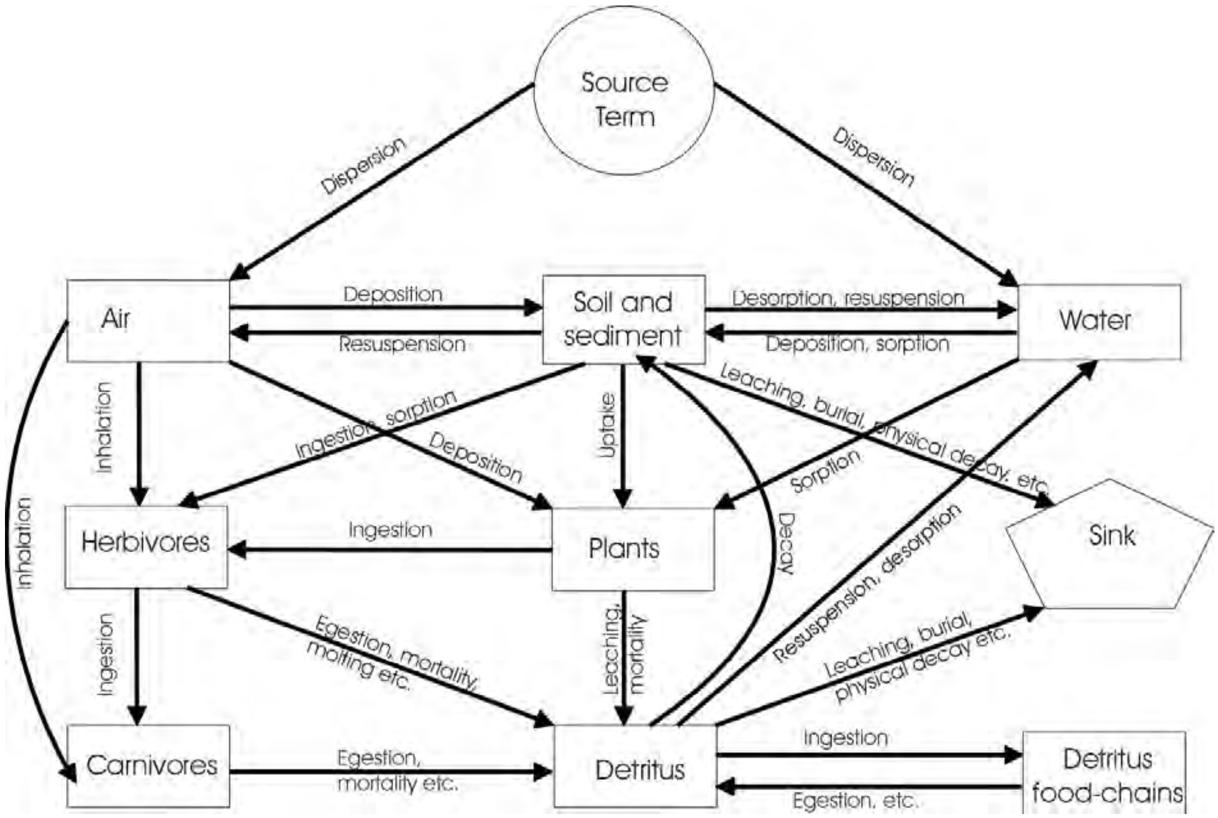


Fig. 1.1 Processes affecting radionuclide behaviour in ecosystems (based on Whicker & Shultz, 1982).

1.2.1 Physical and chemical processes

(8) Once released into air or water, radionuclides are influenced by physicochemical processes that lead to their advection and dispersion in the environment. The physical and chemical forms of the radionuclide, and the turbulence of the receiving medium, play an imortant role in relation to these initial transport mechanisms. Other processes continually cause the transfer of contamination from the air or the water column to the ground or sediment surface. These include the following:

- gravitational settling of suspended particulate material in atmospheric or aquatic releases (the physical size of the particulate is clearly an important attribute with respect to this process);
- precipitation scavenging, whereby aerosols are washed from the atmosphere by water droplets or ice crystals;
- impaction, whereby suspended particles impinge on solid objects within an air or water stream; and
- chemical sorption and exchange, dependent on both the chemical and physical form of the radionuclide and the interacting surface.

(9) Radionuclides interact with all solid materials by numerous mechanisms, including electrostatic attraction and the formation of chemical bonds. In many cases size alone simply dictates the radionuclide activity per unit mass of solid, because the surface area available for adsorption, per unit mass or volume, is greater for smaller objects. In the terrestrial environment, the interception of radionuclides by vegetation occurs by wet and dry deposition; radionuclides may also be deposited to the ground directly. Biomass per unit area clearly affects the interception fraction for all deposition categories, but other factors, including ionic form, precipitation intensity, vegetation maturity, and leaf area index are especially important when considering wet deposition (Pröhl 2008). Radionuclide concentrations on vegetation may be reduced by a number of physical processes, including wash-off by rain or irrigation, surface abrasion, and leaf bending from wind action, resuspension, tissue senescence, leaf fall, herbivore grazing, and growth and evaporation. Various empirical formulae have therefore been derived to model the retention of radionuclides onto vegetation (IAEA, 1994, 2009).

(10) Resuspension of contaminated sediment or soil is an important process in both aquatic and terrestrial systems respectively. In aquatic systems, turbulent action of water can remove surface sediments and transport them considerable distances before they are lost from the water column by sedimentation processes. Such processes are important for redistributing historically labelled sediments from open coastal sites to peripheral marine areas where long-term sediment accumulation is occurring, such as observed by Brown *et al*., (1999). Furthermore, contaminated suspended sediments will be available for entry into marine food chains, especially filter-feeding organisms.

(11) In freshwater lakes, fine particulates with relatively higher associated contaminant concentrations often settle in the deeper depositional areas, with coarser, less contaminated sediments occurring in the shallower erosional zones at the edges (Rowan *et al.*, 1995). In terrestrial systems, wind action and rain "splash" on the soil reintroduce radionuclides to the air where they can be ingested (if deposited on vegetation surfaces) or inhaled by animals. This process is also influenced by factors including the height and type of the plant canopy as well as weather (wind, rain), soil type and animal trampling.

(12) Physical, chemical, and biological processes occurring in soil and sediment lead to the further redistribution of radionuclides within these compartments. In soils, radionuclides can migrate to deeper soil depths by leaching. Rates of leaching are greatest under conditions of high rainfall and for soils containing a relatively large proportion of sand particles (Copplestone *et al*., 2001). Rainfall intensity is also a factor influencing leaching rates. Depending on the site-specific characteristics of the watershed, in poorly buffered surface waters, acidic snowmelt can also solubilise radionuclides, resulting in increased water concentrations at some times of the year. Upward and downward diffusional fluxes of radionuclides result in the redistribution of contaminants within sediments, and the process of physical disturbance and bioturbation can lead to the mixing of radionuclides in the surface layer of the sediment over short time periods. The sedimentation of particulate material will also lead to the long term removal of radionuclides from the surface layers. In the terrestrial environment, animals relocate

material both horizontally and vertically during the construction of burrows, tunnels and chambers, and the roots of plants can cause a similar effect.

(16) The geochemical phase association of radionuclides in sediments and soils can change with time (see Vidal *et al*., 1993). This affects physical transport within the ecosystem and transfer to foodwebs in numerous complex ways. In some cases, a substantial proportion of the radionuclide may become associated with residual phases, and in this way become unavailable for uptake by organisms. Such behaviour is exemplified by radiocaesium, a fraction of which can be fixed by illitic soils, the fixing process leading to a virtually irreversible binding of the radionuclide to the soil matrix (Hird *et al*., 1996). In other cases, changes in solid phase chemistry may lead to redistribution between geochemical phases (Bunker et al., 2000).

(17) Transfer within the sediment compartment can, therefore, also be influenced by factors ranging from bacterial activity to redox conditions. Fractions of many radionuclides persist in exchangeable phases, and in aquatic environments may be prone to re-dissolution processes whereby the contaminant is transferred from the sediment compartment to the water column, as reported by Hunt & Kershaw (1990). The fraction of a particular radionuclide present in exchangeable phases will therefore depend on numerous factors including, amongst others, the sediment or soil characteristics, the presence of competing ions, pH and redox conditions.

1.2.2 Biological accumulation and food chain transfer

(18) Radionuclides can enter the lowest trophic level by numerous processes. In terrestrial systems, these include direct adsorption to plant surfaces followed by foliar uptake (e.g. Zehnder *et al*., 1996), direct uptake via stomata (in the case of radionuclides that can be present in volatile forms, such as ^{14}C or tritium) and, more importantly for the majority of radionuclides, *via* root uptake (or direct absorption) from soil porewater. The transfer of many radionuclides from soil to plant is thus strongly influenced by the general physical and chemical characteristics of the soil.

(19) The transfer of radionuclides from plants (and soil) to herbivores occurs mainly by ingestion, although uptake via the water can be important for tritium. When plants are consumed they are likely to include a component of contamination associated with soil adhered to the plant surface, as well as contamination incorporated within the plant itself. Radionuclides that are organically-bound, or present in ionic form within the body of the plant, may be assimilated by the herbivore to a greater degree than those radionuclides adsorbed to soil matrices (Whicker & Shultz, 1982). An overview of the dependence of bioavailability, and subsequent transfer to ruminants, on the source of radionuclides including ingested soil is given by Beresford et al. (2000). For radionuclides that are not readily taken up by plants, soil adhesion can represent the most important route of intake (IAEA, 1994). In some instances, soil ingestion by animals may be deliberate (e.g. to obtain essential minerals), but soil can also be ingested by licking or preening of fur,

feathers or offspring (Whicker & Shultz, 1982). Predation then leads to the transfer of radionuclides to successively higher trophic levels.

(20) For aquatic organisms, food chains can be very long. Radionuclides may be either adsorbed or absorbed by bacteria, phytoplankton, and single celled organisms and subsequently ingested by zooplankton – which can consist of an enormous variety of larval, juvenile, and adult animal forms. Because of their large surface to volume ratios, very high concentrations per unit weight can be achieved (eg Fisher *et al*., 1983). All of these organisms, in turn, provide food for successively higher trophic levels. The incorporation of radionuclides into sedimentary particles can also result in their being ingested in a variety of ways. In coastal environments, and in freshwater systems, particularly in the smaller water bodies, macrophytes and macroalgae can account for a large fraction of the primary production.

(21) Marine algae do not have roots, but do have 'holdfasts' that serve to anchor them to the substrate. Radionuclides are therefore either adsorbed or absorbed directly from the water. The principal route of accumulation of radionuclides for aquatic animals is, as is the case for terrestrial animals, via ingestion, but a considerable fraction of many radionuclides can be directly absorbed from the water. This route of uptake can also be influenced by the chemistry of the ambient water, particularly in freshwaters.

(22) Absorption from the gastrointestinal tract of all higher animals depends on, amongst other factors, the physico-chemical form of the radionuclide , the composition of the source medium and the nutritional status of the animal; radionuclides may be accumulated in particular organs or body structures of the prey and consumer. For some radionuclides, absorption may be minimal resulting in the passage of the majority of the contaminant through the digestive tract.

(23) The death of plants and animals, secretions and excretions will all contribute inputs of radionuclides to the detritus reservoir in terrestrial and aquatic ecosystems. Detritus can serve as an important reservoir for radionuclides which can cycle within the compartment through linkage to detritus food chains. With time, insoluble organic material, containing radionuclides, is broken down to simpler forms by the action of detritivores and, more importantly, microbes. This leads to the release of radionuclides, to the water column or soil pore water, in soluble forms (or associated with very fine detrital material) which may become available, once more, for uptake by primary producers and other biota. In contrast, deeper soil and sediment layers may act as permanent sinks for contaminants. Some of the processes discussed above, including sedimentation in the aquatic environment, leaching, and vertical relocation of solid material in aquatic and terrestrial systems, may lead to removal of contaminants to compartments to which access by organisms is limited and biological uptake is unlikely.

(26) The kinetics of the overall system, defined by rates of transfer between compartments, will determine the temporally-varying and steady-state (if attained) distribution of radionuclides within any given ecosystem. Rates of inter-compartmental

transport, however, vary with the radionuclides, the nature and activities of the biota, and the properties of the ecosystem.

1.2.3 Radiation exposure of biota

(27) Pathways leading to radiation exposure of plants and animals, in aquatic and terrestrial ecosystems, can be usefully considered in several different ways, as follows.

(i) *Inhalation of (re)suspended contaminated particles or gaseous radionuclides.* This pathway is relevant for terrestrial animals and aquatic birds, and mammals. Respired or otherwise volatile forms of radionuclides may also contribute to the exposure of plants via gaseous exchange at the stomata.

(ii) *Contamination of fur, feathers, skin and vegetation surfaces.* This has both an external exposure component, e.g. β and γ-emitting radionuclides on or near the epidermis cause irradiation of living cells beneath and an internal exposure component as contaminants are ingested and incorporated into the body of the animal.

(iii) *Ingestion of plants and animals.* This leads to direct irradiation of the digestive tract and internal exposure if the radionuclide becomes assimilated and distributed within the animal's body.

(iv) *Direct uptake from the water column*. This may lead to both direct irradiation of, for example, the gills or respiratory system, and internal exposure if the radionuclide becomes assimilated and distributed within the animal's body.

(v) *Ingestion of contaminated water*. The same exposure categories as discussed in (iii) are relevant here. For plants the corresponding pathway relates to root uptake of water.

(vi) *External exposure.* This essentially occurs from exposure to γ-irradiation and to a much lesser extent β-irradiation, originating from radionuclides present in the organism's habitat. For microscopic organisms, irradiation from α-particles is also relevant. The configuration of the source relative to the target clearly depends on the organism's ecological characteristics and habitat. A benthic dwelling fish will, for example, be exposed to radiation from radionuclides present in the water column and deposited sediments, whereas a pelagic fish may only be exposed to the former.

(28) In the context of this report, contamination of fur, feathers and skin (exposure pathway (ii) in the above list) has not been considered explicitly in the derivation of transfer parameters. The ingestion, and direct uptake from water pathways (points (iii) and (iv) in the above list) have been considered in so far as they relate to internal body burdens of contaminants under (assumed) equilibrium conditions. Furthermore, the uptake of radionuclides and incorporation into the body of the organism through inhalation (exposure pathway (i)) and through the ingestion of water (exposure pathway (v)) may be indirectly included in the consideration of empirically derived transfer parameters such as concentration ratios (as defined later) because such approaches do not differentiate between uptake routes.

(29) Exposure arising from unassimilated contaminants in the gastrointestinal tract has not been considered further in this report. External exposures (point (vi)) have been considered in a basic way through reference to simple approaches to derive activity concentrations in (abiotic) media in cases where data for other media are available, specifically the derivation of activity concentrations in sediment if water activity concentration data are available (or *vice-versa*).

(30) The exposure pathways for some aquatic and terrestrial environments are illustrated in Figures 1.2 and 1.3 [ARE THESE DIAGS. CLEAR ENOUGH??]

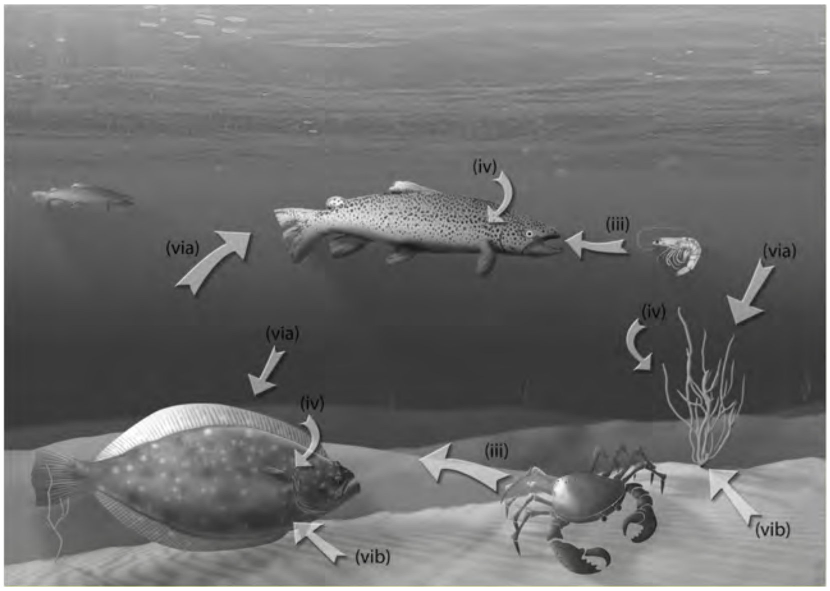


Fig. 1.2 Aquatic exposure pathways for fish and seaweed; (iii) Ingestion of lower trophic level animals (iv) Direct uptake from the water column and (vi)External exposure from (a) water column and (b) sediment.

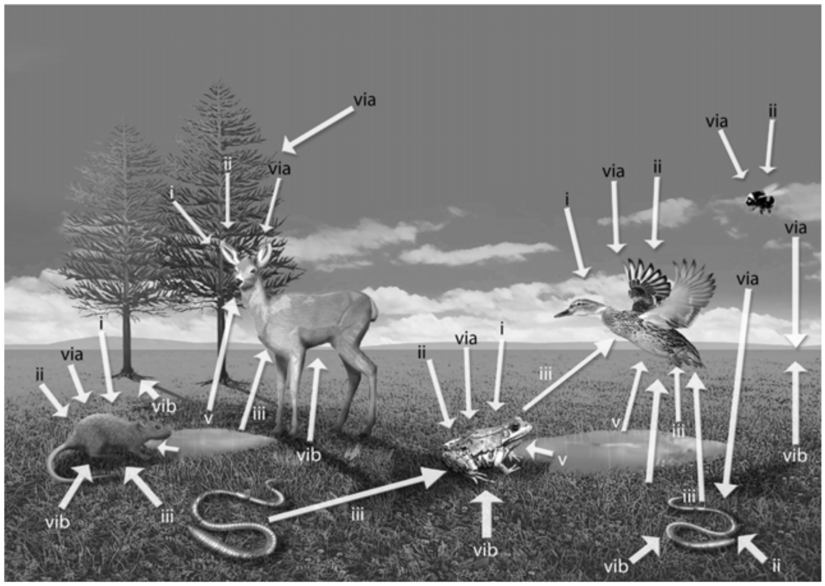


Fig. 1.3 Terrestrial exposure pathways; i) Inhalation of particles or gases ii) contamination of fur/feathers/skin iii) ingestion lower trophic levels v) drinking contaminated water vi) external exposure through a) air or b) soil

1.3 Scope

(31) This report focuses primarily on methods that allow prediction of activity concentrations to Reference Animals and Plants, from a starting point of known activity concentrations of radionuclides within the organism's habitat. Modelling the physical aspects of transfer of radionuclides in the environment is beyond the scope of this work. Extensive consideration of this theme is reported in the open literature (see for example IAEA, 1994; IAEA, 2001, IAEA, 2009). The focus of this report is therefore on the ecological transfer of radionuclides, considering the transfer parameters that are of direct relevance assuming that media concentrations (i.e. activity concentrations of radionuclides in water, sediment, soil or air) are available from either direct measurement or from appropriate model simulations.

(33) The radionuclides considered are those which Committee 5 of the ICRP have already selected and used to provide Dose Conversion Factors for Reference Animal and Plants (see Table 1.1).

Table 1.1. Elements and their radioisotopes considered in this report

Element		**Isotopes**	**Element**		**Isotopes**
Ag	Silver	Ag-110	C	Carbon	C-14
Am	Americium	Am-241	Ca	Calcium	Ca-45
Ba	Barium	Ba-140	Cd	Cadmium	Cd-109

Element		Isotopes	Element		Isotopes
Ce	Cerium	Ce-141, Ce-144	P	Phosphorus	P-32, P-33
Cf	Californium	Cf-252	Pa	Protactinium	Pa-231
Cl	Chlorine	Cl-36	Pb	Lead	Pb-210
Cm	Curium	Cm-242, Cm-243, Cm-244	Po	Polonium	Po-210
Co	Cobalt	Co-57, Co-58, Co-60	Pu	Plutonium	Pu-238, Pu-239, Pu-240, Pu-241
Cr	Chromium	Cr-51	Ra	Radium	Ra-226, Ra-228
Cs	Caesium	Cs-134, Cs-135, Cs-136, Cs-137	Ru	Ruthenium	Ru-103, Ru-106
Eu	Europium	Eu-152, Eu-154	S	Sulphur	S-35
H	Tritium	H-3	Sb	Antimony	Sb-124, Sb-125
I	Iodine	I-125, I-129, I-131, I-132, , I-133	Se	Selenium	Se-75, Se-79
Ir	Iridium	Ir-192	Sr	Strontium	Sr-89, Sr-90
K	Potassium	K-40	Tc	Technetium	Tc-99
La	Lanthanum	La-140	Te	Tellurium	Te-129m, Te-132
Mn	Mangenese	Mn-54	Th	Thorium	Th-227, Th-228, Th-230, Th-231, Th-232, Th-234
Nb	Niobium	Nb-94, Nb-95	U	Uranium	U-234, U-235, U-238
Ni	Nickel	Ni-59, Ni-65	Zn	Zinc	Zn-65
Np	Neptunium	Np-237	Zr	Zirconium	Zr-95

(34) The Commission's recommendations apply to all exposure situations that, in a human radiation protection context, are as follows.

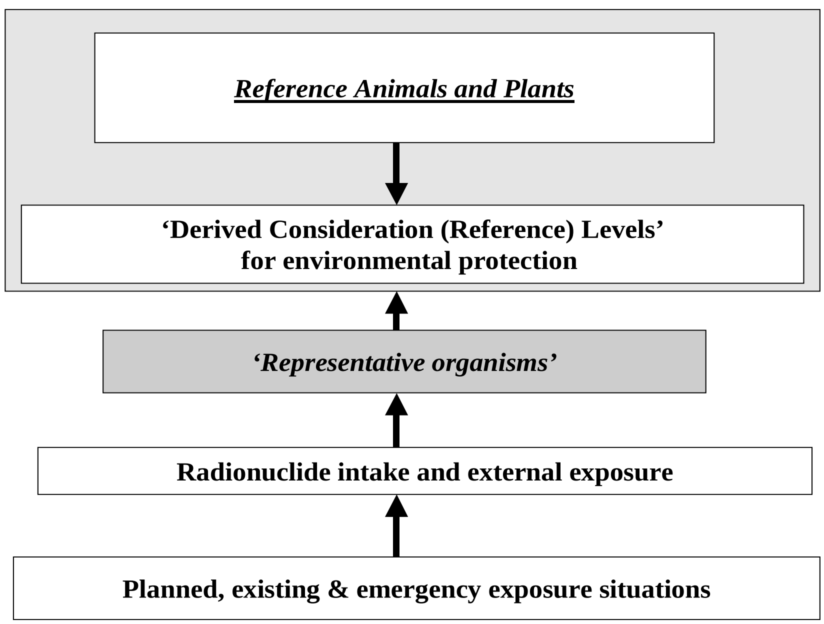
- Planned exposure situations - everyday situations involving planned operations, including decommissioning of nuclear facilities, disposal of radioactive waste and rehabilitation of radioactively contaminated land and other situations.
- Existing exposure situations - exposure situations that already exist when a decision on control has to be taken, including natural background radiation and residues from past practices.
- Emergency exposure situations - unexpected situations that occur during the operation of a practice, requiring urgent action.

(35) For the sake of simplicity, and given the intention to be as broadly applicable as possible, a decision was made to focus on approaches that are appropriate under equilibrium or quasi-equilibrium conditions. These are essentially the conditions that might be expected to exist where the environment is receiving continuous inputs of radionuclides from facilities operating under a regulated discharge regime, or at historically contaminated sites where inputs have ceased. The parameter values provided below should therefore be primarily applicable to planned and existing exposure situations that are in equilibrium and might be considered less suitable for evolving emergency exposure situations.

(36) Finally, it is important to appreciate the difference between Reference Animals and Plants and *Representative Organisms* (See Figure 1.4). Any specific evaluation of the

radiation exposure of animals and plants will normally be carried out for specific reasons, in order to 'comply' or otherwise satisfy specific national or international environmental protection requirements. In many cases the representative organisms chosen for this purpose may be the same as, or very similar to, the Reference Animals and Plants; but in some cases they may be very different. The values compiled in this report are intended to be a dataset that helps to explore the relationships between activity concentrations in Reference Animals and Plants and their habitats. These data should not therefore be considered as surrogate values to be used instead of specific data; for example measured activity concentrations or transfer parameters for specific plants and animals within a studied ecosystem. They are, instead, intended to be *reference* against which other values may be compared, or default values when other data are lacking.

Figure 1.4. Relationships of various points of reference for protection of the environment (from ICRP, 108)



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2. Overview of Approaches Used to Model Transfer of Radionuclides in the Environment

(37) A number of approaches have been proposed, in the context of conducting environmental impact assessments, to estimate transfer of radionuclides to biota when measured activity concentrations are not available. These range from tabulated transfer parameters (e.g. Brown et al. 2003), through to integrated approaches that employ spreadsheets incorporating transfer data (e.g. Copplestone et al. 2001; 2003; Brown et al. 2008) and more highly parameterised food-chain models (Brown et al., 2004; Thoman 1981; USDOE 2004). Details and source references for various approaches that have been used to estimate radionuclide transfer can be found within IAEA (in press a).

2.1 Concentration ratios

(38) The fresh weight (fw) activity concentrations of radionuclides in biota are predicted from media activity concentrations using equilibrium concentration ratios (CRs) for at least some organisms by all of the exisiting approaches. The definitions of CR are:

(39) For Terrestrial biota

$$CR = \frac{Activity\ concentration\ in\ biota\ whole\ body\ (Bq\ kg^{-1}\ \ fresh\ weight)}{Activity\ concentration\ in\ soil\ (Bq\ kg^{-1}\ \ dry\ weight\ (dw))}$$

(40) For some approaches, exceptions exist for chronic atmospheric releases of ^{3}H, $^{32,33}P$, ^{35}S and ^{14}C where:

$$CR = \frac{Activity\ concentration\ in\ biota\ whole\ body\ (Bq\ kg^{-1}\ \ fresh\ weight)}{Activity\ concentration\ in\ air\ (Bq\ m^{-3}\ )}$$

(41) For Aquatic biota

$$CR = \frac{Activity\ concentration\ in\ biota\ whole\ body\ (Bq\ kg^{-1}\ \ fresh\ weight)}{Activity\ \ concentration\ in\ \ filtered\ water\ (Bq\ l^{-1}\ )}$$

(39) The CR approach is simple, combining various transfer pathways (e.g. in the case of terrestrial animals, radionuclide intakes via food, soil ingestion, inhalation and drinking water) and is based on empirical data. Determination and application of CR values is, however, subject to factors such as sampling methodology, the degree of equilibrium between biota and media and environmental parameters such as water chemistry and soil type (see Beresford et al. 2004; Yankovich et al., 2010), although the alternative approaches discussed below are also subject to many of these factors. With

respect to water chemistry, some models propose simple relationships between water stable element concentrations in water and radionuclide transfer to biota (e.g. Smith et al., 2006; IAEA in press a, Yankovich et al., 2010).

(40) The most comprehensive recent review of concentration ratios, based on the concept of generic wildlife groups coined 'reference organisms', was conducted as part of the ERICA project (Larsson, 2008). In this respect, Beresford et al. (2008a) and Hosseini et al. (2008) presented a complete set of CR values for more than 1100 radionuclide-organism combinations in terrestrial, freshwater and marine ecosystems. By preference, values of CR were derived from reviews of original publications. Some CR values were derived using stable element data. A few CR values based upon previous reviews were adopted (rather than being derived from original source data). In terrestrial ecosystems, these data were generally associated with studies of heavy metal pollution, however only data for control ('uncontaminated') sites were used as an input into the CR database as there is evidence of non-linear relationships between concentrations in organisms and media at contaminated sites. A few CR values based upon previous reviews were adopted (rather than being derived from original source data).

2.2 Alternative approaches used in quantifying radionuclide transfer

(41) Some models use alternative approaches to determine the transfer of radionuclides to birds and mammals. To provide transfer parameters when there is a lack of available CR values, USDOE (2002) suggest a kinetic–allometric approach to predicting radionuclide concentrations in animals. Allometry, or "biological scaling", is the consideration of the effect of size on biological variables.

(42) The dependence of a biological variable, Y, on a body mass, M, is typically characterised by allometric equations of the form:

$$Y = aM^{b}$$

where *a* and *b* are constants.

(43) There are a number of publications summarising allometric relationships for a wide range of biological variables (e.g. Hoppeler & Weibel, 2005). Many biological phenomena appear to scale as quarter powers of the mass (Brown et al 2000, West et al 2000). For example: metabolic rates scale as $M^{0.75}$; rates of cellular metabolism and maximal population growth rate, as $M^{-0.25}$; lifespan and embryonic growth and development, as $M^{0.25}$; cross-sectional areas of mammalian aortas and tree trunks, as $M^{0.75}$. Allometric relationships for the biological half-life and dietary transfer coefficient for some radionuclides have been derived by a number of authors, and most of these cefficients also scale to quartile values (see Beresford et al. 2004).

(44) MacDonald (1996) derived allometric relationships describing the transfer of caesium and iodine from feed to the tissues of wild mammalian and bird species which scaled to *circa* - 0.7. Since then, the USDOE (2002) has provided biological half-lives for 15 elements which can be used, together with allometric relationships, to derive daily dietary intake, water intake and inhalation rates, and parameters describing soil/sediment ingestion and gastrointestinal absorption to estimate whole-body activity concentrations

for terrestrial and riparian mammals and birds. In recent inter-comparison exercises, allometric models have been demonstrated to give results comparable to CR value parameterised approaches (IAEA, in press a). Application of allometric models to marine mammals was proposed by Brown et al. (2005) and to marine species generally by Vives I Batlle et al. (2007) .The approach has been used in a limited number of cases to derive equilibrium CR values for some radionuclides (Hosseini et al., 2008).

(45) Using algebraic derivations, and the allometric relationships for radionuclide biological half-lives or transfer coefficients, and dietary dry matter intake, Beresford et al. (2004) proposed that, for many radionuclides, the biota-to-dietary concentration ratio would be constant across species. This has been used subsequently to provide some transfer parameters for assessment models (Beresford et al. 2008a).

(46) Some models have attempted to provide a complete set of transfer parameters for the radionuclides-organisms they consider. As discussed above within USDOE (2002), this was achieved by the development of allometric approaches. Data were only available for approximately 40 % of the >1100 CR values required for the default transfer database of the ERICA Tool (Brown et al., 2008). Consequently, a set of options were established (Beresford et al. 2008a) which were an evolution of the approach initially proposed by Copplestone et al. (2003). The options were as follows.

- Use an available CR value for an organism of similar taxonomy within a given ecosystem for the radionuclide under assessment (preferred option);
- Use an available CR value for a similar reference organism (preferred option);
- Use an available CR value for the given reference organism for an element of similar biogeochemistry;
- Use an available CR value for biogeochemically similar elements for organisms of similar taxonomy;
- Use an available CR value for biogeochemically similar elements available for a similar reference organism;
- Use allometric relationships, or other modelling approaches, to derive appropriate CRs;
- Assume the highest available CR (least preferred option);
- Use CR for same organism in a different ecosystem (least preferred option).

(47) Further details concerning the application of these options are provided in Beresford et al. (2008a) and Hosseini et al. (2008), for terrestrial and aquatic ecosystems respectively.

(48) A number of dynamic models have been proposed for use in assessing exposure of terrestrial (e.g. Avila et al. 2004), freshwater (see IAEA (in press a) for a number of examples) and marine (e.g. Vives i Batlle et al. 2007) biota. Some of these are adaptations of models originally proposed to predict radionuclide contamination of human foodstuffs. For dynamic or biokinetic models, transfer from the environment to plants and animals is modelled as a time dependent function that can take into account

variations in environmental activity concentrations with time. Typically, such models are characterised by discrete compartments representing particular abiotic and biotic components within the environment and with transfer from or between compartments being described by rate constants, e.g. rates characterising biological half-lives of uptake and elimination.

(49) For some radionuclide-organism combinations, comparison of the available models, presented above as concentration ratios and alternative approaches, has demonstrated significant (orders of magnitude) variation in biota activity concentration predictions (IAEA in press a).

(50) In addition to parameterisation for the purpose of estimating activity concentrations in biota, for aquatic ecosystems most approaches also use distribution coefficients (K_d) to describe the relative activity concentrations in sediment versus water. The K_d value is required to estimate sediment concentrations from input water concentrations or vice-versa if data for either are lacking. Whilst biota activity concentrations are determined in aquatic ecosystems from those in water, sediment concentrations are required to estimate external dose rates. Although the application of distribution coefficients forms an integral part of many environmental impact assessments, the concept and application of such models is not unique to Reference Animals and Plants. The collation and derivation of statistical information and representative values for sediment distribution coefficients has been the subject of comprehensive reviews elsewhere (IAEA, 1994, IAEA, 2004 and IAEA, 2010) and the reader is referred to these compilations for further details.

2.3 Selection of approach to provide baseline transfer parameters for the ICRP Reference Animal and Plants

(51) The ICRP Reference Animal and Plants report (ICRP, 2008) considers radionuclides for 40 elements with 12 Reference Animal and Plants and their associated life-stages. A number of datasets are available which can be used to provide baseline information for transfer parameters for the Reference Animal and Plants framework.

(52) The CR value databases as developed within the ERICA project and compiled for the ERICA Tool (Brown et al. 2008) consider 'reference organisms' which encompass all of the adult stages and limited other life-stages of the ICRP's Reference Animal and Plants, and 31 of the 40 elements (Table 3.1). This represents a broader coverage of the requirements of the ICRP framework than other approaches/databases. With some exceptions, the ERICA Tool has given reasonable predictions when applied at sites for which biota activity concentration data were available (Beresford et al. 2007; 2008b; submitted; Wood et al. 2008; IAEA, in press a; Yankovich et al 2010) and generally compares favourably against other approaches (Beresford et al 2008c; IAEA, in press a). The ERICA transfer databases incorporated all sources used in some previous reviews (including Copplestone et al. 2001; Brown et al. 2003) and some source references used by USDOE (2002).

(53) From a pragmatic perspective, CR values are simple to apply and represent the most comprehensive databases available and the methodology is analogous to approaches used for some aspects of human radiological assessments (e.g IAEA, 2010). At the moment the ICRP considers the CR approach to provide a good starting point from which to further develop its framework. Consideration of the applicability of and robustness of underlying datasets for CRs also allows the relationship between activity concentrations in Reference Animals and Plants and their habitats to be examined for Reference Animals and Plants.

(54) In selecting this approach there are, however, some notable caveats. The application of CR values represents an amalgamation and simplification of many transfer processes and is not appropriate to short-term assessments of dynamic situations such as those following accidents. The use of CR values can nevertheless provide a ‘snapshot’ of a dynamic situation to allow different options to be evaluated on the likely radiation exposure under different scenarios. Furthermore, an emergency situation eventually, without a sharp borderline in time, transforms into an existing situation, where the use of equilibrium transfer models may be more robustly justified. The application of equilibrium transfer models should be more than adequate when hypothetical accidents need to be considered and the consequences associated with selecting various options are being compared (e.g. in conducting assessments potential impacts of accidents at new facilities).

(55) The implementation of a CR methodology is not consistent with the ICRP approach used by the Commission system for calculating human exposures from radiation. For humans, emphasis has been placed on compiling data for physiology, form and structure of the body, elemental composition of the organs etc. based originally on Reference Man (ICRP, 1975). The calculations of dose coefficients for specified radionuclides ($Sv\ Bq^{-1}$) use defined biokinetic and dosimetric models. The biokinetic models are used to describe the entry of various chemical forms of radionuclides into the body and their distribution and retention within different organs and parts of the body after entering the blood (as exemplified by ICRP, 1996). For the initial work on transfer of radionuclides in the context of environmental radiological protection, it was considered impracticable to adopt a similar approach, and the use of CRs is sufficient for the purpose of examining the relationship beween activity concentrations in Reference Animals and Plants and their habitats. The underpinning data sets that have been elaborated for humans in relation to anatomy, physiology and elemental composition (e.g. ICRP 1975, 2002) would be difficult to obtain rapidly for Reference Animals and Plants although some information does exist for numerous wildlife groups (see e.g. Bowen, 1979). Furthermore, the development of biokinetic models for each Reference Animal and Plant, with concomitant experimental studies to derive the requisite parameters, is not justified without a preliminary examination of transfer approaches and applicability with regards to the Commission’s objectives concerning environmental protection from ionising radiation.

(56) Many radionuclides will be deposited and retained internally within organisms, sometimes over very long time scales. It has been assumed for humans, by way of example, that plutonium deposited in liver has a biological half-life of 20 years and

plutonium deposited in bone has a biological half-life of 50 years (ICRP, 1988). Using such protracted retention times in biokinetic models essentially results in no equilibrium being attained during the lifetime of the (human) individual, and for a constant ingestion rate of this actinide the body burden simply increases with time. A similar situation might be expected for some of the Reference Animals that are vertebrates (Rat, Deer, Duck, Frog and Flatfish and Trout), even allowing for the fact that the metabolic rates and the life expectancy for these groups are distinctly different

(57) Derivations of baseline CR data pertaining to Reference Animals and Plants are described below. For K_d values, the recent comprehensive reviews by IAEA for marine (IAEA 2004) and freshwater ecosystems (IAEA, 2010) respectively are recommended for use although the latter does not include all radionuclides that have been considered in this report.

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3. DERIVATION OF CONCENTRATION RATIOS FOR REFERENCE ANIMALS AND PLANTS

3.1 Collation of data

(58) An online database entitled the 'Wildlife transfer database' (web address: [http://www.wildlifetransferdatabase.org]) was specifically developed for the purpose of providing parameter values for use in environmental radiological impact assessments to estimate the transfer of radioactivity to non-human biota (i.e. 'wildlife'). The database was initiated to aid: (i) the derivation of transfer parameter values for the International Commission on Radiological Protections (ICRP) list of *Reference Animals and Plants* and (ii) the International Atomic Energy Agency (IAEA) in the production of a handbook on non-human biota transfer parameters (to be published as an IAEA Technical Report Series) which will be of value for application to representative organisms. In this way, it was hoped that both organisations would draw upon the same primary source data in the process of deriving transfer parameters. The database was compiled in collaboration with the International Union of Radioecologists (IUR) and it is hoped that this will provide a future and evolving source of up-to-date information to those conducting assessments and developing/maintaining models.

(59) The wildlife transfer database incorporates the ERICA transfer databases (Beresford et al., 2008; Hosseini et al., 2008) discussed in the previous section, but also significant data contributed by numerous organisations and individuals elicited via direct contact and various bespoke meetings under the auspices of the IAEA (in prep). All data were quality controlled before being accepted as suitable data for the derivation of baseline values. Furthermore, the intention is that the database will remain 'live' so that new data can be added for the ICRP Reference Animals and Plants which can be used in future revisions of the CR values.

3.2 Categorisation of Reference Animal and Plants

(60) The wildlife transfer database is structured in terms of broad habitats and wildlife groups which, although not strictly based on accepted taxonomical classifications, have been selected to be representative of the major types of organisms. Such wildlife groups have also been designed to be generally compatible with the broad categories defined within the ERICA assessment methodology (Larsson, 2008) with some additional designations for the sake of expanding the collation to represent potential organisms of interest worldwide.

(61) As discussed above, the Commission has generalised their Reference Animal and Plants to the taxonomic level of Family and consequently this level of taxonomic classification has been used to identify representative species from which transfer parameters can be determined in the available scientific literature as documented in this report. The Family level specified by the Commission is presented in Table 3.1 for each Reference Animal and Plant, along with the ecosystem in which that Reference Animal

and Plant, or its respective life stage, may be found. A full description of the individual Reference Animals and Plants is given in ICRP (2008).

Table 3.1The ICRP Reference Animal and Plants and their life-stages and specified taxonomic Family as identified by ICRP (2008). The table also list species for which data are available within the Family groups.

Reference Animal and Plant	*Ecosystem*	*Family*	*Species for which data are available*
Deer	Terrestrial	Cervidae	*Alces alces; Capreolus capreolus; Cervus elaphus; Odocoileus hemionus; O. virginiannus*
Calf	Terrestrial		
Adult Deer	Terrestrial		
Rat	Terrestrial	Muridae	*Apodemus flavicollis; A. sylvaticus; Hydromys chrysogaster; Peromyscus leucopus; P. maniculatus; Rattus rattus*
Duck	Terrestrial, Freshwater	Anatidae	*Anas crecca; A. penelope; A. Platyrhynchos; Anseres spp.; Cygnus olor; Mergus merganser; Somateria mollissima*
Duck egg	Terrestrial		
Adult duck	Terrestrial, Freshwater		
Frog	Terrestrial, Freshwater	Ranidae	*Rana arvalis; R. catesbeiana; R. clamitans; R. esculenta; R. palustris; R. pipiens; R. temporia; R. terrestris*
Frog egg	Freshwater		
Frog mass of spawn	Freshwater		
Tadpole	Freshwater		
Adult frog	Terrestrial, Freshwater		
Trout	Freshwater, Marine	Salmonidae	*Coregonus albula; C. clupeaformis; C. hoyi; C. lavaretus; Oncorhynchus kisutch; O. mykiss; O. tschawytscha; Prosopium cylindraceum; Salmo trutta; Salvelinus alpinus; S. fontinalis; S. fontinalis; S. namaycush; S. siscowet; Stenodus leucichthys*
Trout egg	Freshwater		
Adult trout	Freshwater		
Flatfish	Marine	Pleuronectidae	*Glyptocephalus stelleri; Hippoglossoides dubius; Hippoglossus hippoglossus; Kareius bicoloratus; Limanda herzensteini; L. schlencki; L. yolohamae; Microstomus ache; Paralichthys olivaceus; Pleuronectes flesus; P. platessa; Reinhardtius hippoglossoides; Synaptura marginata*
Flatfish egg	Marine		
Adult flatfish	Marine		
Bee	Terrestrial	Apidea	
Bee colony	Terrestrial		
Adult bee	Terrestrial		
Crab	Marine	Cancridae	*Cancer pagarus*
Crab larvae	Marine		
Crab egg mass	Marine		
Adult crab	Marine		
Earthworm	Terrestrial	Lumbricidae	*Aportectodea caliginosa; Dendrobaena octaedra; Eisenia andrei; E. foetida; E. nordenskioldi; Lumbricus terrestris; L. rubellus*
Earthworm egg	Terrestrial		
Adult earthworm	Terrestrial		
Pine Tree	Terrestrial	Pinaceae	*Larix decidua; L. occidentalis; Picea abies; Pinus banksiana; P. contorta; P. strobus; P. taeda*
Wild Grass	Terrestrial, Freshwater	Poaceae	*Agropyron cristatum*; *A. dasystachyum*; *Agrostis stolonifera*; *Alopecurus spp.*; *Avena pubescens*; *Bromus tectorum*; *Calamagrostis rubescens*; *Cynodon*
Meristem	Freshwater, Terrestrial		

Grass spike	Freshwater, Terrestrial		*nlemfuensis*; *Deschampsia alpine*; *D. caespitosa*; *D. flexuosa*; *Echinochloa colonum*; *E. polystachya*; *Erianthus arundinaceum*; *Festuca rubra*; *Hemarthria altissima*; *Hordeum jubatum*; *Lolium perenne*; *Molinia caerulea*; *Nardus stricta*; *Pennisetum purpureum*; *Phleum pratense*; *Puccinellia nuttalliana*; *Spartina densiflora*; *Sporobulus airoides* ; *Trisetum spicatum*; *Typha latifolia*
Brown Seaweed	Marine	Fucaceae	*Fucus disticus*; *F. evanescenes*; *F. inflatus*; *F. serratus*; *F. spiralis*; *F. vesiculosus*

(62) The relationship between the wildlife groups and the corresponding Reference Animals and Plants is shown in Table 3.2. Furthermore, the database allows the information being entered to be described in terms of whether it is for the adult form or the various lifestages of Reference Animals and Plants.

Table 3.2. Wildlife groups (broad group) and the corresponding Reference Animal and Plants (identified in parenthesis against the Wildlife group into which they fit).

Freshwater	Marine	Terrestrial
Amphibian (*Frog*)	Fish *Fish – Benthic Feeding (*Flat fish*)	Amphibian (*Frog*)
		Bird (*Duck*)
Bird (*Duck*)	Crustacean *Crustacean – Large (*Crab*)	Bird egg (*Duck egg*)
		Flying insect (*Bee*)
Fish *Fish – piscivorous (*Salmonid*)	Macroalgae (*Brown seaweed*)	Grasses and herbs (*Wild grass*)
		Mammal (*Rat, Deer*)
Vascular Plant (*Wild Grass*)	Fish (*Salmonid*) *Fish – piscivorous (*Salmonid*)	Earthworm (*Earthworm*)
		Tree (*Pine tree*)

* Wildlife group "Subcategory"

(63) Entered data can also be grouped by organ/tissue type for at least some of the wildlife groups. Although the focus of this collation and review has been placed on the derivation of whole-body concentration ratios, the organisation of the database allows relevant data on transfer to various organs/body parts to be identified and extracted for preliminary consideration. The issue of heterogeneous distributions of radionuclides within the bodies of animals in terms of implications for exposure has been recognised by the Commission (ICRP, 2008).

3.3 Data manipulation

(64) The principal objective of the data collation and manipulation was to derive baseline CR values that were based, as far as possible, upon summarised statistical information for Reference Animals and Plants derived from empirical datasets. In cases where this was not possible, the aim was to provide surrogate values, the selection of which could be reasonably justified from an understanding of the transfer processes involved, and in all cases to document clearly the provenance of the values describing any derivations performed.

3.3.1 Deriving summaried statistical information for CRs from empirical data sets

(65) The collated data encompassed a wide range of radioelement-organism combinations, often comprised of different studies with variable sample sizes. Empirical data were not always available in an internally compatible format, and therefore a number of data manipulations were applied. The main conversions performed on the data (preferentially using information supplied in the source, or associated, references) were:

(i) where data were presented in the original publication as an activity per unit ash weight or dry weight, a conversion was required to transform the data to activity per unit fresh weight. The conversion factors used are described eslewhere (Beresford et al., 2008; Hosseini et al., 2008);

(ii) where data were presented in the original publication as an activity concentration for a specific body part or organ, conversion factors were required to transform the data to activity concentration in the whole body. This data manipulation required data on total organism live-weight comprised by given tissues and distribution of radionuclides within different tissues. The conversion factors used are described eslewhere (Beresford et al., 2008; Hosseini et al., 2008; Yankovich et al. in press);

(iii) for terrestrial organisms, if transfer data were related to radionuclide deposition (i.e. Bq m^{-2} soil rather than Bq kg^{-1}), a soil bulk density of 1400 kg m^{-3} and a sampling depth of 10 cm were assumed if source publications lacked the required information to convert soil activities (Beresford et al., 2008).

(66) There are some uncertainties associated with the database resulting from additional compromises that had to be made. For instance, some CR values for aquatic systems may have been estimated using unfiltered water. Similarly, soil sampling depths were often not given. Furthermore, whilst the CR is assumed to represent an equilibrium transfer value it is likely that some, if not many, of the values within the databases were not derived under equilibrium conditions. To mitigate this problem to some degree, data for terrestrial ecosystems that were collected during either the period of above ground nuclear weapons testing fallout, assumed to be before 1970, or the year of the Chernobyl accident (1986), were not used to derive transfer parameter values for radionuclides of

Cs, Pu, Sr and Am to avoid effects of surface contamination of vegetation. A full discussion of these issues when deriving CR values for wild species is given by Beresford et al. (2004).

(67) A lack of information in source publications again resulted in some assumptions and compromises sometimes having to be made to derive weighted mean values. These were: (i) a sample number of one was assumed if information was not given; (ii) if a measure of error (e.g. standard deviation of standard error) was reported and it was apparent that multiple samples had been collected but no sample number was given, it was assumed that the sample number was three; (iii) if a measure of error was reported for either only media or biota activity concentrations, this was carried through (proportionally) to give a standard deviation estimate on the calculated CR values; (iv) a sample number of two was assumed if a minimum and maximum were reported with no details of sample number. For organism-radionuclide combinations for which there were many reported values, references which did not give all the required information were rejected.

(68) CR values from the database for Reference Animal and Plants have been extracted and compiled (see section 3.1). A combined weighted mean (M) and an overall standard deviation value for CR values from the empirical dataset was produced using the following approach as described by Hosseini et al. (2008). It was assumed that the combined variance is comprised of two parts; one describing the variations *within* studies (V_W) and the other expressing the variations *between* studies (V_B). Hence, the total/combined variance can be defined as below (Eq. 1.):

$$\boldsymbol{V_{combined}} = \frac{\boldsymbol{V_w} + \boldsymbol{V_B}}{\boldsymbol{N}-1} = \frac{(\sum_i (\boldsymbol{n_i}-1)\boldsymbol{E_i}) + (\sum_i \boldsymbol{n_i CR_i^2} - \boldsymbol{NM^2})}{\boldsymbol{N}-1} \quad (1)$$

$$\boldsymbol{N} = \sum_i \boldsymbol{n_i} \qquad \text{and} \qquad \boldsymbol{M} = \frac{\sum_i \boldsymbol{n_i CR_i}}{\boldsymbol{N}}$$

where:
n_i is the number of observations in study i and CR_i is the mean CR value associated with that study. E_i stands for the reported measure of error in study i, this can be variance ($E_i = V_i$), standard deviation ($E_i = (Sd)_i^2$) or standard error ($E_i = n_i(Se)_i^2$). N is the total number of observations in all studies and M defines the weighted mean composed of means associated with all the considered studies.

(69) The geometric mean, M_G, and geometric standard deviation, σ_G, w were estimated using the following equations:

$$M_G = \exp\left(-0.5\ln\left(\frac{\sigma_A^2 + M_A^2}{M_A^4}\right)\right) \quad (2)$$

Where

σ_A = the standard deviation of the concentration ratio;

m_A = the mean concentration ratio.

$$\sigma_G = \exp\left(\sqrt{\ln\left(\frac{\sigma_A^2 + M_A^2}{M_A^2}\right)}\right) \qquad (3)$$

Where

σ_A = the standard deviation of the concentration ratio;

m_A = the mean concentration ratio.

(70) Both the geometric and arthimetic means and standard deviations are presented in this report. When data sets are large, and it is possible to test statistically that the data are log-normally distributed, the geometric mean provides the most suitable indicator of central tendency and, in conjunction with the geomteric standard deviation, most appropriately characterises the dataset. In cases where few measurements are available, where the data do not lend themselves to robust statistical analyses, it is more prudent to represent the data using the arithmetic mean and standard deviation, because such values tend to provide a somewhat more conservative quantification of transfer.

(71) Summarised statistical information derived from empirical data of CR values specifically for species falling within the ICRP definitions of Reference Animals and Plants are presented in Annex A of this report.

(72) For the derivation of ^{3}H and ^{14}C CRs in terrestrial ecosystems, values were derived using a specific activity approach (rather than data review) as described by Galeriu et al. (2003). The approach used for ^{3}H considered both tritiated water and organically bound tritium. Similarly, a specific activity approach has been taken to estimate CRs for biota inhabiting aquatic ecosystems (e.g., Yankovich et al., 2007).

3.3.2 Deriving surrogate CR values via data gap filling methods

(73) Because the aim of this work was to provide CR values for all element Reference Animal and Plant combinations, a set of rules to facilitate the derivation of surrogate values in other cases where limited or no empirical data were available was considered. This also provided a systematic process for documenting how baseline values have been derived in all cases when data were unavailable.

(74) The options used were:

- Use an available CR value for the generic wildlife group ‘Subcategory” within which the Reference Animal and Plant fits for the radionuclide under assessment (Table 3.2);

- Use an available CR value for the generic wildlife group 'Broad group" within which the Reference Animal and Plant fits for the radionuclide under assessment (Table 3.2);
- In the case of the marine ecosystem use CR data from the estuarine ecosystem;
- Use an available CR value for the given Reference Animal and Plant for an element of similar biogeochemistry;
- Use an available CR value for biogeochemically similar elements for the generic wildlife group within which the Reference Animal and Plant fits;
- Use allometric relationships, or other modelling approaches, to derive appropriate CRs;
- Expert judgement of CR data within that ecosystem for the radionuclide under assessment which might include, for example, the use of data from general reviews on this subject. In all cases the reasoning underpinning the selection of values is transparently recorded.

(75) Although the first and second methods listed above might be considered the preferred options in most cases, this may not always be true. For example, very few data might be available for the first option, but many data might be available for subsequent options. Thus an element of subjective judgement was sometimes required in deriving some values, and this has been documented.

(76) Summarised statistical information derived from empirical data specifically for CR values for generic wildlife groups, that encompass Reference Animals and Plants, are reported elsewhere (IAEA, in prep). Surrogate CR data with a detailed description of how values have been derived are presented in Annex B.

3.3.3 Concentration ratio - Baseline values

(77) The summary statistics and derived values presented in Annexes A and B have been used in the derivation of baseline CR values for Reference Animals and Plants (see Chapter 4). Where empirical data exist (for both Reference Animals and Plants and for the generic wild-life groups to which they belong) the baseline value has been based on the geometric mean. The underlying transfer datasets are generally believed, or can be explicitly shown, to follow log-normal distributions. Because the geometric mean provides the most suitable measure of central tendency when data follow a lognormal distribution, it was considered appropriate to assign the baseline value to this statistical parameter. In cases where no empirical data exist, the derived values presented in Annex B have been used to provide a baseline CR value.

(78) No attempt has currently been made to derive CR values for the various life stages of Reference Animals and Plants, for resasons discussed in the next chapter of this report.

3.4 References

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4. CONCENTRATION RATIOS FOR REFERENCE ANIMALS AND PLANTS

4.1 Applicability of CRs for Reference Animals and Plants

(79) A key aim of this report is to explore how internal exposures of Reference Animals and Plants are related to the radionuclide content of the surrounding environment. The assumption in using Concentration Ratios is that these two quantities are correlated but, as noted in Chapter 2, this may not be valid in some cases. At a generic level, the existence of "steady-state" or equilibrium conditions is a crucial consideration in establishing the validity of applying CRs for any given case. In many instances the concentrations of radionuclides in environmental media may fluctuate. Furthermore, equilibrium between the different Reference Animals and Plants and environmental media is dependent upon a number of factors (e.g. biological half-life, lifespan etc.) which are radionuclide and Reference Animal and Plant specific. This is discussed for each Reference Animal and Plant in more detail below.

(80) Notwithstanding these limitations, CR values have traditionally been widely applied, as noted in Chapter 3, and have either been derived from field data or from laboratory experiments. Water and food provide a route of contamination from environmental media to animals throughout their life time. Laboratory experiments almost never reproduce these conditions, and only serve to inform with regard to the relevant importance of different pathways, chemical form, and so on. Field-data are also dependent on factors such as biological half-lives, physical half-lives, ecological characteristics (e.g. water chemistry) and source term.

(81) For some animals, many elements (and their radioisotopes) are under some form of homeostatic control that regulates their concentrations internally, irrespective of fluctuations in their intake (via food or water) and thus irrespective of their ambient levels within a reasonably tolerable range. For example, stable potassium and ^{40}K are controlled homeostatically in the body of higher animals, and the concentration of potassium in fish and other animals is effectively constant (e.g. Koulikov and Meili 2003).

(82) Stable element data have often been used in the derivation of aquatic CRs, and these may well be better representative values of steady-state conditions. Elemental concentrations in seawater for many, but not all, elements are reasonably constant (Millero, 1996) and hence the application of stable data to derive CR values is relatively well founded. The situation is, however, very different for fresh waters, and thus differentiation between those elements that are under homeostatic control and those that are not, might be a useful classification. For the former, their internal elemental concentration remains relatively constant irrespective of that in the ambient water; whereas for the latter, such concentrations will tend to vary in direct relationship to the concentrations in their immediate environment. In the terrestrial environment, the

situation is often more complex, and the link between concentrations in the tissues of organisms and those in the surrounding media are open to variation predominantly due to soil characteristics and heterogeneity of contamination. This is explored in more detail below.

4.2 Baseline CR values for Terrestrial ecosystems and their applicability

(83) CR data for adult terrestrial Reference Animal and Plants are presented in Table 4.1 and Table 4.2. These data are based on the detailed tables reported in Annexes A and B, which include full references.

Table 4.1 CR values (Geometric mean or best estimate-derived value in units of Bq kg^{-1} f.w. per Bq kg^{-1}) for Adult terrestrial Reference Animal and Plants – vertebrates; values in grey shading are derived.

Element	Rat	Deer	Duck	Frog
Ag	3e-1(g)	3e-1(g)	3e-1(g,c)	3e-1(g,c)
Am	4e-4	2e-3	1e-2	2e-2
Ba	6e-3(c)	6e-3(c)	6e-3(c)	6e-3(c)
C	1e3(h)	1e3(h)	1e3(h)	1e3(h)
Ca	2e0(g)	2e0(g)	2e0(g,c)	2e0(g,c)
Cd	7e0(c)	7e0(a)	7e0(c)	1e-2
Ce	6e-4(i)	6e-4(i)	6e-4(i,c)	6e-4(i,c)
Cf	3e-2(e)	2e-3(f)	1e-2(f)	2e-2(f)
Cl	7e0(j)	7e0(j)	7e0(j)	7e0(j)
Cm	3e-2(e)	2e-3(f)	1e-2(f)	2e-2(f)
Co	8e-2(c)	8e-2(c)	8e-2(c)	8e-2(c)
Cr	2e-4(g)	2e-4(g)	2e-4(g,c)	2e-4(g,c)
Cs	3e-1	2e0	2e-1	3e-1
Eu	2e-3(i)	2e-3(i)	2e-3(i,c)	2e-3(i,c)
H	2e2(h)	2e2(h)	2e2(h)	2e2(h)
I	4e-1(j)	4e-1(j)	4e-1(j,c)	4e-1(j,c)
Ir	7e-3(g)	7e-3(g)	7e-3(o,c)	7e-3(o,c)
K	??	??	??	??
La	6e-4(i,k)	6e-4(i,k)	6e-4(i,k,c)	6e-4(i,k,c)
Mn	2e-3(c)	2e-3(c)	2e-3(c)	2e-3(c)
Nb	2e-1(g)	2e-1(g)	2e-1(w,c)	2e-1(w,c)
Ni	7e-2(c)	7e-2(c)	7e-2(c)	7e-2(c)
Np	3e-2(e)	2e-3(f)	1e-2(f)	2e-2(f)
P	1e3(l)	1e3(l)	1e3(l)	1e3(l)
Pa	3e-2(e)	2e-3(f)	1e-2(f)	2e-2(f)
Pb	1e-2(c)	1e-3(a)	2e-2(d)	3e-3
Po	1e-2(c)	5e-3(a)	1e-2(d)	1e-2(c,d)
Pu	3e-2	9e-4	1e-2(f)	2e-2(f)
Ra	2e-3(c)	6e-4(a)	6e-2	3e-2(d)
Ru	1e-2(j)	1e-2(j)	1e-2(j,c)	1e-2(j,c)
S	5e1(m)	5e1(m)	5e1(m)	5e1(m)
Sb	2e-6(i)	2e-6(i)	2e-6(i)	2e-6(i)
Se	1e-2(c)	1e-2(c)	1e-2(c)	1e-2(c)
Sr	2e0	2e0	1e-1	1e0
Tc	4e-1(j)	4e-1(j)	2e-1	6e-1(b)
Te	2e-1(g)	2e-1(g)	2e-1(g,c)	2e-1(g,c)
Th	1e-4(c)	1e-4(a)	4e-4(d)	4e-4(d)
U	1e-4	1e-4(a)	5e-4(d)	5e-4(d)

Zn	7e1(i)	7e1(i)	7e1(i,c)	7e1(i,c)
Zr	1e-5(n)	1e-5(n)	1e-5(n,c)	1e-5(n,c)

(a) Mammal-herbivorous; (b) Amphibian; (c) Mammal; (d) Bird; (e) Pu; (f) Am; (g) Stable element review data (Coughtrey & Thorne 1983a,b; Bowen 1979) soils and animals; (h) Specific activity model; (i) allometric prediction or derived dietary CR; (j) model prediction Brown et al 2003; (k) Ce; (l) C; (m) Copplestone et al. 2003; (n) from dietary CR; (o) stable element data – rock not soil (Bowen 1979);

Table 4.2 CR values (Geometric mean or best estimate-derived value in units of Bq kg^{-1} f.w. per Bq kg^{-1}) for Adult terrestrial Reference Animal and Plants – invertebrates and plants; values in grey shading are derived.

Element	Bee	Earthworm	Wild grass	Pine tree
Ag	7e-1(e)	7e-1(c,e)	2e0(a)	6e0(t)
Am	1e-1(c)	2e-1	2e-3(a)	2e-3(a,s)
Ba	5e-2(h)	5e-2(h)	1e-1(q)	1e-1(q,s)
C	4e2(f,g)	4e2(f)	9e2(f)	1e3(f)
Ca	1e1(e)	1e1(e)	5e0(x)	5e0(x,s)
Cd	2e1(c)	2e0	1e0(a)	4e-1(b)
Ce	4e-4(g)	4e-4	9e-3(q)	9e-3(q,s)
Cf	1e-1(c,d)	2e-1(d)	2e-2(u)	2e-2(u)
Cl	3e-1(h)	2e-1	1e1(a)	1e0
Cm	1e-1(c,d)	2e-1(d)	3e-4(q)	9e-3(b)
Co	5e-3(c)	5e-3(c)	1e-2(q)	1e-2(b)
Cr	5e-3(c)	5e-3(c)	5e-4(q)	5e-4(q,s)
Cs	7e-3(c)	8e-2	6e-2	6e-2
Eu	8e-4(g)	8e-4	2e-1(v)	2e-1(v)
H	2e2(f,g)	2e2(f)	2e2(f)	2e2(f,a)
I	3e-1(h)	1e-1	5e-2(a)	5e-2(a,s)
Ir	7e-3(m)	7e-3(m)	5e0(w)	5e0(w,s)
K	??	??	??	??
La	4e-4(g,j)	4e-4(j)	5e-3(q)	5e-3(q,s)
Mn	5e-2(i)	1e-2	2e-1(q)	2e-2(b)
Nb	5e-1(g)	5e-4	5e-3(q)	5e-3(q,s)
Ni	8e-3(c)	7e-3	2e-1	2e-2(b)
Np	1e-1(c,d)	2e-1(d)	2e-2(q)	2e-2(q,s)
P	4e2(g,k)	4e2(k)	5e-1(q)	5e-1(q,s)
Pa	1e-1(c,d)	2e-1(d)	2e-2(u)	2e-2(u)
Pb	6e-2(c)	2e-2	3e-1	5e-2
Po	1e-1(g)	1e-1	5e-1	4e-2
Pu	1e-2(c)	2e-1(d)	8e-3(a)	8e-3(a,s)
Ra	9e-2(h)	9e-2	6e-2	6e-4
Ru	4e-4(c)	6e-3	2e-1(x)	2e-1(x,s)
S	5e1(l)	5e1(l)	2e2(l)	2e2(l)
Sb	3e-1(i)	6e-3	4e1(a)	4e1(a,s)
Se	1e0(g)	1e0	1e-1(a)	1e-1(a,s)
Sr	4e-3(c)	9e-3	2e-1(a)	5e-1(b)
Tc	6e-1(m)	6e-1(m)	2e1(a)	2e1(a,s)
Te	4e-2(i)	4e-2(i)	3e-1(q)	3e-1(q,s)
Th	9e-3(g,o)	9e-3(o)	5e-2	1e-5
U	9e-3(g)	9e-3	4e-2	1e-3
Zn	2e0(e)	2e0(e)	3e0	3e0(s)
Zr	5e-4(g,p)	5e-4(p)	3e-3(q)	3e-3(q,s)

(a) Grasses and herbs; (b) Trees; (c) Flying insect; (d) Am; (e) Stable data for Insecta (f) Specific avtivity model; (g) earthworm; (h) detritivorous invertebrate; (i) gastropod; (j) Ce; (k) C; (l) Copplestone et al. 2003; (m) maximum animal value; (o) U; (p) Nb; (q) IAEA472 pasture; (r) La; (s) Assume grass value based on Tagami et al. in-press; (t) stable element data for woody plants; (u) Np; (v) understorey vegetation ERICA default; (w) stable element data – rock not soil; (x) crop CR from IAEA472

(84) Empirical CR data for terrestrial animals and plants are evidently limited. Although the coverage for earthworms extends to 18 of the 40 elements considered, there are far fewer elements included for all other Reference Animals and Plants, and in some cases such as the ***Bee***, no specific data were found. There is therefore a heavy reliance on the use of surrogate CR values. The methods used to derive the values are generally of a type employing data from the broader wildlife groups, but in a few cases recourse was made to element analogues.

(85) For terrestrial systems, soils are known to vary widely in terms of their lithology and chemical composition, and are classified accordingly. Soil type clearly affects the bioavailablity of elements and their potential for transfer through terrestrial food-chains (IAEA, 2010). Soil types have been used to categorise the degree of transfer to various crops in tropical and sub-tropical environments (Velasco et al., 2009).

(86) The Reference ***Grass*** appears to lend itself most readily to the CR approach because many elements are obtained through direct uptake from the dissolved phase in pore waters and thus the link between activity concentrations in the plant tissues and soil might be considered to be clearly evident. Nonetheless, some elements, a notable example being carbon, are incorporated via direct exchange with elements in the ambient atmosphere, and for atmospheric releases, plant surfaces may be contaminated through the processes of dry and wet deposition (Pröhl, 2009) which may complicate a simple correlation between soil and plant concentrations. Where aerial discharges have occurred over long time scales, or in cases where long time periods (several months to years) have elapsed following a pulsed or accidental release, CRs should, however, provide a reasonable indication of transfer to grass and are an accepted approach in human foodchain modelling (e.g. IAEA 2010). The transfer pathways to Reference ***Pine Tree*** are of a similar nature to those expressed for grass, but the fact that trees are long-lived adds a caveat in applying CRs because many elements have the potential to be incorporated within non-living tissue. As shown by IAEA (2001), the inventory of radioaceasium expressed as a percentage of total phytomass increased in stem wood for pine forests following the Chernobyl accident.

(87) ***Earthworms*** live in soil and derive their nutrition from organic matter in a wide variety of forms including plant matter (various forms, fresh-decayed), protozoans, rotifers, nematodes, bacteria, fungi and decomposing remains of other animals. The link between body concentrations of elements in earthworms and soil, at least for those that are not homeostatically controlled, is clear. Nonetheless, the availability of CR data for soil invertebrates with the exception of lead is limited (Annex A; Beresford et al., 2008) and this limitation should be recognised in the event of applying the CR values presented in this report.

(88) ***Bees*** spend a large part of their life away from direct contact with soil. During the process of gathering nectar and/or pollen, bees have an indirect route of transfer from soil in the sense that soil provides the source for many radionuclides in the plants that the bees habitually visit. The relationship between activity concentrations in soil and the individual bees is, therefore, not immediately apparent and further efforts to investigate this particular food-chain would be helpful.

(89) The ***Duck***, as defined at the level of the family *Anatidae*, consists of a number of species that generally undertake annual migrations. Although they may spend up to several months at any single location, the degree of equilibration the bird attains with soil in this time is clearly debatable. Furthermore, ducks spend time on land, on water and in air. It is not therefoe immediately apparent which environmental media activity concentration, if any, should constitute the starting point in the derivation of CR values. For the duck's egg (probably the most radiosensitive stage for this Reference Animal) virtually the entire elemental/radionuclide content will have been derived from its female parent. In such cases, therefore, it may be more appropriate to relate the concentrations of radionuclides in the egg with those in the parent female.

(90) The final categories of terrestrial Reference Animal and Plant are the mammals, ***Rat*** and ***Deer***. Both animals derive body burdens primarily through ingestion of food and water and, to a lesser extent, via inhalation (of gases and/or dust) depending on the radionuclide under consideration. Consideration of the home range of rats or deer, and spatial averaging, should be used in deriving applying CR values.

4.3 Baseline CR values for Freshwater ecosystems and their applicability

(91) CR data for adult freshwater Reference Animals are presented in Table 4.3. These data are based on the detailed tables reported in Annexes A and B which include full references.

(92) CR data specifically for freshwater Reference Animals are characterised by a fairly extsneive coverage of elements for ***Trout***, but far fewer elements for the categories ***Duck*** and ***Frog***. (*In fact there are no data for ducks, in spite of their being an important food item for humans!*) Many of the CR data for frog have been derived from the CR data for trout. [**Is this at all sensible??]**

(93) Freshwaters exhibit a high degree of chemical variability and are often classified as being 'hard' or 'soft' depending on associated calcium levels. The chemical composition of water is known to affect the uptake of many radionuclides. For example, Kolehmainen et al. (1966) having classified lakes according to numerous physical, chemical and biological properties, and determined that highest levels of ^{137}Cs were observed in fish from oligotrophic lakes with waters of low conductivity.

(94) For ***Trout***, the application of a generic CR based on an arbitrary suite of sampling locations, with differing unspecified water chemistries might not be ideal. In line with the

reasoning presented in relation to flatfish (see below), steady state conditions for many radionuclides between ambient freshwater and trout may not exist unless contact times have been protracted. By contrast, equilibration times for trout eggs and larvae are likely to be much shorter, but the almost complete lack of data on transfer to these life-stages renders any derivation of baseline transfer values inappropriate.

(95) Although some data in relation to ***Frog*** spawn and tadpoles for some radionuclides exist (Yankovich, pers. Comm.. Ophel and Fraser, 1973), these are extremely limited. The fact that adult frogs often spend the majority of their time in terrestrial environments also raises questions about which environmental media should be used to estimate body concentrations. In this regard, it would seem sensible to consider both soil and water. This is, in fact, the approach that has been adopted in the collation of baseline values in this report.

Table 4.3 CR values (Geometric mean OR best estimate-derived value in units of Bq kg^{-1} f.w. per Bq kg^{-1}) for for Adult freshwater Reference Animal and Plants. Values in grey shading are derived.

Element	Trout	Frog	Duck
Ag			
Am	2e0(d)	2e1(c)	1e1(k)
Ba	1e1	1e1(g)	1e1(k)
C	5e4	5e4(g)	5e4(k)
Ca	4e2	9e2	9e2(k)
Cd	4e2(d)	4e2(d,g)	4e2(k)
Ce	2e2	2e2(g)	2e2(k)
Cf	2e1(e)	2e1(e,g)	2e1(k)
Cl	1e2(d)	1e2(d,g)	1e2(k)
Cm	2e-1(d)	3e-1(c)	3e-1(k)
Co	9e1	9e1(g)	9e1(k)
Cr	2e2	2e2(g)	2e2(k)
Cs	3e3	3e3(g)	2e3(k)
Eu	3e1	3e1(g)	3e1(k)
H	1(f)	1(f)	1(f)
I	6e1	6e1(g)	6e1(k)
Ir			
La	2e2	2e2(g)	2e2(k)
Mn	2e3	2e3(g)	2e3(k)
Nb	4e2(i)	4e2(i)	4e2(k)
Ni	1e1	1e1(g)	1e1(k)
Np	2e1(e)	2e1(e,g)	2e1(k)
P	7e5	7e5(g)	7e5(k)
Pa	2e1(e)	2e1(e,g)	2e1(k)
Pb	2e2	2e2(g)	2e2(k)
Po	2e2	2e2(g)	2e2(k)
Pu	2e1	1e1(c)	2e1(k)
Ra	4e1	4e1(g)	
Ru	3e1(b)	3e1(b,g)	3e1(k)
S			
Sb	4e1	4e1(g)	4e1(k)
Se	6e3	6e3(g)	6e3(k)
Sr	1e2	1e2(g)	1e2(k)
Tc	7e2(d)	7e2(d,g)	7e2(k)

Te	3e2(b)	3e2(b,g)	3e2(k)
Th	1e2(d)	1e2(d,g)	1e2(k)
U	8e0	8e0(g)	8e0(k)
Zn	9e3	9e3(g)	9e3(k)
Zr	4e2	4e2(g)	4e2(k)

(b) Fish – piscivorous; (c) Amphibian; (d) Fish; (e) Pu; (f) Simple specific activity assumption; (g) 'Trout'; (h) Assumes ratio with Cs as calculated from terrestrial wild grass; (i) Zr; (j) Assumes ratio between terrestrial duck and frog; (k) Assumes highest animal value

4.4 Baseline CR values for Marine ecosystems and their applicability

(96) CR data for adult marine Reference Animal and Plants are presented in Table 4.4. These data are based on the detailed tables including full references, reported in Appendix A.

Table 4.4 CR values (Geometric mean, arithmetic mean (n<2) OR best estimate-derived value in units of Bq kg^{-1} f.w. per Bq kg^{-1}) for Adult marine Reference Animal and Plants; values in grey shading are derived

Element	Flatfish	Crab	Brown seaweed
Ag	8×10^{3} (b)	2×10^{5} (g)	2×10^{3}
Am	2×10^{2}	5×10^{2} (b)	8×10^{1}
Ba	4×10^{-1} (d)	7×10^{-1} (g)	4×10^{0} (d)
C	1×10^{4} (b)	1×10^{4} (b)	8×10^{3} (b)
Ca	4×10^{-1}	5×10^{0} (g)	4×10^{0} (c)
Cd	1×10^{4} (b)	8×10^{2} (a)	2×10^{3}
Ce	2×10^{2} (b)	1×10^{2} (b)	1×10^{3}
Cf	2×10^{2} (d)	5×10^{2} (e)	1×10^{2} (d)
Cl	6×10^{-2} (g)	6×10^{-2} (b)	7×10^{-1} (b)
Cm	2×10^{2} (d)	5×10^{2} (e)	8×10^{3}
Co	3×10^{2}	5×10^{3} (a)	7×10^{2}
Cr	2×10^{2} (g)	1×10^{2} (g)	6×10^{-3}(g)
Cs	4×10^{1}	1×10^{1}	1×10^{1}
Eu	7×10^{2} (b)	4×10^{3} (g)	1×10^{3} (b)
H	1×10^{0} (g)	1×10^{0} (g)	1×10^{0}
I	9×10^{0} (g)	3×10^{0} (g)	1×10^{3} (b)
Ir	2×10^{1} (g)	1×10^{2} (g)	1×10^{3} (g)
K	??	??	??
La	??	??	5×10^{3} (c)
Mn	3×10^{2}	3×10^{3} (a)	1×10^{4}
Nb	3×10^{1} (g)	1×10^{2} (b)	8×10^{1}
Ni	2×10^{2} (b)	1×10^{3} (g)	2×10^{3}
Np	2×10^{1} (d)	4×10^{1} (d)	6×10^{1}
P	??	3×10^{4} (g)	1×10^{4} (b)
Pa	5×10^{1} (g)	1×10^{1} (g)	1×10^{2} (g)
Pb	3×10^{3}	3×10^{3} (a)	2×10^{3}
Po	1×10^{4} (b)	4×10^{3} (a)	2×10^{3} (b)
Pu	2×10^{1}	4×10^{1}	2×10^{3}
Ra	6×10^{1} (a)	7×10^{1} (b)	4×10^{1} (b)
Ru	1×10^{1} (b)	1×10^{2} (g)	3×10^{2}
S	1×10^{0} (g)	1×10^{0} (g)	2×10^{0} (b)
Sb	6×10^{2} (g)	3×10^{2} (g)	2×10^{3}
Se	1×10^{4} (g)	1×10^{4} (g)	2×10^{2} (b)

Sr	1 x 10^1	4 x 10^1 (b)	4 x 10^1
Tc	8 x 10^1 (g)	2 x 10^2	4 x 10^4
Te	1 x 10^3 (g)	1 x 10^3 (g)	1 x 10^4 (g)
Th	1 x 10^3 (b)	1 x 10^3 (g)	3 x 10^3 (b)
U	4 x 10^0 (a)	1 x 10^1 (g)	3 x 10^1
Zn	2 x 10^4	3 x 10^5 (g)	2 x 10^3 (g)
Zr	5 x 10^1	5 x 10^1 (b)	6 x 10^2

(a) CR value for a similar generic wildlife group "Subcategory" within that ecosystem for the radionuclide under assessment (b) CR value for a similar generic wildlife group "Broad Group" within that ecosystem for the radionuclide under assessment (c) CR data from estuarine environment (d) CR value for the given Reference Animal and Plant for an element of similar biogeochemistry (e) CR value for biogeochemically similar elements for similar generic wildlife group (f) allometric relationships, or other modelling approach (g) Expert judgement.

(97) The data coverage for ***Brown Seaweed*** extends to 50 % of the elements considered within this review. The number of elements for ***Flatfish*** is limited to 10, and falls to just 3 elements for ***Crab*** [??] In most cases, surrogate values could be derived through recourse to generic wild-life groups. The recommended CR values compiled within IAEA (2004) were also employed in a few cases.

(98) For ***Brown Seaweed***, radionuclides incorporated into the thallus are adsorbed directly from seawater. Because seawater comprises the predominant source of elements and radionuclides to seaweed, and there appears to be little regulation of concentrations within the organism, CR values clearly constitute an appropriate measure of transfer.

(99) For ***Crab***, the adsorption of radionuclides to the surface of eggs and larvae is an important process, and for many radioisotopes exchanges between the ambient seawater and incorporation within the organism at this stage of development is important. Evidence from various studies on organisms with dimensions commensurate with crab eggs and larvae suggests that equilibration occurs relatively rapidly (e.g. Stewart & Fisher, 2003; Brown et al. 2004) and thus under conditions where seawater concentrations remain constant with time, the CR approach might be expected to produce reasonable predictions of transfer. For adult crabs, most elements are acquired primarily through the ingestion of food, and equilibrium may not be attained over protracted time periods, as demonstrated by studies of technetium by marine crustaceans (Smith et al., 1998; Olsen & Vives i Batlle, 2003). Application of CRs in such cases may thus require some degree of caution. In the short term, relative to processes involving uptake and depuration, many radionuclides will adsorb onto the crustacean exoskeleton which may be an important source of radiation exposure for radionuclides emitting beta and low energy gamma radiations, although the shell will effectively shield the living organism from lower energy radiation emissions. The empirical database collated within the present work shows that there are few data on the assimilation of radionuclides by crab shells, the majority of data having been derived from muscle and hepatopancreas. It would be useful to collate more information on the association of radionuclides with crustacean exoskeletons, in order to further elucidate the importance of this exposure pathway (although this would require more complex dosimetric models).

(100) The processes leading to the exposure of eggs and larvae of flatfish are likely to be the same as those for crab, with adsorption playing an important role. Uptake by adult flatfish occurs via ingestion and, for some radionuclides, via direct uptake from water over the gill surfaces. The relative importance of these factors depends on the radionuclide of interest. The CR values for flatfish collated within this report are likely to give a reasonable first indication of transfer from seawater to the organism where it can be established that ambient water activity concentrations are not fluctuating substantially with time but there should be awareness that for radionuclides such as actinides, where turnover rates in the body are slow, the CR approach has limitations. The most comprehensive review of the uptake of radionuclides by marine fish is that of Pentreath (1977).

4.5 Transfer factor data for different life stages of development for Reference Animals and Plants

(101) Few CR data were found for the various life stages of Reference Animals and Plants and, in view of the lack of available information, it was considered premature, if not impracticable, to attempt to derive values for each and every lifestage-element combination. For this reason, baseline values have not been provided. In order to consider how such values might be derived, the following set of rules has been developed as a basis for further discussion and elaboration.

(102) For ***Deer*** calf, adult transfer data might provide reasonable proxy values if no direct empricial data are available. Results for unborn lambs have shown that Cs activity concentrations were approximately the same as those for adults. Furthermore, the resultant tissue activity concentrations of lambs and adult sheep fed herbage contaminated with ^{60}Co, ^{95}Nb, ^{106}Ru, ^{134}Cs, ^{137}Cs, ^{238}Pu, ^{239,240}Pu and ^{241}Am for the same time period were similar (Beresford et al 2007). Alternatively, biokinetic models using milk (and herbage intake if the model is used to derive values for the complete period of lactation) as an intake source might be developed (although consideration of how to estimate ***Deer*** milk concentrations and an intial activity concentration in the calf would be required).

(103) The ratio between activity concentrations in poultry meat to those in eggs for the particular radioisotope being considered could be extracted from relevant literature sources (e.g. Fesenko et al 2009) to derive CR values for ***Duck*** egg. Such an approach was used within the derivation of values for the ERICA Tool database (Beresford et al 2008) using data for poultry from IAEA (1994). This ratio could then be applied to the adult ***Duck*** CR. Recent work (Fesenko et al. 2009) includes a fairly comprehensive data set for poultry, but there will be many elements for which there are no data. Application of data for biogeochemically similar elements could be considered as a means of deriving a CR value for radionuclides lacking specific data.

(104) In the case of the ***Frog*** egg's mass of spawn (for the purposes of transfer, these are considered to be the same) there are some empirical data. The concentration ratios for biogeochemically similar elements might be used as proxy values where no data exist for the radioisotope being considered. There are likely to be more data on fish egg:fish activity concentration ratios, and these data might be applied to frog whole-body CR values to provide an estimate of transfer for frog eggs. [Is this a sensible thing to do?]

(105) There are also some limited empirical data for tadpoles. Trophic position may lead to differences in radionuclide CR values between life stages. A notable example is the transfer of ^{60}Co into tadpoles versus adult amphibians. Tadpoles are important primary consumers in aquatic ecosystems, and as adults they become secondary consumers. ^{60}Co is synthesised by primary producers at the base of the food chain, and is quickly utilised by these organisms and depleted with increasing trophic position. This can lead to differences in CRs between tadpoles and adult amphibians. Ophel and Fraser (1973) have reported ^{60}Co CR values of 250 and 50 for tadpoles and bullfrogs, respectively, from Perch Lake, Ontario.

(106) For ***Trout*** eggs, there are some data available for tissue to egg ratios for some freshwater species of teleost fish. These conversion factors could be applied to the CRs for adult trout. In cases where egg CR values are available for biogeochemically similar elements, these values might be used as a reasonable surrogate. The adult CR value may also provide a first approximation for the egg CR, although there are caveats in applying this approach. For instance, Jeffree et al. (2008) found that the accumulatory and kinetic characteristics of the egg-case for some marine chondrichthian species led to enhanced exposures of embryos to certain radioisotopes. Although the trout is a teleost with a quite different egg composition and structure, the point that adult and egg may exhibit quite divergent uptake of contaminants is still pertinent.

(107) Transfer to a ***Bee*** colony might be considered to be similar to that for the individual adult bee, but the colony consists of all different life stages, plus the non-living components of the nest within which the bees live. Because it forms an integral part of the colony being used as a food source for larvae and bees, transfer to and activity concentrations within the honey may provide useful information in relation to exposure estimates, notably in terms of external dose quantification.

(108) The larval stage of ***Crab***, known as the zoea, is a minute transparent organism with a rounded body that swims and feeds as part of the plankton. Data for zooplankton in general have previously been published (IAEA, 2004; Hosseini et al., 2008).

(109) With no detailed empirical information on transfer to ***Earthworm*** eggs, transfer data for the adult earthworm may provide suitable surrogate CR data. That earthworm egg and adult earthworm express similar CR values is an hypothesis that requires further testing.

4.6 Distributions of radionuclides within the organs/body parts of reference plants and animals

(110) The Commission has noted that, for the purpose of relating dose received to the biological endpoints of interest, the critical information required for alpha particles and low-energy electrons is the concentration of the relevant radionuclide in the 'tissue or organ of interest' (ICRP, 2008). For animals, these tissues or organs of interest would appear to be the reproductive organs, as reproduction is a primary biological endpoint of interest (especially with respect to the maintenance of populations), and accumulating organs because clearly the highest exposures will be associated with these body compartments. For plants, the tissues of relevance may be the active growing points of the shoot and root tips, the ring of phloem and xylem underneath the bark (much of the centre of the tree trunk is literally 'dead wood'), the seeds (within cones), and the root mass beneath the soil surface (ICRP, 2008). The Commission has started the process of considering the relative dosimetry of internal organs, such as the liver and gonads of the ***Reference Deer***, but initially for illustrative purposes rather than as definitive models (ICRP, 2008).

(111) Whole-body concentration ratios have been widely used in models associated with assessing the environmental impacts of radioactivity in a regulatory context (Brown et al., 2008). This partly reflects the consideration that, because a large proportion of dose-effects relationships from laboratory investigations are whole body exposures, the most appropriate dose-rates to consider are ones associated with the entire organism (Andersson et al., 2009). Nonetheless, it is recognised that for radionuclides emitting relatively short range radiations (such as alpha particles and low energy beta radiations) and for organisms above a certain size and complexity, doses to radiosensitive tissues are likely to dictate the resultant radiation effect. The dependence on radionuclide concentrations in that particular tissue, which can be very different from the average concentration in the body, might therefore be critical. A detailed analysis of heterogeneity of radionuclides and it implication for dose in relation to a small number of examples would elucidate this source of uncertainty (Ulanovsky, et al., 2008) and is subject currently being examined by the Commission.

(112) Although the data collation work conducted in the process of deriving baseline transfer parameters in this report has allowed information to be categorised in terms of organ/body parts, and indeed such information has been used where practicable to derive equivalent whole body concentration ratios, it was considered premature to report these data explicitly in the form of baseline CR number tables at this stage. The conversion factors used to derive whole body concentration ratios from organs and body parts can be considered as a first step in collating and tabulating baseline values on this subject, but a more comprehensive derivation of values awaits further deliberation and guidance from the Commission. In this respect, the recent work of Yankovich and co-workers (Yankovich et al., submitted) has provided a useful input to the process.

4.7 The way forward

(113) The previous sections in this report have shown that there is some information available on the transfer of radionuclides for Reference Animal and Plants, but very limited information on their lifestages. The available information has usually been described in the form of equilibrium based concentration ratios. It is recognised that there are a number of limitations with the application of Concentration Ratios (as described above). Furthermore, there are many data gaps associated with several elements. Whilst approaches for filling these gaps have been proposed and used in this report to account for the lack of empirical data, these do not present a long-term solution and alternatives should be sought for the ICRP framework.

(114) At the current time, however, the ICRP believes that, given the current state of knowledge, the Concentration Ratio approach and the associated data gap filling approaches described in this report will have to provide an initial baseline on the transfer of radionuclides to the Reference Animals and Plants. This will allow the ICRP to continue to develop its framework for radiological protection of the environment, but with recognised limitations regarding the derivation of the CRs for those cases where direct measurements of radionuclides in the environment are not available.

(115) There may be more appropriate means of obtaining transfer data for the Reference Animals and Plants and their lifestages to provide an internally consistent and complete data set for different tissues. This information could then be used as a set of reference values analogous to approaches used for human radiological protection. Such reference values would provide a consistent and reproducible radiation protection framework, and the Commission urges that such work be done.

(116) One possible approach is to identify a series of sites where samples of each Reference Animal and Plant, and their different lifestages, could be collected and analysed. At each 'reference' site, all the samples should come from the same (known and coordinated) location (e.g. the duck, frog and trout should all come from the same lake). An appropriate number of samples of each Reference Animal and Plant and their lifestages should be collected, along with corresponding samples of media (water, soil). The number and specific location of any media samples would need to be taken into account, and spatial aspects - such as the home range of the Reference Animal and Plant (and its lifestages) as identified in ICRP (2008) – would also need to be taken into account. Consideration would also need to be given to the timing of the sample collection. Whilst these 'reference' sites would provide relevant data for the Reference Animals and Plants the data will be, clearly, site-specific in nature. However, such 'reference' values can then be compared with the wider CR data that is available (such as that collated in this report for the Reference Animal and Plants) to help understand how CRs may vary between different geographic areas.

(117) For each of the adult Reference Animals and Plants, the composition of the 40 elements should be determined for a number of the tissues of interest. These include the

gonads (as reproduction is a key endpoint when considering possible effects on populations of non-human species), muscle and liver and so on, depending upon the specific Reference Animal and Plant in question. During the development of the radiological protection system for humans, the ICRP gathered data on the elemental composition of the human body in a similar way, and has used this information to understand the relationship between internal organ concentrations, the associated doses, and the biological effects. By deriving a reference set of transfer data for different tissues of the Reference Animals and Plants, it will be practicable to evaluate more fully how their internal exposure is related to the radionuclide concnetrations within the surrounding environment.

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ANNEX A: DETAILED STATISTICAL INFORMATION ON CONCENTRATION RATIOS FOR REFERENCE ANIMALS AND PLANTS

A.1. Terrestrial ecosystems

Table A.1.1 Wild grass (Poaceae) - CR values (units of Bq kg^{-1} f.w. per Bq kg^{-1});

Element	Arithmetic Mean	Arithmetic Standard Deviaton	Geometric Mean	Geometric Standard Deviation	Minimum	Maximum	N	RefID
As	1.3E-2	0.0E+0			1.3E-2	1.3E-2	2	334,344
Cs	6.4E-2	2.1E-2	6.1E-2	1.4E+0	4.0E-2	8.0E-2	3	272
K	2.1E-1	6.0E-2	2.0E-1	1.3E+0	1.7E-1	2.8E-1	3	272
Ni	2.2E-1	1.7E-1	1.7E-1	2.0E+0	1.3E-2	7.1E-1	50	285,286,334, 344
Pb	3.1E-1	2.2E-1	2.6E-1	1.9E+0	4.7E-3	5.5E-1	21	282,334,344
Po	7.2E-1	7.8E-1	4.9E-1	2.4E+0	1.7E-2	1.9E+0	6	334,344
Ra	3.5E-1	2.0E+0	5.8E-2	6.6E+0	3.6E-3	1.2E+1	150	266,272,273, 282,284,287, 288,291,292, 334,344
Th	8.6E-2	1.2E-1	5.2E-2	2.8E+0	2.0E-3	6.5E-1	53	272,283,334, 344
U	1.8E-1	7.5E-1	4.2E-2	5.5E+0	8.7E-4	5.5E+0	118	266,269,272, 279,282,283, 292,334,344
Zn	3.5E+0	3.2E+0	2.6E+0	2.2E+0	2.4E-1	8.7E+0	6	334,344

Table A.1.2 Pine tree (Pinaceae) - CR values (units of Bq kg^{-1} f.w. per Bq kg^{-1});.

Element	Arithmetic Mean	Arithmetic Standard Deviaton	Geometric Mean	Geometric Standard Deviation	Minimum	Maximum	N	RefID
Cl	1,5E+0	1,4E+0	1,1E+0	2,2E+0	2,6E-1	3,9E+0	5	251
Cs	9,6E-2	1,1E-1	6,2E-2	2,6E+0	1,3E-2	1,8E-1	90	183
Pb	6,1E-2	3,4E-2	5,3E-2	1,7E+0	2,2E-2	7,1E-2	10	220
Po	4,7E-2	2,8E-2	4,0E-2	1,7E+0	1,3E-2	5,5E-2	10	220
Ra	9,2E-4	9,9E-4	6,3E-4	2,4E+0	5,6E-4	2,4E-3	10	220
Th	1,0E-5	0,0E+0	1,0E-5	1,6E+0	1,0E-5	1,0E-5	3	200
U	1,3E-3	1,0E-3	9,9E-4	2,0E+0	2,0E-4	1,8E-3	13	200,220

Table A.1.3 Earthworm (Lumbricidae) - CR values (units of Bq kg^{-1} f.w. per Bq kg^{-1})

Element	Arithmetic Mean	Arithmetic Standard Deviaton	Geometric Mean	Geometric Standard Deviation	Minimum	Maximum	N	RefID
Am	2.0E-1	1.5E-1	1.6E-1	1.9E+0	6.0E-2	4.0E-1	4	171
Cd	2.1E+0	9.8E-1	1.9E+0	1.6E+0	3.9E-1	3.7E+0	15	199,229,264
Ce	3.7E-4						1	264
Cl	1.8E-1	6.0E-2	1.7E-1	1.4E+0	1.7E-1	2.0E-1	17	238
Cs	1.4E-1	2.0E-1	8.4E-2	2.8E+0	2.7E-2	6.9E-1	11	171,207,264
Eu	7.9E-4						1	264
I	1.6E-1	6.7E-2	1.4E-1	1.5E+0	1.5E-1	1.6E-1	10	238
Mn	1.6E-2	9.1E-3	1.3E-2	1.7E+0	1.1E-3	2.4E-2	5	199,264
Nb	5.0E-4						1	264
Ni	7.3E-2	7.4E-1	7.2E-3	8.6E+0	5.7E-3	3.2E-1	75	165,199,219, 237,264
Pb	2.9E-2	4.4E-2	1.5E-2	3.0E+0	2.3E-3	1.6E-1	264	159,199,229, 247,264
Po	1.0E-1	3.9E-2	9.6E-2	1.4E+0	1.0E-1	1.0E-1	7	384
Sb	6.0E-3						1	264
Se	1.5E+0						1	231
Sr	9.0E-3						1	264
U	8.8E-3						1	264

Table A.1.4 Bee (Apidea) - CR values (units of Bq kg^{-1} f.w. per Bq kg^{-1});

No Data

Table A.1.5 Frog (Ranidae) - CR values (units of Bq kg^{-1} f.w. per Bq kg^{-1});

Element	Arithmetic Mean	Arithmetic Standard Deviaton	Geometric Mean	Geometric Standard Deviation	Minimum	Maximum	N	RefID
Am	2.1E-2	1.8E-3			2.1E-2	2.1E-2	2	263
Cd	1.5E-2	7.9E-3	1.3E-2	1.7E+0	5.0E-3	2.4E-2	5	213
Cs	5.7E-1	9.2E-1	3.0E-1	3.1E+0	2.0E-2	2.1E+0	100	188,205,256,263
Pb	3.1E-3	2.2E-3	2.6E-3	1.9E+0	8.8E-4	6.2E-3	6	213
Sr	1.4E+0	1.4E+0	1.0E+0	2.3E+0	2.9E-1	2.5E+0	14	188,263

Table A.1.6 Duck (Anatidae) - CR values (units of Bq kg^{-1} f.w. per Bq kg^{-1})

Element	Arithmetic Mean	Arithmetic Standard Deviaton	Geometric Mean	Geometric Standard Deviation	Minimum	Maximum	N	RefID
Am	1.1E-2	6.6E-3			1.1E-2	1.1E-2	2	263
Cs	4.7E-1	8.0E-1	2.4E-1	3.2E+0	1.7E-2	4.3E+0	38	163,190,263
Ra	8.4E-2	9.7E-2	5.5E-2	2.5E+0	1.1E-2	2.0E-1	5	239
Sr	1.6E-1	1.1E-1	1.3E-1	1.9E+0	5.3E-2	2.8E-1	3	190,263

Table A.1.7 Rat (Muridae) CR values (units of Bq kg^{-1} f.w. per Bq kg^{-1})

Element	Arithmetic Mean	Arithmetic Standard Deviaton	Geometric Mean	Geometric Standard Deviation	Minimum	Maximum	N	RefID
Am	3.7E-4	1.0E-4	3.6E-4	1.3E+0	3.7E-4	3.7E-4	9	382
Cs	5.1E-1	7.9E-1	2.8E-1	3.0E+0	1.7E-2	1.5E+0	48	268,382
Pu	1.1E-1	3.7E-1	3.0E-2	4.9E+0	9.2E-4	1.6E+0	20	268,382
Sr	2.5E+0	2.5E+0	1.8E+0	2.3E+0	1.2E+0	3.4E+0	30	268

Table A.1.8 Deer (Cervidae) - CR values (units of Bq kg^{-1} f.w. per Bq kg^{-1})

Element	Arithmetic Mean	Arithmetic Standard Deviaton	Geometric Mean	Geometric Standard Deviation	Minimum	Maximum	N	RefID
Am	7.5E-3	2.6E-2	2.1E-3	4.9E+0	4.2E-4	3.1E-2	13	184
Cs	4.1E+0	9.4E+0	1.6E+0	3.9E+0	1.4E-2	1.4E+2	1723	163,184,190, 208,209,228, 230,294
Pu	2.6E-3	7.2E-3	8.9E-4	4.3E+0	8.8E-4	9.5E-3	15	184,222
Sr	2.9E+0	2.8E+0	2.1E+0	2.3E+0	1.1E-2	1.2E+1	57	163,190,228

Table A.1.9. References for Terrestrial Reference Animal and Plants (Tables A.1.1 to A.1.8)

Ref ID	Reference short		Ref ID	Reference short
159	Andrews et al. (1989)		247	Scheuhammer et al. (2003)
163	Beresford et al. (2005)		251	Sheppard et al. (1999)
165	Beyer et al. (1982)		256	Stark et al. (2004)
171	Copplestone (1996		263	Wood et al. (2008)
183	Ertel and Zielgler (1991)		264	Yoshida et al. (2005)
184	Ferenbaugh et al. (2002)		266	Apps et al. (1988)
188	Gaschak (pers comm.)		268	Beresford et al. (2008)
190	Gaschak et al. (2003)		269	Bouda (1986)
199	Henriks et al. (1995)		272	Dowdall et al. (2005)
200	Hinton et al. (20059		273	Gerzabek (1998)
205	Jagoe et al. (2002)		279	Idiz et al. (1986)
207	Janssen et al. (1996)		282	Mahon and Mathewes (1983)
208	Johanson (1994)		283	Martinez-Aguirre et al. (1997)
209	Johanson and Bergstrom (1994)		284	Martinez-Aguirre and perianez (1998)
213	Karasov et al. (2005)		285	Mascanzoni (1989a)
219	Ma (1982)		286	Mascanzoni (1989b)
220	Mahon and Mathews (1983)		287	et al. (1989)
222	Mietelski (2001)		288	Mortvedt (1994)
228	Miretsky et al. (1993)		291	Pokarzhevskii and Krivolutzkii (1997)
229	Morgan and Morgan (1990)		292	Rumble et al.. (1986)
230	Nelin (1995)		294	Steinnes et al. (2009)
231	Nielsen and Gissel-Nielsen (1975)		334	AREVA (2000)
237	Pietz et al. (1984)		344	AREVA (2000)
238	Pokarzhevskii and Zhulidov (1995)		382	Wood et al. (2009)
239	Pokarzhevskii and Krivolutskii (1997)		384	Brown et al. (2009)

A.2. Freshwater ecosystems

Table A.2.1 Wild grass (Poaceae) - CR values (units of Bq kg^{-1} f.w. per Bq l^{-1})

Element	Arithmetic Mean	Arithmetic Standard Deviaton	Geometric Mean	Geometric Standard Deviation	Minimum	Maximum	N	RefID
Po	4.3E+3						1	311

Table A.2.2 Trout (Salmonidae) - CR values (units of Bq kg^{-1} f.w. per Bq l^{-1})

Element	Arithmetic Mean	Arithmetic Standard Deviaton	Geometric Mean	Geometric Standard Deviation	Minimum	Maximum	N	RefID
Ba	2.0E+1	2.9E+1	1.2E+1	2.9E+0	3.0E-1	1.2E+2	53	333,336,376
C	1.8E+5	6.6E+5	4.7E+4	5.2E+0	8.3E+3	4.0E+6	36	330
Ca	5.1E+2	5.1E+2	3.6E+2	2.3E+0	8.3E+1	4.0E+3	79	333,339,343,361,371
Ce	4.0E+2	5.7E+2	2.3E+2	2.9E+0	2.0E+1	2.3E+3	38	333
Co	9.9E+1	4.4E+1	9.1E+1	1.5E+0	5.5E+1	2.1E+2	32	333
Cr	1.9E+2	1.4E+2	1.6E+2	1.9E+0	2.6E+1	5.0E+2	40	333,343
Cs	4.1E+3	3.1E+3	3.2E+3	2.0E+0	2.6E+2	1.4E+4	93	313,326,327,332,333
Eu	3.3E+1	1.7E+1	3.0E+1	1.6E+0	1.9E+1	6.8E+1	9	333
Fe	1.3E+3	1.5E+3	8.5E+2	2.5E+0	8.7E-1	7.0E+3	88	333,336,339,343,361,371,376
I	7.7E+1	5.3E+1	6.4E+1	1.9E+0	2.5E+1	1.7E+2	9	329,333
La	2.7E+2	3.2E+2	1.7E+2	2.6E+0	5.1E+1	1.3E+3	35	333
Mn	4.1E+3	6.1E+3	2.3E+3	2.9E+0	3.8E+0	2.6E+4	83	333,336,339,343,361,376
Mo	8.7E+0	6.3E+0	7.0E+0	1.9E+0	1.1E+0	2.3E+1	50	333
Ni	1.8E+1	1.4E+1	1.4E+1	2.0E+0	4.3E+0	4.4E+1	8	333,343
P	7.5E+5	2.5E+5	7.1E+5	1.4E+0	3.6E+5	1.2E+6	49	333
Pb	6.8E+2	2.2E+3	2.1E+2	4.7E+0	9.2E+0	7.5E+3	12	336,361,383
Po	2.0E+2	1.7E+2	1.5E+2	2.1E+0	8.3E+1	4.8E+2	5	336,343
Pu	2.6E+1	2.3E+1	2.0E+1	2.1E+0	1.8E+0	5.8E+1	5	306,321
Ra	7.6E+1	1.1E+2	4.2E+1	2.9E+0	6.7E+0	5.6E+2	25	305,339,343,361,371
Sb	7.9E+1	1.6E+2	3.6E+1	3.5E+0	6.9E+0	7.5E+2	24	333
Se	6.6E+3	3.2E+3	5.9E+3	1.6E+0	3.2E+3	1.3E+4	15	361,371,376
Sr	2.1E+2	2.9E+2	1.3E+2	2.8E+0	5.3E+0	1.5E+3	86	333,336,339,361,371,376,389
U	2.1E+1	4.7E+1	8.4E+0	3.8E+0	6.6E-1	1.8E+2	18	339,361,371
Zn	1.0E+4	5.4E+3	8.9E+3	1.7E+0	7.7E+2	2.0E+4	57	333,336,339
Zr	4.7E+2	1.9E+2	4.3E+2	1.5E+0	3.6E+2	6.9E+2	3	333

Table A.2.3 Frog (Ranidae) - CR values (units of Bq kg^{-1} f.w. per Bq l^{-1})

Element	Arithmetic Mean	Arithmetic Standard Deviaton	Geometric Mean	Geometric Standard Deviation	Minimum	Maximum	N	RefID
Ca	1.2E+3	1.3E+3	8.5E+2	2.4E+0	2.8E+2	3.7E+3	8	333

Table A.2.4 Duck (Anatidae) - CR values (units of Bq kg^{-1} f.w. per Bq l^{-1})

No data

Table A2.5 References for Freshwater Reference Animal and Plants (Tables A.2.1 to A.2.4)

Ref ID	Reference short		Ref ID	Reference short
305	Clulow et al. (1998)		333	Yankovich (2010)
306	Edgington et al. (1976)		336	AREVA (2010)
311	Hameed et al. (1993)		339	AREVA (2005)
313	Hewett and Jefferies (1978)		343	AREVA (1998)
321	Marshall et al. (1975)		361	Cameco (2001)
326	Preston and Dutton (1967)		371	Cameco (2000)
327	Rowan and Rasmussen (1994)		376	Cameco (2005)
329	Shorti et al. (1969)		383	Saxen and Outola (2009)
330	Stephenson et al. (1994)		389	Outola et al. (2009)
332	vanderploeg et al. (1975)			

A.3. Marine ecosystems

Table A.3.1 Brown seaweed (Fucaceae) - CR values (units of Bq kg^{-1} f.w. per Bq l^{-1})

Element	Arithmetic Mean	Arithmetic Standard Deviaton	Geometric Mean	Geometric Standard Deviation	Minimum	Maximum	N	RefID
Ag	3.8E+3	6.3E+3	1.9E+3	3.2E+0	4.0E+2	1.5E+4	10	149,16,21,7
Am	9.8E+1	7.7E+1	7.7E+1	2.0E+0	3.9E+1	3.3E+2	33	16,381
Cd	2.0E+3	1.5E+3	1.6E+3	2.0E+0	6.4E+2	4.7E+3	6	97
Ce	9.7E+2	2.1E+2	9.5E+2	1.2E+0	8.0E+2	1.2E+3	3	114
Cm	1.1E+4	8.0E+3	8.4E+3	2.0E+0	2.5E+3	1.6E+4	13	35
Co	1.2E+3	1.6E+3	7.3E+2	2.7E+0	9.0E+0	5.7E+3	59	108,120,149,26,381
Cs	7.2E+1	4.1E+2	1.2E+1	6.5E+0	1.3E+1	4.8E+3	397	107,108,109,110,111,114,120,125,146,381,43,63,70,78,90,91
H	3.7E-1	0.0E+0	3.7E-1	1.0E+0	3.7E-1	3.7E-1	13	381
K	1.8E+2	2.5E+2	1.0E+2	2.9E+0	1.6E+1	6.3E+2	29	26,381
Mn	1.2E+4	7.4E+3	1.1E+4	1.7E+0	2.0E+3	2.3E+4	9	10,120,47
Nb	1.3E+2	1.5E+2	8.1E+1	2.6E+0	2.0E+1	3.0E+2	3	120
Ni	2.0E+3	1.1E+3			1.2E+3	2.8E+3	2	47
Np	5.7E+1	1.9E+1	5.5E+1	1.4E+0	2.0E+1	6.6E+1	46	35,86
Pb	2.5E+3	1.8E+3	2.0E+3	1.9E+0	5.8E+2	4.6E+3	5	97
Pu	3.2E+3	2.6E+3	2.4E+3	2.1E+0	3.3E+2	1.5E+4	146	107,108,111,127,146,381,50,51,63,68
Ru	3.5E+2	2.3E+2	2.9E+2	1.8E+0	1.5E+2	6.0E+2	3	114
Sb	1.5E+3	2.1E+3			7.0E+1	3.0E+3	2	149,89
Sr	5.4E+1	4.0E+1	4.3E+1	1.9E+0	8.0E+0	1.3E+2	40	107,108,111,118,120,146,381
Tc	5.6E+4	6.3E+4	3.7E+4	2.5E+0	7.1E+3	4.3E+5	160	109,110,112,12,23,38,381,66,78,89
U	2.9E+1	0.0E+0	2.9E+1	1.0E+0	2.9E+1	2.9E+1	17	381
Zr	6.4E+2	1.2E+2	6.3E+2	1.2E+0	5.2E+2	7.6E+2	3	114

Table A.3.2 Crab (Cancridae) CR values (units of Bq kg^{-1} f.w. per Bq l^{-1})

Element	Arithmetic Mean	Arithmetic Standard Deviaton	Geometric Mean	Geometric Standard Deviation	Minimum	Maximum	N	RefID
Cs	1.7E+1	1.2E+1	1.4E+1	1.9E+0	1.7E+1	1.7E+1	66	78
Pu	3.8E+1						1	51
Tc	2.1E+2	1.1E+2	1.9E+2	1.6E+0	5.0E+1	3.8E+2	17	25,78

<u>Table A.3.3 Flatfish (Pleuronectidae)</u> CR values (units of Bq kg^{-1} f.w. per Bq l^{-1})

Element	Arithmetic Mean	Arithmetic Standard Deviaton	Geometric Mean	Geometric Standard Deviation	Minimum	Maximum	N	RefID
Am	3.2E+2	4.2E+2	1.9E+2	2.7E+0	4.0E+4	1.5E+3	23	116,55,78
Ca	4.0E-1						1	153
Co	4.2E+2	3.3E+2	3.3E+2	2.0E+0	1.3E+2	9.6E+2	6	147,67,72
Cs	5.6E+1	6.9E+1	3.5E+1	2.6E+0	5.0E+0	5.2E+2	310	110,111,117,125,132,137,143,145,147,386,61,67,78,90,99
Cu	1.5E+3	4.3E+2	1.4E+3	1.3E+0	1.1E+3	2.0E+3	5	153
K	1.1E+1	8.8E-1	1.0E+1	1.1E+0	9.6E+0	1.1E+1	5	153
Mg	1.9E-1						1	153
Mn	2.6E+2	8.0E+1	2.5E+2	1.4E+0	1.8E+2	4.1E+2	6	147,153
Na	1.3E-1						1	153
Ni	2.8E+2	5.3E+1	2.7E+2	1.2E+0	2.1E+2	3.5E+2	5	153
Pb	4.4E+3	3.7E+3	3.3E+3	2.1E+0	9.9E+2	8.8E+3	5	153
Pu	4.4E+1	1.1E+2	1.7E+1	4.1E+0	2.0E+0	3.9E+2	24	120,126,145,386,51,55,78
Sr	1.4E+1	1.1E+1	1.0E+1	2.1E+0	3.0E+0	2.8E+1	12	110,145,91
Zn	2.2E+4	3.4E+3	2.2E+4	1.2E+0	1.9E+4	2.7E+4	4	153
Zr	5.2E+1						1	83

<u>Table A.3.4 Trout (Salmonidae)</u> CR values (units of Bq kg^{-1} f.w. per Bq l^{-1})

Element	Arithmetic Mean	Arithmetic Standard Deviaton	Geometric Mean	Geometric Standard Deviation	Minimum	Maximum	N	RefID
Co	3.9E+4	1.6E+4	3.7E+4	1.5E+0	1.9E+4	7.8E+4	10	74
Cs	6.9E+1	4.3E+1	5.9E+1	1.8E+0	4.1E+1	1.6E+2	11	74
Ra	8.8E+2	6.5E+2	7.1E+2	1.9E+0	9.0E+1	1.9E+3	7	74

Table A3.5. References for Marine Reference Animal and Plants (Tables A.3.1 to A.3.4)

Ref ID	Reference short		Ref ID	Reference short
7	Amiard, J.C. (1978)		91	Matishov et al. (1994)
10	Ancellin et al. (1979)		97	Melhuus et al. (1978)
12	ARCTICMAR (2000)		99	Naustvoll et al. (1997)
16	Boisson et al. (1997)		107	NRPA (1994)
21	Bowen (1979)		108	NRPA (1997)
23	Brown et al (1999)		109	NRPA (1999)
25	Busby et al. (1997)		110	NRPA (2000)
26	Buyanov and Boiko (1972)		111	NRPA (1995)
35	Coughtrey et al. (1984)		112	NRPA (1998)
38	Dahlgaard et al. (1997)		114	Pentreath (1976)
43	Fisher et al. (1999)		116	Pentreath and Lovett (1978)
47	Foster (1976)		117	Pertsov (1978)
50	Germain et al. (2000)		118	Polikarpov (1964)
51	Gomez et al. (1991)		120	Polikarpov (1966)
55	Hayashi et al. (1990)		125	Rissanen et al. (1997)
61	Holm et al. (1994)		126	Rissanen et al. (2000)
63	Holm et al. (1983)		127	Rissanen et al. (1995)
66	Hurtgen et al. (1988)		132	Shutov et al. (1999)
67	Ichikawa and Ohno (1974)		137	Steele (1990)
68	Ikaheimonen et al. (1995)		143	Tateda and Koyanagi (1996)
70	Ilus et al. (2005)		145	Templeton (1959)
72	Ishii et al. (1976)		146	Vakulovsky (2008)
74	Jenkins (1969)		147	Van As et al. (1975)
78	Kershaw et al. (2005)		149	Van Weers and Van Raaphorst (1979)
83	Kurabayashi et al. (1980)		153	Yankovich (2010)
86	Lindahl et al. (2005)		381	WSC (2010)
89	Masson et al. (1995)		386	Lee (2006)
90	Matishov et al. (1999)			

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ANNEX B: DERIVED CONCENTRATION RATIOS

B.1. Terrestrial ecosystems

Table B.1.1 Wild grass (Poaceae) - CR values (units of Bq kg^{-1} f.w. per Bq kg^{-1})

Table B.1.2 Pine tree (Pinaceae) - CR values (units of Bq kg^{-1} f.w. per Bq kg^{-1})

Table B.1.3 Earthworm (Lumbricidae) - CR values (units of Bq kg^{-1} f.w. per Bq kg^{-1})

Table B.1.4 Bee (Apidea) - CR values (units of Bq kg^{-1} f.w. per Bq kg^{-1})

Table B.1.5 Frog (Ranidae) - CR values (units of Bq kg^{-1} f.w. per Bq kg^{-1})

Table B.1.6 Duck (Anatidae) - CR values (units of Bq kg^{-1} f.w. per Bq kg^{-1})

Table B.x. Rat (Muridae) CR values (units of Bq kg^{-1} f.w. per Bq kg^{-1})

Table B.x. Deer (Cervidae) - CR values (units of Bq kg^{-1} f.w. per Bq kg^{-1})

B.2. Freshwater ecosystems

Table B.x. Wild grass (Poaceae) CR values (units of Bq kg^{-1} f.w. per Bq l^{-1})

Table B.x. Trout (Salmonidae) CR values (units of Bq kg^{-1} f.w. per Bq l^{-1})

Table B.x. Frog (Ranidae) CR values (units of Bq kg^{-1} f.w. per Bq l^{-1})

Table B.x. Duck (Anatidae) CR values (units of Bq kg^{-1} f.w. per Bq l^{-1})

B.3. Marine ecosystems – Derived CR values

Table B.3.1 **Brown seaweed (Fucaceae)** CR derived values (units of Bq kg^{-1} f.w. per Bq l^{-1})

Element	Best estimate	Derivation method
Ba	4×10^{0}	Assume CR value for Ca – Macroalgae (This table)
C	8×10^{3}	Assume same as Macroalgae; Ref IDs : 21
Ca	4×10^{0}	Assume same as Estuarine Macroalgae; Ref IDs : 101
Cf	1×10^{2}	Assume CR value for Am – Brown Seaweed (Table A.3.1)
Cl	7×10^{-1}	Assume as Macroalgae, Ref ID 21, 65
Cr	6×10^{3}	Recommended value for Macroalgae from IAEA (2004)
Eu	1×10^{3}	Assume as Macroalgae, Ref ID 141
I	1×10^{3}	Assume as Macroalgae, Ref ID 10,120,21,62, 65
Ir	1×10^{3}	Recommended value for Macroalgae from IAEA (2004)
La	5×10^{3}	Assume same as Estuarine macroalgae; Ref ID : 101
P	1×10^{4}	Assume as Macroalgae, Ref ID : 21
Pa	1×10^{2}	Recommended value for Macroalgae from IAEA (2004)
Po	2×10^{3}	Assume as Macroalgae, Ref ID : 133, 28, 29, 4, 46, 95
Ra	4×10^{1}	Assume as Macroalgae, Ref ID : 18, 29
S	2×10^{0}	Assume as Macroalgae, Ref ID : 21
Se	2×10^{2}	Assume as Macroalgae, Ref ID : 65, 87
Te	1×10^{4}	Recommended value for Macroalgae from IAEA (2004)
Th	3×10^{3}	Assume as Macroalgae, Ref ID : 100, 29, 64
Zn	2×10^{3}	Recommended value for Macroalgae from IAEA (2004)

Table B.3.2 Crab (Cancridae) CR derived values (units of Bq kg^{-1} f.w. per Bq l^{-1})

Element	Best estimate	Derivation method
Ag	2×10^{5}	Recommended value for crustaceans from IAEA (2004)
Am	5×10^{2}	Assume as Crustacean; Ref ID : 133
Ba	7×10^{-1}	Recommended value for crustaceans from IAEA (2004)
C	1×10^{4}	Assume as Crustacean; Ref ID : 21
Ca	5×10^{0}	Recommended value for crustaceans from IAEA (2004)
Cd	8×10^{2}	Assume as Large Crustacean; Ref ID : 53
Ce	1×10^{2}	Assume as Crustacean; Ref ID : 83
Cf	5×10^{2}	Assume CR value for Am – Crustacean (This table)
Cl	6×10^{-2}	Assume as Crustacean; Ref ID : 21
Cm	5×10^{2}	Assume as Am CR for Crustacean (This Table)
Co	5×10^{3}	Assume as Large Crustacean; Ref ID : 120, 147
Cr	1×10^{2}	Recommended value for crustaceans from IAEA (2004)
Eu	4×10^{3}	Recommended value for crustaceans from IAEA (2004)
H	1×10^{0}	Recommended value for crustaceans from IAEA (2004) – tritiated water
I	3×10^{0}	Recommended value for crustaceans from IAEA (2004)
Ir	1×10^{2}	Recommended value for crustaceans from IAEA (2004)
La	??	
Mn	3×10^{3}	Assume as Large Crustacean; Ref ID : 53, 85
Nb	1×10^{2}	Assume as Crustacean; Ref ID : 10
Ni	1×10^{3}	Recommended value for crustaceans from IAEA (2004)
Np	4×10^{1}	Assume CR value for Pu – crab (Table

		A.3.2)
P	3×10^{4}	Value derived from stable P in crustaceans from Hosseini et al. (2008)
Pa	1×10^{1}	Recommended value for crustaceans from IAEA (2004)
Pb	3×10^{3}	Assume as Large Crustacean; Ref ID : 4, 59
Po	4×10^{3}	Assume as Large Crustacean; Ref ID : 4
Ra	7×10^{1}	Assume as Crustacean; Ref ID : 96
Ru	1×10^{2}	Recommended value for crustaceans from IAEA (2004)
S	1×10^{0}	Recommended value for crustaceans from IAEA (2004)
Sb	3×10^{2}	Recommended value for crustaceans from IAEA (2004)
Se	1×10^{4}	Recommended value for crustaceans from IAEA (2004)
Sr	4×10^{1}	Assume as Crustacean; Ref ID :110,120,13,133,145,22,51,83
Te	1×10^{3}	Recommended value for crustaceans from IAEA (2004)
Th	1×10^{3}	Recommended value for crustaceans from IAEA (2004)
U	1×10^{1}	Recommended value for crustaceans from IAEA (2004)
Zn	3×10^{5}	Recommended value for crustaceans from IAEA (2004)
Zr	5×10^{1}	Assume as Crustacean; Ref ID : 83

Table B.3.3 <u>Flatfish (Pleuronectidae)</u> CR derived values (units of Bq kg^{-1} f.w. per Bq l^{-1})

Element	Best estimate	Derivation method
Ag	8×10^{3}	Assume as Marine Fish; Ref ID : 21, 31, 8
Ba	4×10^{-1}	Assume CR value for Ca – Flatfish (A.3.3)
C	1×10^{4}	Assume as Marine Fish; Ref ID : 21
Cd	1×10^{4}	Assume as Marine Fish; Ref ID : 10, 31, 36, 87
Ce	2×10^{2}	Assume as Marine Fish; Ref ID : 141, 83
Cf	2×10^{2}	Assume CR value for Am – Flatfish (A.3.3)
Cl	6×10^{-2}	Recommended value for fish from IAEA (2004)
Cm	2×10^{2}	Assume CR value for Am – Flatfish (A.3.3)
Cr	2×10^{2}	Recommended value for fish from IAEA (2004)
Eu	7×10^{2}	Assume as Marine Fish; Ref ID : 141
H	1×10^{0}	Recommended value for fish from IAEA (2004), tritiated water
I	9×10^{0}	Recommended value for fish from IAEA (2004)
Ir	2×10^{1}	Recommended value for fish from IAEA (2004)
La	??	
Nb	3×10^{1}	Recommended value for fish from IAEA (2004)
Ni	2×10^{2}	Assume as Marine Fish Ref ID : 10, 153, 31
Np	2×10^{1}	Assume CR value for Pu – Flatfish (A.3.3)
Pa	5×10^{1}	Recommended value for fish from IAEA (2004)
Po	1×10^{4}	Assume as Marine Fish; Ref ID :

		28, 29, 4, 46, 51
Ra	6×10^{1}	Assume Fish – Benthic feeding; Ref ID : 121, 96
Ru	1×10^{1}	Assume as Marine Fish; Ref ID : 10,
S	1×10^{0}	Recommended value for fish from IAEA (2004)
Sb	6×10^{2}	Recommended value for fish from IAEA (2004)
Se	1×10^{4}	Recommended value for fish from IAEA (2004)
Tc	8×10^{1}	Recommended value for fish from IAEA (2004)
Te	1×10^{3}	Recommended value for fish from IAEA (2004)
Th	1×10^{3}	Assume as Marine Fish; Ref ID : 29
U	4×10^{0}	Assume Fish – Benthic feeding; Ref ID : 122

2181 **Table B.3.4 <u>Trout (Salmonidae) Marine</u>** CR derived values (units of Bq kg^{-1} f.w. per
2182 Bq l^{-1})
2183

Element	Best estimate	Derivation method
Ag	8×10^{3}	Assume as Marine Fish; Ref ID : 21, 31, 8
Am	2×10^{2}	Assume as Marine Fish; Ref ID : 116, 55, 78
Ba	5×10^{0}	Assume CR value for Ca – Marine Fish (This table)
C	1×10^{4}	Assume as Marine Fish; Ref ID : 21
Ca	5×10^{0}	Assume as Marine Fish; Ref ID : 153
Cd	1×10^{4}	Assume as Marine Fish; Ref ID : 10, 31, 36, 87
Ce	2×10^{2}	Assume as Marine Fish; Ref ID : 141, 83
Cf	2×10^{2}	Assume CR value for Am – Marine Fish (This table)
Cl	6×10^{-2}	Assume as Marine Fish; Ref ID : 21
Cm	2×10^{2}	Assume CR value for Am – Marine Fish (This table)
Cr	2×10^{2}	Recommended value for fish from IAEA (2004)
Eu	7×10^{2}	Assume as Marine Fish; Ref ID : 141
H	1×10^{0}	Recommended value for fish from IAEA (2004); tritiated water
I	9×10^{0}	Recommended value for fish from IAEA (2004)
Ir	2×10^{1}	Recommended value for fish from IAEA (2004)
La	??	
Mn	1×10^{2}	Assume Fish – piscivorous; Ref ID : 153, 85
Nb	3×10^{1}	Recommended value for fish from IAEA (2004)
Ni	2×10^{2}	Assume Fish – piscivorous; Ref

		ID : 153
Np	1×10^{2}	Assume CR value for Pu, Fish – piscivorous (This Table)
P	9×10^{4}	Assume as Marine Fish; Ref ID : 75
Pa	5×10^{1}	Recommended value for fish from IAEA (2004)
Pb	1×10^{3}	Assume Fish – piscivorous; Ref ID : 153
Po	2×10^{4}	Assume Fish – piscivorous; Ref ID : 28, 46
Pu	1×10^{2}	Assume Fish – piscivorous; Ref ID : 108, 111, 126, 146, 51
Ru	1×10^{1}	Assume as Marine Fish; Ref ID : 10
S	1×10^{0}	Recommended value for fish from IAEA (2004)
Sb	6×10^{2}	Recommended value for fish from IAEA (2004)
Se	1×10^{4}	Recommended value for fish from IAEA (2004)
Sr	2×10^{1}	Assume Fish – piscivorous; Ref ID : 110, 111, 120, 91
Tc	8×10^{1}	Recommended value for fish from IAEA (2004)
Te	1×10^{3}	Recommended value for fish from IAEA (2004)
Th	1×10^{3}	Assume as Marine Fish; Ref ID : 29
U	2×10^{1}	Assume Fish – piscivorous; Ref ID : 122
Zn	3×10^{4}	Assume Fish – piscivorous; Ref ID : 153
Zr	8×10^{1}	Assume as Marine Fish; Ref ID : 10, 123, 83

Table B.3.5 References for Derived values for Marine Reference Animal and Plants (Tables B.3.1 to B.3.4)

Ref ID	Reference short		Ref ID	Reference short
4	Al Masri et al. (2000)		85	Lentsch et al. (1971)
8	Amiard (1978)		87	Locatelli and Torsi (200)
10	Ancellin et al. (1979)		91	Matishov et al. (1994)
13	Bachurin et al. (1967)		95	McDonald et al. (1992)
18	Bonotto et al (1981)		96	Meinhold and Hamilton (1990)
21	Bowen (1979)		100	Nilsson et al. (1981)
22	Brown and Iosjpe (2001)		101	NIRS (pers comm.)
28	Carvalho (1988)		108	NRPA (1997)
29	Cherry and Shannon (1974)		110	NRPA (2000)
31	Cohen (1985)		111	NRPA (1995)
36	Coughtrey and Thorne (1983)		116	Pentreath and Lovett (1978)
46	Folsom et al. (1973)		120	Polikarpov (1966)
51	Gomez et al. (1991)		121	Porntepkasemsan and Nevissi (1990)
53	Guthrie et al. (1979)		122	Poston and Klopfer (1986)
55	Hayashi et al. (1990)		123	Poston and Klopfer (1988)
59	Heyraud and Cherry (1979)		126	Rissanen et al. (2000)
62	Holm et al. (1994)		133	Sivintsev et al. (2005)
64	Holm and Persson (1980)		141	Suzuki et al. (1975)
65	Hou and Yan (1998)		145	Templeton (1959)
75	Kahn and Turgeon (2005)		146	Vakulovsky (2008)
78	Kershaw et al. (2005)		147	Van As et al. (1975)
83	Kurabayashi et al. (1980)		153	Yankovich (2010)

B.4. References for Annex B

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