Strålevern Rapport 2005:5

Environmental Impact Assessments in Arctic Environments

Protection of plants and animals

Statens strålevern

Norwegian Radiation Protection Authority
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Key words:
European Arctic, reference organism, concentration factors/ratios, dose conversion coefficients, internal and external dose, dose-effect relationship.

Abstract:
This report considers an approach to conduct environmental impact assessments in the European Arctic based on the EC funded project "EPIC". Reference Arctic organisms and representative species are proposed based on the application of suitable selection criteria. Datasets providing information on concentration ratios/factors (CR/CF) and radionuclide specific Dose Conversion Coefficient (DCCs) are generated for reference organism groups and a suite of 13 radioelements. Methodologies for calculation of doses to reference organisms (internal and external) are presented.

Referanse:
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Emneord:
Arktis, referanseorganismer, konsentrasjonsfaktorer, dosekonverteringskoeffisient, interndose, eksterndose, doseeffekter.

Resymé:
Denne rapporten beskriver en tilnærming til miljøkonsekvensanalyser i arktiske strøk basert på EU-prosjektet EPIC. Det er, med grunnlag i gitte utvelgelseskriterier, foreslått egnede referanseorganismer og representative arter. Og det er utarbeidet tabeller over nuklidespesifikke konsentrasjonsfaktorer (CR/CF) og dosekonverteringskoeffisienter (DCCs) for referanseorganismer og ulike radioisotoper av 13 elementer. Metoder for å beregne doser til referanseorganismer (intern og ekstern) er også presentert.

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Table of Content

I SUMMARY

This report outlines an approach to conduct environmental impact assessment in Arctic regions based on findings from the EC funded project "EPIC" (Environmental Protection from Ionising Contaminants in the Arctic) and explores how the advances made in that project may provide input towards the development of criteria and standards ensuring protection of the Arctic environment from ionising radiation. The proposed system consists of a problem formulation stage and an assessment methodology. In a geographical context it is limited to the European Arctic, and with respect to contamination sources to a suite of 13 radioelements. The starting point for the assessment has been selected to be a unit concentration of a specified radionuclide in the environment with emphasis placed upon food chain transfer as opposed to physical transport processes.

Lists of reference organisms have been constructed based on suitable selection criteria and guidance on the types of ecological information required for reference fauna has been provided. Datasets on concentration ratios/factors (CRs/CFs) have been collated for reference organism types and the suite of radionuclides considered. In cases where data coverage is poor or non-existent use has been made of allometric relationships and biokinetic models in order to provide estimates. The method for deriving absorbed doses is based on an approximation of the dose distribution using Dose attenuation and Chord distribution functions. External doses to organisms are calculated using a variant of a simple formula for a uniformly contaminated isotropic infinite absorbing medium. A two-step method has been used for the estimation of external exposures at the interface of environments with different densities. Radionuclide specific Dose Conversion Coefficient(DCCs) have been generated for all reference organism groups and the suite of radionuclides considered. For internal exposure, DCCs have been derived assuming a homogeneous distribution of the radionuclide in the organism. Weighted DCCs have been calculated using provisional weighting factors. Data of dose-effects relationships in biota have been collated and then organised under "umbrella" end-point categories including e.g. reproduction, mortality and cytogenetic effects. Preliminary scales defining the severity of radiation effects at different levels of chronic exposure for different organisms groups have been constructed.

Based on the available information it is not possible to justify any Arctic specific dose-standards at the present time. However, an evaluation of potential effects from a given dose rate may be obtained using the information collated within the present approach. Finally, areas of information deficiencies are identified and re-commendation made for further development of the system. In particular, these relate to the development of better transfer data and a more detailed exploration of dose-effects on Arctic species.

II Sammendrag

Denne rapporten beskriver en tilnærming til miljøkonsekvensanalyser i arktiske strøk, basert på EU-prosjektet EPIC, og utforsker hvordan resultatene fra prosjektet kan brukes i forbindelse med utarbeidelse av kriterier og standarder for beskyttelse av arktisk miljø mot ioniserende stråling.

Systemet som foreslås, består hovedsakelig av et problemformuleringstrinn og en metode til å bestemme (og til en viss grad evaluere) doser til biota – med vekt på det siste punktet. Det omfatter ulike radioisotoper av 13 elementer og er geografisk avgrenset til den europeiske delen av Arktis.

Det er utarbeidet lister over egnede referanseorganismer, basert på spesifiserte utvelgelseskriterier, for tre bredt definerte økosystemer (marint, ferskvann og terrestrisk). Konsentrasjonsfaktorer for forskjellige nuklider og referanseorganismer er samlet i tabeller. I tilfeller der mengden empiriske data er begrenset, eller når slike data ikke er tilgjengelige, er konsentrasjonsfaktorene estimert ut fra allometriske forhold og biokinetiske modeller.

Ved bestemmelse av absorberte doser er det gjort antakelser om dosefordeling i ulike geometriske former. For intern eksponering er det beregnet nuklidespesifikke dosekonverteringskoeffisient – her er det antatt en homogen fordeling av radionukliden i organismen. Dosekonverteringsfaktorer er også brukt i forbindelse med ekstern eksponering. Her er det antatt en uniform kontaminering i et isotropisk, uendelig absorberende medium, og det er benyttet en totrinns metode til å estimere doser fra overflater med forskjellig tetthet.

Det er samlet informasjon om effekter av ioniserende stråling på arktisk biota. Innsamlede data omfatter en rekke plante- og dyrearter og et stort spenn i doserate. Effektdataene er kategorisert i bredt definerte endepunkter (mortalitet, effekter på reproduksjon etc.). Videre er det utarbeidet foreløpige doseeffektskalaer for ulike organismer. Potensielle effekter av gitte doserater kan til en viss grad evalueres ved å sammenlikne beregnede doser med disse doseeffektskalaene, men tilgjengelig informasjon er for begrenset til at det kan settes spesifikke dosegrenser for arktisk miljø på det nåværende tidspunkt. Det trengs særlig bedre overføringsdata og en mer detaljert utforskning av doseeffekter på Arktiske organismer før dette kan fastsettes.

Anbefalinger for videre utvikling av det foreslåtte systemet er gitt til slutt i rapporten.

1 The concept of environmental protection from ionising radiation

The main part of this report is concerned with a presentation of the approach proposed for Arctic based on the EPIC assessment system. This methodology is a key part of a system of protection that has been developed for ionising radiation, largely based on the Ecological Risk Assessment (ERA) approach. Specifically, ERA is built on the three phases of problem formulation, exposure and effects analysis, and risk characterisation (Suter, 1993). A discussion of the proposed system with respect to these three steps can be found in the following chapters.

1.1 Special considerations for the protection of the Arctic environment

At the scientific level, there are considerations that make the Arctic an interesting study case. There is evidence to suggest that the *in situ* physical conditions in the Arctic may hypothetically alter radionuclide transfer to biota (Kryshev & Sazykina, 1986, 1990; Sazykina, 1995, 1998), at least in the case of poikilotherms. Indeed, the slower digestion and metabolism of cold water animals resulting in slower efflux rates than in warm water species has been cited as a possible reason that differences may be observed in biological uptake within Arctic marine environments (Fisher *et al*., 1999). The modifying influence of Arctic climatic conditions upon the expression of radiation induced effects has been considered in some detail in Section 6.6. However, low temperatures, extreme seasonal variations in incoming solar radiation and lack of nutrients are physical and chemical environmental stressors of Arctic organisms which limit biodiversity. These also make Arctic ecosystems potentially more vulnerable to contaminants than organisms in other European climatic regions (AMAP, 1998). In addition, the Arctic contains several potential radionuclide sources (e.g. the Kola nuclear power plants, dumped radioactive waste, sunken reactor-driven submarines). A full discussion of the potential sources of anthropogenic radioactive pollution in the Arctic is given by Strand *et al*. (1997).

1.2 Environmental protection – Arctic legal regime

The Arctic consists of territories of various nations, and as such has no overall and binding legal regime. As elsewhere, the framework for environmental protection of the Arctic is constituted by national laws. However, global treaties and norms to a larger and larger extent influence the national laws – something that is undoubtedly linked to the special status of the Arctic environment discussed above. In particular, marine treaties have influenced the domestic laws, and much of the focus of environmental protection of the Arctic has therefore been upon marine conservation (Brown *et al*., 2003b).

1.3 Framework and scope of a system for environmental protection

A number of recent publications (Pentreath 1998; Pentreath, 1999; Strand *et al*., 2000; Strand & Larsson, 2001) have called for the development of a system for protecting the environment from ionising radiation. Discussion within the scientific community has led to the formalisation of the proposed framework within EPIC, and a larger EURATOM project entitled **F**ramework for **ASS**essment of **E**nvironmental Impac**T**

"FASSET". Furthermore, the approach adopted by these projects has now been advocated by a number of international authorities including the International Commission on Radiological Protection (ICRP) (Strand & Holm, 2002), the International Union of Radioecology (IUR) (IUR, 2002) and the International Atomic Energy Agency (IAEA) (Robinson, 2002).

Larsson *et al.* (2002a) provide an overview of the elements characteristic of an environmental assessment and management procedure (Figure 1.1). The overall system is typical of the Ecological Risk Assessment (ERA) approach promoted by US Environmental Protection Agency (EPA), based primarily on pathway based assessment systems (Suter, 1993). The system is divided into five different steps: planning, problem formulation (to guide further assessment, i.e. to define the assessment context), assessment (using the appropriate methods according to the assessment context), risk characterisation and decision and management.

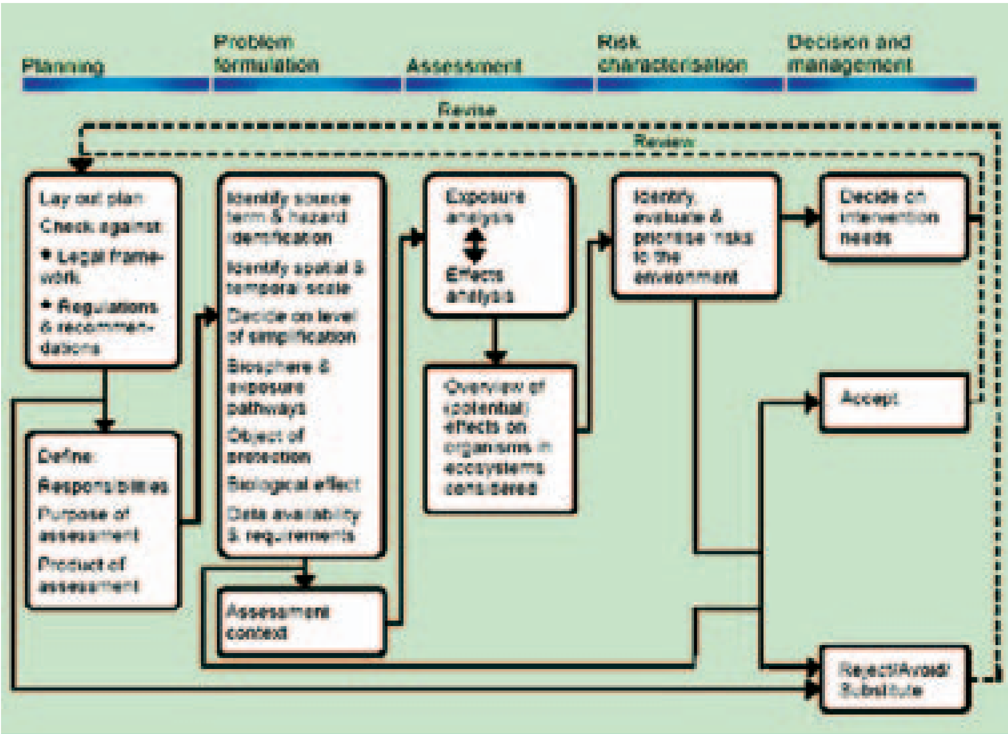


Figure 1.1 *Elements in a stepwise environmental assessment and management procedure (Larsson et al., 2002a).*

In the proposed system, the scope of the assessment methodology consists of the problem formulation stage and an assessment methodology that should enable an assessor to quantify the probable effect of radiation exposure to selected biota following a defined release of radionuclides. Although aspects of planning (e.g. compatibility check with underlying principles and international regulation) were deemed necessary in order to facilitate compatibility with legislative requirements at national levels, it was recognised that any system needs to be generic enough to allow broad applicability. Thus, standards and limits have not been integrated into the system, since these are likely to be imposed through national regulation. However, the system may be used to structure information in a way that could allow standards to be developed – as will be attempted in this report.

Efforts have been made to ensure compatibility between the approaches taken within FASSET and EPIC. Whereas FASSET has focussed primarily on the development of a generic system or at least a system that has utility within a broad European setting, EPIC has centred on the development of common ideas using the example case of the European Arctic with the advantage of being able to utilise Russian expertise and extensive data sets from the former Soviet Union relating to environmental exposure from radiation.

1.4 Scope of the EPIC assessment system

The area considered in EPIC is the European Arctic, defined as northern Scandinavia, northwest Russia (west of the Urals), the islands of Franz Joseph Land, Novaya Zemyla and Svalbard, and the Barents, Kara, White and Greenland Seas including the northern part of the Norwegian Sea (Figure 1.2).

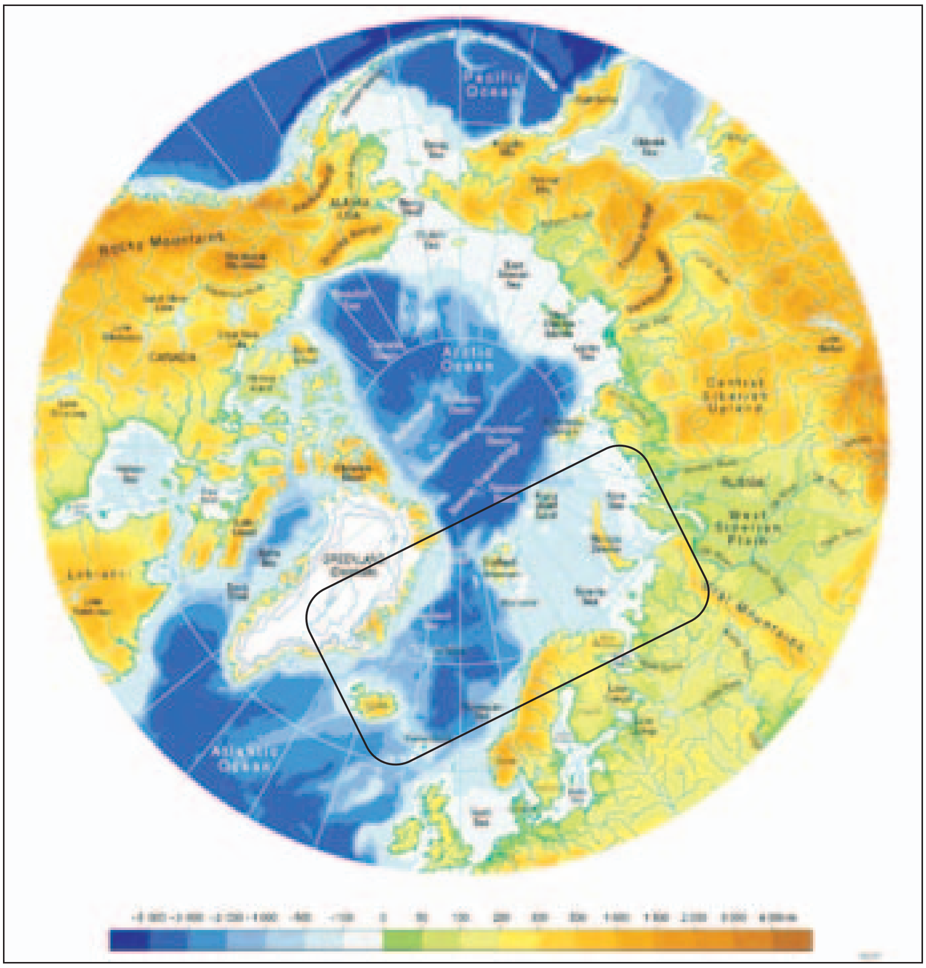


Figure 1.2 *Topography and bathymetry of the Arctic (taken from AMAP 1998); the box delimits the approximate area of the European Arctic as defined within EPIC.*

The assessment methodology, as presented here, is limited in terms of radionuclides considered for reasons related to the practicability of producing robust data sets within limiting time constraints. Ideally the initial list will be expanded to cover all radionuclides that may be of interest in an assessment context. Table 1.1 presents the initial list of 13 radionuclides considered in the EPIC project. These are broadly representative of (i) routine release scenarios from power plants and reprocessing facilities, (ii) accidental releases and (iii) naturally-occurring or technologically-enhanced naturally-occurring (TENORM) radio-nuclides. The selected radionuclides cover a broad range of environmental mobility and biological uptake and hence the system should be flexible enough to allow other radionuclides to be assessed with the provision of appropriate parameters. For aquatic systems, ^{32}P, ^{54}Mn, ^{60}Co and ^{65}Zn were also considered for biological transfer as they are routinely released into waters of the study area.

Table 1.1 Selected radionuclides with generalised characteristics adapted from Whicker & Schultz (1982).

Radioelement (Periodic Group)	Principal Radioisotopes ($T_{1/2}$)	Sources	Nutrient analogues	Principal biospheric reservoirs	Environmental mobility	Concentration increase with trophic level	Critical organ (vertebrates)	Biological half-life (mammals)
K (Ia)	^{40}K (1.3 x 10^9 y)	Primordial	K	Lithosphere	High	Approaches 1	Total body	Moderate (weeks)
Cs (Ia)	^{134}Cs (2.06 y), ^{137}Cs (30 y)	Fission	K	Soil, sediments	High	Approaches 3	Total body	Moderate (weeks-months)
Sr (IIa)	^{89}Sr (50.5 d) ^{90}Sr (28.5 y)	Fission	Ca	Soil, biota	High	< 1	Bone	High (years)
Tc (VIIa)	^{99}Tc (2.13 x 10^5 y)	Fission	None	Biota, soil	High	< 1	Gastrointestinal tract, lung	Low (days)
Po (VIb)	^{210}Po (138 d)	^{238}U decay series	None	Soil, sediment	High	<1-10	Spleen, kidney, lung	Moderate (weeks)
Pu (Actinide series)	^{238}Pu (88 y) ^{239}Pu (2.4 x 10^5 y) ^{240}Pu (6.5 x 10^3 y) ^{241}Pu (14.4 y)	Neutron activation,	None	Soil, sediment	Very low	< 10^{-2}	Bone, lung	High (years)
Am (Actinide series)	^{241}Am (432 y)	Neutron activation,, decay of ^{241}Pu	None	Soil, sediment	Very low	< 10^{-2}		High (years)
I (VIIb)	^{129}I (1.57 x 10^7 y) ^{131}I (8.04 d)	Fission	I	Biota, soil	High	Up to 10^3 (thyroid/plants)	Thyroid	Moderate (weeks-months)
Ra (IIa)	^{226}Ra (1600 y)	^{238}U decay series	Ca	Lithosphere	Moderate	< 1	Bone	High (years)
H (Ia)	^{3}H (12 y)	Cosmic, fission, neutron activation	H	Hydrosphere (tritiated water)	High	Approaches 1	Total body	Low (days)
C (IVb)	^{14}C (5600 y)	Cosmic, neutron activation	C	Atmosphere (CO_2)	High	Approaches 1	Total body	Low (days)
Th (Actinide series)	^{227}Th (18.7 d) ^{228}Th (1.9 y) ^{230}Th (7.7 x 10^4 y) ^{231}Th (25.5 h) ^{232}Th (1.4 x 10^{10} y) ^{234}Th (24.1 d)	Natural, U & Th series decay chains	None	Lithosphere	Very low	< 10^{-2}	Bone, lung	High (years)
U (Actinide series)	^{234}U (2.45 x 10^5 y) ^{235}U (7.04 x 10^8 y) ^{238}U (4.47 x 10^9 y)	Natural	None	Lithosphere	Low-moderate	< 1	GI, kidney, lung	Moderate (months)

For the generic applicability of the system, focus has mainly been on biological uptake. Environmental (physical) transport models have not been considered within the exposure assessment methodology although their inclusion within the overall framework should not be problematic. As long as an assessor can produce (transport) model output in the form of activity concentrations in reference media (e.g. water, soil) compatibility with the assessment methodology is straight forward.

Three broad ecosystem categories were selected for further consideration, namely: terrestrial, freshwater and marine. The starting point for the assessment has been selected to be a unit concentration in the organisms' habitat, e.g. unit activity concentration per litre of water in the case of the aquatic environment and a unit activity concentration per kg of soil (or in the case of ^{3}H and ^{14}C Bq per m^{-3} air) in terrestrial environments. In the absence of monitoring data, it is assumed that the assessor will have access to appropriate models to allow activity concentrations in abiotic compartments of the environment to be calculated.

1.5 Stages in the proposed exposure assessment

The stages in the assessment are depicted in Figure 1.3. The initial stage of the assessment requires the selection of radionuclides and of appropriate reference biota and suitable representative organisms (normally defined at the species level) with concomitant collation of life history data sheets (see Section 2.2). Following these steps, the exposure assessment is conducted using the basic methodology outlined in Chapter 5. Methods for deriving the transfer and fate of radionuclides in Arctic ecosystems are necessary during this procedure as are methods for deriving (weighted or unweighted) dose rates. Once exposures for reference biota have been derived, they need to be interpreted in terms of biological effects.

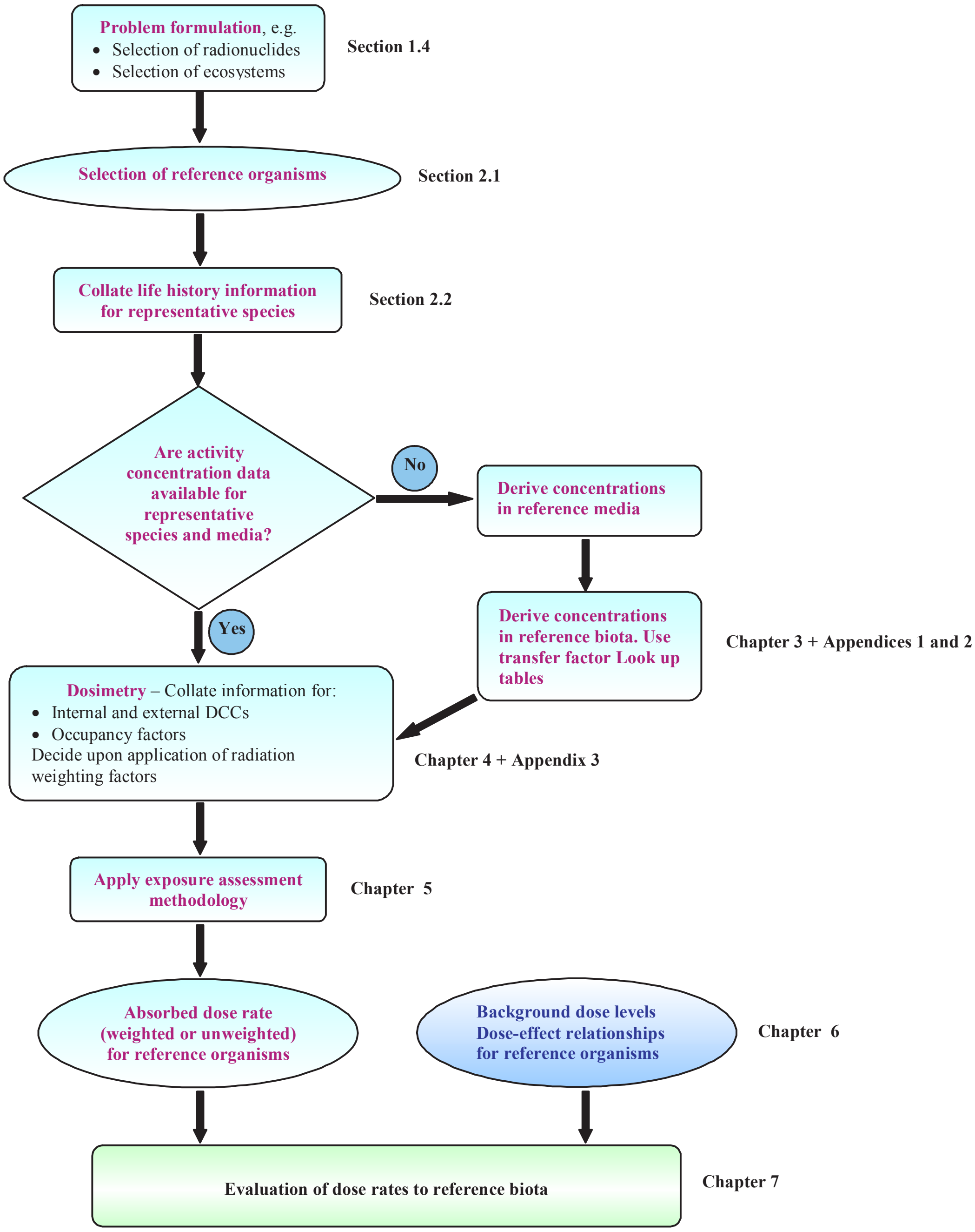


Figure 1.3 *Flow diagram showing stages in the proposed exposure assessment. The indicated Sections and Chapters refer to the present report.*

1.5.1 Issues related to selection of data for use in the assessment

In some cases, it will be necessary to predefine the evaluation area, i.e. site boundary or area of elevated contamination, and then collate data from within these boundaries. The subsequent method of "averaging" data or selecting which data are appropriate for the assessment is currently a point for contention and will depend upon the purpose of the assessment. The approach adopted by the present framework is based on the average absorbed dose rates to a relatively small subset of the population (in line with the critical group approach for humans). In this approach choice will have to be made about what fraction of population is appropriate for assessment. However, here, flexibility should be seen as an advantage since what is appropriate will in turn be dependent on other factors such as the size of population, number of offspring, etc.

A direct consideration of the uncertainties involved in the exposure assessment have not been addressed within the present assessment system, although it is acknowledged that there are many sources of uncertainty limiting the confidence with which outputs can be viewed. In some cases both the range and best estimate values (e.g. transfer factors, activity concentrations in reference media and biota etc.) have been tabulated. Furthermore such data may have utility not only in compliance situations (where maximum values may be required) but also within sensitivity and uncertainty analyses. In evolving a true environmental risk assessment wherein a method is required to assess not only the severity of a hazard but also the probability of that hazard occurring, addressing uncertainty is recognized as being crucial.

1.6 Aims and structure of the present report

This report aims to describe how the different components of the EPIC impact assessment framework can be combined to form a complete system to allow an environmental impact assessment for ionising radiation in the Arctic. These components comprise selection of reference organisms/species, radionuclide transfer, dose models and dose-effects relationships. The report also aims to provide recommendation towards the development of Arctic radiological standards for non-human biota.

In Chapter 2, guidance on the selection of reference organism and representative groups is presented. Thereafter, transfer factors appropriate for Arctic conditions (Chapter 3), dosimetric models relevant for the derivation of absorbed doses to Arctic biota (Chapter 4) and the assessment methodology in its entirety (Chapter 5) are provided. Effects data pertaining to the assessment of effects arising from exposure to boreal/Arctic species are presented in Chapter 6. The development of numeric standards (e.g. dose limits) for Arctic biota is explored in Chapter 7. Finally, in Chapter 8, conclusions and recommendations for future work are presented.

2 Reference organisms

This chapter deals with the selection of suitable Arctic reference organisms. The “reference organism” is defined as: “a series of entities that provides a basis for the estimation of the radiation dose rate to a range of organisms that are typical, or representative, of a contaminated environment. These estimates, in turn, would provide a basis for assessing the likelihood and degree of radiation effects.” (Larsson *et al.*, 2002b).

2.1 Selection of reference organisms

The EPIC approach requires the selection of reference organisms during the initial stages of the assessment. For freshwater, marine and terrestrial environments, selection criteria have been applied in order to select a reference organism suite although this forms only a subset of numerous other criteria that could be applied (see for example Pentreath & Woodhead, 2001). The criteria applied in EPIC are:

- **Ecological niche**. This is simply applied as a requirement to have at least one representative from each trophic level.
- **Intrinsic radiosensitivity**. In this case comparison is made between the acute lethal doses expressed by various organism groups.
- **Radioecological sensitivity**. Identification of which organisms are likely to be most exposed either through an expression of relatively high radionuclide bioaccumulation or relatively high activity concentrations in their habitat.
- **Distribution**. Preference is given to those organisms that are common and widely distributed through the Arctic region, preferably year-round residents in the Arctic.
- **Amenability to research and monitoring**. This criterion involves an assessment of whether data sets documenting activity concentrations in various groups of organism are available from monitoring studies and whether future research might be conducted upon the various groups (e.g. exposure experiments etc.).

The reference European Arctic organisms for marine, freshwater and terrestrial ecosystems as proposed by the EPIC project are given in Tables 2.1-2.3. The generic reference organism lists have been used as a basis for deriving appropriate environmental transfer data information and selecting suitable target geometries for dosimetric modelling. With respect to these points, it became apparent that the identification of actual species (or in some cases families or classes of organisms) representing each of the broadly defined groups would be helpful in some instances, these are included in Tables 2.1-2.3. This was true in the case of deriving food-chain model parameters where detailed information was often required, beyond a generic consideration, with respect to organism characteristics. It was also true in the case of geometry construction where quantitative information on size, shape and density are required and can be derived, simply and transparently, from a consideration of real flora and fauna. Examples of suitable representative species of selected reference organisms were subsequently chosen giving preference to species ubiquitous throughout the European Arctic and the availability of appropriate data (Tables 2.1 -2.3).

Table 2.1 Reference organisms and representative families/species for marine ecosystems

Reference organism	*Representative species*	*Availability of information*		
		Life History	*CF*	*DCC*
Benthic bacteria	Not applicable	No	No	No
Phytoplankton	Not applicable	Yes	Yes	No
Macroalgae	*Fucus* spp.	Yes	Yes	No
Pelagic crustacean	*Pandalus borealis*	Yes	Yes	Yes
Benthic mollusc	*Mytilus edulis*	Yes	Yes	Yes
Polychaetes	*Arenicola marina Lumbrineris* spp.	Yes	Yes	No
Pelagic planktotrophic fish	*Boreogadus saida* (polar cod) *Mallotus villosus* (capelin) *Clupea harengus* (herring)	Yes	Yes	Yes
Benthic crustacean	*Cancer pagurus*	*	Yes	Yes
Pelagic carnivorous fish	*Gadus morhua* (cod)	Yes	Yes	Yes
Benthic fish	*Pleuronectes* spp. (e.g. *Pleuronectes platessa*, plaice)	Yes	Yes	Yes
Sea bird	*Larus spp.*	Yes	Yes	Yes
Carnivorous mammal	'Seals' *(Erignathus barbatus, Phoca hispida, Phoca groenlandica)*	Yes	Yes	Yes
Fish egg	Not applicable	No	No	No

* Life history data available for European Lobster (*Homarus gammarus*)

Table 2.2 Reference organisms and representative families/species for freshwater ecosystems

Reference organism	*Representative species*	*Availability of information*		
		Life history	*CF*	*DCC*
Benthic bacteria	Not applicable	No	No	No
Aquatic plants	'Freshwater monocotyledons' (e.g. *Carex* spp.)	No	No	No
Phytoplankton	Not applicable	No	No	No
Zooplankton	Rotifera	No	No	No
Insect larvae	*Chironomid* spp.	No	No	No
Pelagic planktotrophic fish	*Coregonus peled* (northern whitefish), *Coregonus laveretus* (cisco) & *Coregonus albula* (shallow-water cisco)	No	* *	No
Pelagic carnivorous fish	*Esox lucius* (pike)	No	*	No
Benthic fish	*Coregonus lavaretus* (cisco) & *Salvelinus alpinus* (Arctic char)	No	*	No
Carnivorous mammal	*Mustela lutrecla* (mink)	No	No	No
Fish egg	Not applicable	No	No	No

* Some information is available only for ^{137}Cs and ^{90}Sr

Table 2.3 Reference organisms and representative families/species for terrestrial ecosystems

Reference organism	*Representative species*	*Availability of information*		
		Life history	*CR*	*DCC*
Soil micro-organism	Not applicable	No		No
Lichens & Bryophyte	*Cladonia* spp.	Yes	*	No
Gymnosperm	*Juniperus* spp., *Larix dahurica, Picea obovata*	Yes	*	Yes (plant roots)
Monocotyledon	*Carex* spp., *Luzula* spp., *Festuca* spp.	Yes	*	Yes (plant roots)
Dicotyledon	*Vaccinium* spp.	Yes	*	Yes (plant roots)
Soil invertebrate	Collembola & mites	Yes	*	Yes
Herbivorous mammal	'Lemmings and voles' (*Dicrostonyx* spp., *Myopus* spp., *Lemmus* spp., *Microtus* spp., *Clethrionomys* spp. & *Eothenomys* spp.)	Yes	*	Yes
	Reindeer (*Rangifer tarandus*)	Yes	*	Yes
Carnivorous mammal	'Foxes' (*Vulpes vulpes* & *Alopex lagopus*)	Yes	*	Yes
Herbivorous bird	*Lagopus* spp.	Yes	*	Yes
Egg from ground-nesting bird	*Lagopus* spp.	Yes		Yes

* CRs not available for all radionuclides

Life history data have been collated for most representative species in marine and terrestrial ecosystems. Recommended CR/CF values are provided for both terrestrial and marine systems (Appendices 1 and 2, respectively). Although in the case of the former system, data availability has limited this exercise to only a few radionuclides for many of the reference biota considered.

As shown in Tables 2.1 - 2.3, DCCs are not available for all reference organisms. DCCs for phytoplankton, macroalgae and polychaetes have not been derived. In view of the radioresistance of marine flora and the lack of data on polychaetes (uptake and dose-effect information), it was considered unlikely that these organism types would feature strongly in any environmental impact assessment. In the terrestrial ecosystem, DCCs for plant roots have been derived for *Vaccinium spp*. and these may be applied for Gymnosperms and Monocotyledons. No DCCs for freshwater have been derived. Phantoms that correspond in dimensional terms may be suitably adopted from the marine list. For example, the DCC for cod may suitably be used as a proxy for pike.

For the case of micro-organisms/bacteria in both terrestrial and aquatic environments, it has been shown (Pröhl *et al.,* 2003) that absorbed dose will be dominated by the external component of dose. If dose rates to these organisms require calculation, simple assumptions can be made. For example it can be assumed that the organism resides in an infinite absorbing medium and that all radiation energies are absorbed by the organism.

2.2 Life history data sheets

Basic ecological information needs to be collated for each of the selected flora and fauna. The specific organism attributes that should be considered relate directly to the subsequent assessment of exposure. For example, information should be provided on habitat and, where applicable, the fractional occupancy of various organisms in their habitats. This information is important for the weighting of external dose rates in order to account for the behaviour of the organism (see Section 5.1.2). Guidance on the types of ecological information required for reference fauna is provided in Table 2.4.

Table 2.4 Ecological information required for reference fauna

Information	*Assessment*	*Comments*
(i) Latin and common English name of the selected species.	Simple[1]	
(ii) Biota dimensions (mass, dimensions)	Simple[1]	Dimension – represent as ellipsoid with defined length, width and depth. Required for geometry configuration
(iii) Habitat – configuration and occupancy factors	Simple[1]	Required for target source configuration – external dose assessment. - Marine – e.g. pelagic, benthic; - Terrestrial – e.g. at soil surface, in soil (depth and orientation) Occupancy factors – fraction of time spent in different habitats – required for average dose rate calculation
(iv) Habitat (dynamic)	Advanced[2]	Examples: - The animal spends parts of its life cycle in different habitats (e.g. meroplanktonic larvae) - The animal hibernates (where and when?) Information required in the calculation of integrated doses
(v) Distribution – Home range.	Advanced[2]	Information required in the calculation of integrated doses
(vi) Average life expectancy	Advanced[2]	Information required in the calculation of integrated doses
(vii) Feeding habits	Advanced[2]	E.g. main prey species Information required for input to ecological models
(viii)Additional information on lifecycle	Advanced[2]	E.g. viviparous fish, periods spent in freshwater Information required in the calculation of integrated doses; sensitive periods in life-cycle

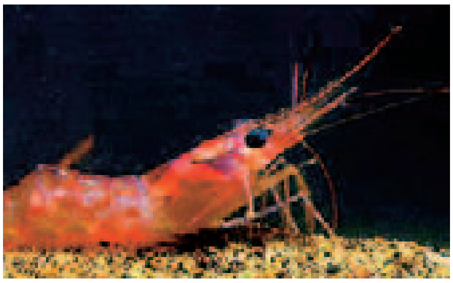
[1]Simple assessment – basic information required for the calculation of dose rates.
[2]Advanced assessment – beyond the scope of EPIC aspirations. However, such information may prove useful in the parameterisation of food-chain and exposure models.

It should be noted that some of the information specified in Table 2.4 , for selected biota, is redundant for the purpose of conducting the impact assessment described in this report. Essentially, only information on the dimensions and habitat of a particular organism are required to allow informed application of appropriate DCCs with occupancy factors being required to subsequently use these. Organism mass, life expectancy and feeding habits have been used in some cases to provide appropriate values for allometric relationships, which have subsequently been implemented within the dynamic radioecological models (Beresford *et al.*, 2003). The additional information, e.g. home range, special life-cycle data etc. may be useful in the application of a more detailed ecological risk assessment (e.g. Sample *et al.*, 1997) or in the parameterisation of models simulating how populations might respond to radiation induced changes in individual attributes (e.g. Woodhead, 2003).

Life history data sheets have been collated for the representative reference biota (Brown *et al.*, 2003b). An example of such a data sheet is given below:

Northern shrimp (*Pandalus borealis*)

Classification



Kingdom: *Animalia*
Phylum: *Crustacea*
Class: *Malacostraca*
Order: *Decapoda*
Family: *Pandalidae*
Genus: *Pandalus*

Geographical distribution and habitat

Pandalus borealis, the northern shrimp, is a very important commercial product. It is one of the most common and numerous of invertebrate species in the Atlantic, from the North Sea to Spitsbergen, Iceland, along the shores of Newfoundland and Greenland, and in the Pacific Ocean, from the Japan Sea and British Columbia to the Bering Sea.*P. borealis* is most common over a soft mud bottom. Its bathymetric range is from 9 to 1380 m but fishable concentrations normally occur between 54 and 400 m. There is a direct relationship between abundance of this shrimp and high organic content in sediment. This shrimp exhibits migratory behaviour, inshore-offshore migrations, which are related to seasonal and inshore-offshore temperature differences. Both the distribution and migratory behaviour of northern shrimp change with age. Adult shrimps tolerate water temperatures from -1.68 to 11.13 Celsius, whereas larvae may live at 14 Celsius. Both larvae and adults have been found at salinities from 25.9 to 35.7 per cent.

Feeding behaviour

The diet of *P. borealis* is obtained from the plankton as well as from the benthos. The shrimp feed on euphausiacea, copepods, mysids, decapod larvae, harpacticids, isopods, tanaidaceans, cumaceans and benthic amphipods. The polychaetes are second in importance to the crustaceans in terms of the number of species consumed. The spectrum of food organisms is determined essentially by the prey available, the time of day, and the developmental stage of the shrimp. Following stomach investigations it has been reported that the shrimps have a nocturnal activity phase during which they mainly feed on plankton. On the other hand, there is also a diurnal activity phase during which benthic species are consumed, and the stomachs are filled to a maximum degree in the afternoon. The males feed on plankton in the pelagic zone more actively than do females. In its habitat, *P. borealis* is eaten by large fish such as dogfish, Greenland halibut, turbot, and hake.

Sex change, spawning and hatching

Pandalus borealis is a protandric hermaphrodite, which reproduce first as male and subsequently changes into female and spawn as such for the rest of its life. Temperature plays a significant role in determining the time (age) of sex change. Over its geographic range, the northern shrimp has different seasons of spawning and hatching, and water temperature appears to be the controlling factor. In southern Norway, where mean annual bottom temperature is about 7 Celsius, spawning take place in October and November and hatching of eggs in March and April, for an ovigerous period of between five and six months. Upper north in Norway (Ofoten and Mist Fjords), where mean annual bottom temperature is about 5 Celsius, spawning occurs in September and October and hatching in April and May. In the far northern areas (Spitsbergen, Jan Mayan, western Greenland), having mean temperatures of 1 Celsius or less, the ovigerous period (including spawning and hatching periods) may begin as early as July or August and last 10 to 12 months. The life span of *P. borealis* range from 3 to over 8 years in various locations in the Atlantic and its length can reach up to 120 mm or larger. In high latitudes and at colder ambient temperatures the growth rate is slower, the life span and ovigerous period longer and age at sex changes later.

Sources of information

BUTLER, T. H., 1971. A review of the biology of the pink shrimp, *Pandalus borealis*. In: Proceedings – Conference on the Canadian Shrimp Fishery, St. John, N.B., Oct. 27-29, 1970. *Can. Fish. Rep.*, No. **17**, 17-24.

Figure 2.1 *Example of life history data sheet, here for northern shrimp.*

3 Radionuclide Transfer to reference Arctic biota

Several approaches have been explored in the process of deriving concentrations in the bodies of reference flora and fauna. An overview of how recommended values were derived is provided here.

3.1 Empirically-derived transfer factor approach

This approach assumes that information is available on activity concentrations in a predefined reference material, i.e. filtered water in aquatic environments (Bq l^{-1}) or surface soil in terrestrial environments (Bq kg^{-1}).

3.1.1 Overview of approach

When the concentrations in the reference organisms are not available, these can be calculated by multiplying the concentrations in the reference media with the appropriated Concentration Ratios (CR) or Concentration Factors (CFs).

For the terrestrial ecosystems the CRs are defined as:

$$CR_{b,i} = C_{b,i} / C_{soil,i} \qquad (3.1)$$

where,
$CR_{b,i}$ *(dimensionless)* = Concentration ratio for reference organism *b* and radionuclide *i*;
$C_{b,i}$ = Activity concentration of radionuclide *i* in whole body of reference biota (Bq kg^{-1}, fresh weight);
$C_{soil,i}$ = Activity concentration of radionuclide *i* in surface soil (Bq kg^{-1} d.w.)

For the aquatic ecosystems the transfer factor, commonly known as Concentration Factors (CFs), are defined as:

$$CF_{b,i} = C_{b,i} / C_{aq,i} \qquad (3.2)$$

where
$CF_{b,i}$ *(dimensionless or 1 kg^{-1})* = Concentration Factor for reference organism *b* and radionuclide *i*;
$C_{b,i}$ = Activity concentration of radionuclide *i* in whole body of reference biota (Bq kg^{-1}, fresh weight);
$C_{aq,i}$ = Activity concentration of radionuclide *i* in aqueous phase (Bq l^{-1} or Bq kg^{-1}) - normally filtered water.

3.1.2 CRs in Arctic terrestrial environments

A database of the transfer of the EPIC radionuclides from soil to reference organisms was generated predominantly from literature review of published data (western and Russian-language publications) and data provided by Russian partners in EPIC. More than 300 publications (refereed literature, books, institute reports and conference proceedings) were reviewed.

An overview of the empirical transfer factor data coverage is presented in Table 3.1. It is apparent that very few transfer factor data are available for radionuclides other than radioacaesium and radiostrontium. Data were available for many of the reference organisms for natural radionuclides; these data were dominated by studies from within the EPIC area. No Arctic specific data for the transfer of actinide elements from soil to biota were found during this review. Even for these well-studied radionuclides, very little information is available on transfer to selected representative organism groups, e.g. see data coverage for lemmings and voles (*Microtus spp./Lemmus spp.*).

Table 3.1 Coverage of empirical transfer factors for terrestrial reference organisms (values given in columns show number of data (C_{ag}* or CR) found for each radionuclide

Reference organism	*Representative species*	*Cs*	*Sr*	*I*	*Tc*	*Pu*	*Am*	*C*	*H*	*U*	*Ra*	*Th*	*Po*
Lichens+bryophytes	*Cladonia spp.*	388	356	-	-	-	-	-	-	1	6	6	5
Gymnosperms		22	13	-	-	-	-	-	-	11	4	2	-
Dicotyledons	*Vaccinium spp.*	457	63	-	-	-	-	-	-	10	7	6	4
Monocotyledons		435	321	-	-	-	-	-	-	-	1	-	2
Herbivorous mammal	*Microtus spp. /Lemmus spp.*	4	-	-	-	-	-	-	-	2	17	2	-
Herbivorous mammal	*Rangifer tarrandus*	845	365	-	-	-	-	-	-	-	16	6	42
Carnovorous mammal		12	8	-	-	-	-	-	-	1	17	2	3
Herbivorous bird		56	51**	-	-	-	-	-	-	4	31	4	-

*The *aggregated transfer coefficient*, C_{ag} (m^2 kg^{-1}), is the *mass activity density*, A_m (Bq kg^{-1}) in a specified object per unit *areal activity density*, A_a (Bq m^{-2}) in the soil (ICRU Report 65 (2001)).
** *Lagopus spp.* only

Consequently there is only sufficient data to provide recommended transfer parameters for application in the exposure assessment for some of the radionuclide – reference organism combinations. The approach suggested by Higley *et al.* (2003) was used, in combination with suitable soil-plant transfer values for dietary components, to determine soil-biota transfer values for Arctic reference organisms by Beresford *et al.* (2003). Where comparison was possible, predicted values generally compared well to the available measurements for some radionuclides (e.g. Cs and U) but not for others (e.g. Pu, Am and Th). The initial model was simplistic and did not include soil ingestion which could result in underestimated values for those radionuclides with low plant uptakes. Beresford *et al.* (in press) revised these estimates assuming a soil ingestion rate of 10 % dry matter intake for herbivores (USDoE, 2002) and 6 % for fox (Sample and Suter, 1994). For Cs and Pu gastrointestinal absorption factors for soil associated radionuclides were taken from Beresford *et al.* (2000), Am absorption was taken to be the same as Pu, and all other radionuclides were assumed to have the same bioavailability as herbage associated radionuclides; Beresford *et al.* (2000) suggest this is a valid assumption for Sr and I. Daily dry matter ingestion rates were predicted using the allometric relationships of Nagy (2001) for carnivorous mammals (fox), rodents (vole) and galliformes (*Lagopus* spp.); intakes of grass and lichen by reindeer were assumed from Golikov (2001). Voles were assumed to eat grass, *Lagopus* spp. to eat *Vaccinium* spp., and fox to consume the soft tissues of voles. Estimates were made for animals of average age for each species. Predicted transfer values for Cs, U and Sr were generally comparable with the range of observed data, although predicted values for Ra were high compared with observed data. The inclusion of soil ingestion improved comparisons with the observed data for Pu, Am and Th.

Tritium and ^{14}C are radionuclides of macro-elements which are structural components of plant and animal tissues and water. Therefore, conventional modelling techniques for modelling radionuclide transfer are not appropriate. For ^{14}C a specific activity approach was used to derive transfer parameter (Galeriu *et al.,* 2003). For ^{3}H an approach was developed (including limited Arctic specific parameters) enabling (unlike other biota assessment frameworks) organically bound and body water ^{3}H concentrations to be derived (Galeriu *et al.,* 2003). For both ^{14}C and ^{3}H CR values represent the ratio of activity concentration in biota to that in air (Bq m^{-3}).

3.1.3 CFs in Arctic freshwater environments

CF data for Arctic freshwater environments are limited to few species and few radionuclides. Mean values ± standard deviation pertaining to CFs for ^{137}Cs (water ➔muscle) and ^{90}Sr (water ➔bone) have been provided for 4 species of fish from Arctic Russian lakes. For all other radionuclides and organism types, other methodologies must be applied in the derivation of transfer information. Such methods include the application of allometric relationships and biokinetic models (Beresford *et al.* 2003).

3.1.4 CFs in Arctic marine environments

Site-specific radionuclide CF values for Arctic marine biota have been collated within EPIC for European Arctic sea areas including the Norwegian, Barents, White, Kara, and Greenland Seas. CF values have been calculated for Arctic fish, birds, sea mammals, zoobenthos and macroalgae for the following radionuclides: ^{90}Sr, ^{137}Cs, ^{239}Pu, ^{240}Pu and ^{99}Tc based upon a number of literature reviews. Collated data are for the period 1961-1999, and a summary is shown in Table 3.2. For some radionuclide-organism combinations, data for neighbouring sea regions (i.e. the North Sea and North Atlantic) were also used because of the scarcity of Arctic-specific data. For all other radionuclide-biota combinations very few data are available.

Table 3.2 Summarised information on number of data compiled from Arctic marine biota from Beresford *et al.* (2003)

Reference organism group	*Caesium-137*	*Strontium-90*	*Plutonium-239,240*	*Technetium-99*	*Total*
Fish	630	37	23	1	691
Bird	55	-	6	-	61
Mammal	175	17	15	-	207
Crustacea	41	7	8	8	64
Mollusc	31	-	10	5	46
Macroalgae	116	14	46	18	194
Invertebrate*	33	3	10	-	46
Total	1081	78	118	32	1309

*Includes data for species such as *Strongylocentrothus* spp., foraminefera and polychaetes.

Where there are no Arctic specific transfer data, generic information for the world's oceans (IAEA, 1985 and 2004) will have to be used although it is recognised that such data are biased towards edible marine organisms and the edible parts of these organisms.

By comparing region specific data sets with recommended generic values for CFs (IAEA, 1985 and 2004), the hypothesis that transfers to Arctic biota differs from what is observed in temperate areas, was tested for ^{90}Sr, ^{137}Cs, ^{239,240}Pu and ^{99}Tc (see Brown *et al.*, 2004). Despite the general paucity of data and large uncertainties regarding radionuclide CFs to reference biota, the use of Arctic-specific CFs for Sr, in the case of crustaceans and fish, and Pu, in the case of molluscs, is preferable because differences with generic CFs are apparent.

The EPIC review provides mean CF values that may be applied in an exposure assessment. These values have been used in conjunction with other data derived from other literature sources and modelling methodologies in order to produce appropriate Look-up tables, providing recommended radionuclide-specific CFs for reference organism groups, presented in Appendix 2 of this report.

3.1.5 Management of information gaps

Several approaches may be adopted in cases where no transfer factors are available (see Copplestone *et al.*, 2003). These include:

(1) A transfer value (fresh weight activity concentration in organism: fresh weight activity concentration in soil) of 1 is recommended as being generally conservative for <u>terrestrial</u> environments. There will be exceptions where this assumption is not conservative (e.g. for radiocaesium) but in these case data will generally be available for some organism groups for these radionuclides on which an expert judgement can be based.

(2) For aquatic systems, the highest available concentration factor for a specified radionuclide considering all reference organism types should be compared with the distribution coefficient, k_d (l kg^{-1}) for that radionuclide. The larger number can be selected for the assessment.

(3) Consider if transfer can be justifiably ignored. For some organisms exposed to beta/gamma emitters the total dose is likely to be dominated by external radiation (e.g. a worm inhabiting soil contaminated by gamma-emitters).

(4) For some radionuclides transfer values for radionuclides with a similar biogeochemical behaviour could be employed. For instance, transfer values for Pu could be used to estimate Am activity concentrations.

3.1.6 Limitations in the application of equilibrium transfer factors

The application of concentration ratios provides a simply implemented methodology for estimating radionuclide concentrations in biota. Similar approaches have been suggested by other developers of assessment methodologies (e.g. USDoE, 2002; Copplestone *et al.*, 2001). However, we acknowledge that the CR/CF approach is open to criticism because:

(1) it provides no information concerning the types of processes/mechanisms in operation during biological uptake, (although the amalgamation of these processes into one parameter can conversely be considered to be an advantage),

(2) the relationship between the radionuclide concentration in an abiotic compartment (e.g. soil, water) and within (the organs or whole body of) a high trophic-level organism, deriving most of its contaminant load from ingested food, may not be a simple and linear one,

(3) the assumption that the system is under equilibrium, a requirement for CRs/CFs to be truly applicable, is often invalid.

In numerous cases, application of CR/CF recommended values would not provide robust prognoses for activity concentrations in biological compartments. A case in point was demonstrated by Jackson *et al.* (2001) who considered the implications of activity concentrations of ^{99}Tc in lobster following pulsed releases to the environment.

The various limitations associated with CFs renders the application of dynamic models desirable. Furthermore, such models may help to fill numerous data gaps on radionuclide transfer for many biota types. Within EPIC, attempts have been made in employing methods which include the application of allometric relationships and the biokinetic models to estimate activity concentrations for some reference organisms (Beresford *et al.*, 2003).

4 Dose models for Arctic environments

4.1 Introduction

Numerous models already exist for the purpose of deriving absorbed doses to individual organisms including the analyses and solution of dose distribution functions, conservative approaches (whereby all radiations emitted by radionuclides within the organism are absorbed) and Monte Carlo methodologies. Examples of dose calculation methodologies include IAEA, 1979; Copplestone *et al*., 2001; USDoE, 2002; Pröhl *et al*., 2003. Dose conversion coefficients have been derived for generic biota (Amiro, 1997) and specific reference plants and animals (Pröhl *et al*., 2003).

In the adopted approach reference organisms have been used as the basis for further dosimetric modelling. The selection of appropriate reference geometries has been addressed in Section 2.1 of this report. The actual dimensions of the organisms have been based, in most cases, on the adult form of representative organisms and have been specified in the Look-up tables presented in Appendix 3 of this report. For the derivation of Dose Conversion Coefficient(DCCs), ellipsoids have been used to represent the various geometric forms of representative plants and animals.

Due to the complexity of the processes involved and the enormous variability of organisms and their natural habitats, it was not possible to derive external DCCs for all possible exposure conditions. Therefore, typical exposure situations appropriate to and based around the geometries for reference organisms were selected for detailed consideration. These are:

- For the DCCs pertaining to species living *in the soil*, two source descriptions were assumed: (a) uniformly contaminated volume source for natural radionuclides and (b) a planar isotropic source, located at the depth 0.5 g·cm^{-2} in the soil[1], for artificial radionuclides.
- For the DCCs pertaining to species living *on the ground*, two source descriptions were assumed: (a) a semi - infinite volume source for natural radionuclides and (b) a planar isotropic source, located at a depth of 0.5 g·cm^{-2} in the soil, for artificial radionuclides.
- For the DCCs pertaining to aquatic species at the sediment/water interface, two source descriptions were assumed: (a) a volume source with a depth of 5 cm for artificial radionuclides[2] and (b) semi - infinite volume source for natural radionuclides.

4.2 Methodology for deriving absorbed doses

The method for deriving absorbed doses is based on an approximation defining the dose distribution of radiation within an organism's body. This distribution can be defined using two functions:

1. Dose attenuation function describing the dose at any point along the path length for radiation travelling through matter. This can be solved using exact numerical methods.
2. Chord distribution function describing numerous possible path

[1] This represents a (thin) surface layer contamination selected to represent a period shortly after a deposition episode.
[2] A depth of 5 cm was arbitrarily selected to represent common artificial radionuclide profiles – bioturbation and post depositional migration of radionuclides often lead to the rapid development of a finite layer of contamination.

lengths within the body. This can be calculated using a Monte Carlo methodology for each specific geometry.

External doses to organisms from radionuclides present in soil or in the water column are calculated using a variant of the simple formula for uniformly contaminated isotropic infinite absorbing medium: this equation approximates the dose rate to an organism immersed in an infinite contaminated medium but neglects density differences between the organism and the medium. Furthermore, it allows for self shielding by the organism itself, and averages the dose rate throughout the volume of the organism. This approach has been used to calculate the external dose from β- and γ-radiation for organisms buried in soil or free swimming in the water column; the relevant concentrations being those in the soil or water media as appropriate.

The estimation of external exposures at the interface of environments with different densities is more complex than cases pertaining to infinite, uniformly-contaminated environments. A two-step method has been used. In the first step, the kerma in a specified location (above the soil/air interface, in soil at the given depth) is derived. In the second step, the ratio of the dose in an organism and the kerma is calculated .In this way, the value of absorbed dose rate in an organism can be calculated from the value of kerma in medium (Golikov & Brown, 2003).

4.3 Dose Conversion Coefficients (DCCs)

Radionuclide specific DCCs have been derived for all radionuclides listed in Table 1.1. In the case of ^{238}U and ^{232}Th decay series, all radionuclides with half-lives greater than 1 day are treated separately and are presented with their own DCC. All progeny with half-lives less than 1 day are included within the DCC value of the parent. In cases where decay chains branch (e.g. ^{212}Bi and ^{234}Th), the DCC value is weighted according to the yield of daughters.

Within this report, weighted DCCs have been derived using provisional weighting factors of 3 for ^{3}H (all other β -emitters have been assigned a radiation weighting factor of 1) and 10 for alpha radiation. These DCC values are presented in Appendix 3 of this report – for an overview see Tables 4.1 and 4.2.

The application of a dose rate within radiological assessments has a distinct advantage in the sense that it allows radiation exposures arising from numerous radionuclides and sources, i.e. internal and external, to be integrated within a single, unified measurement. A disadvantage with the application of absorbed dose rate relates to the observation that exposures to different radiation types cause varying degrees of biological damage and thus a biological weighting factor needs to be applied to the various categories of radiations emitted by selected radionuclides to account for this. The methodology to circumvent this disadvantage is not difficult to implement as will be illustrated in the next chapter. However, the fact that the relative biological effectiveness (RBE) of different radiation types is dose rate, species and end-point dependent means that consensus on appropriate radiation weighting factors is not easily attained.

Table 4.1 Aquatic reference organisms - exposure pathways considered and references to relevant Look-up tables for DCCs in Appendix 3.

Reference organism	*DCCs derived*	*Reference*
Pelagic planktotrophic fish	Internal External (from water column)	Section A3.1
Pelagic carnivorous fish	Internal External (from water column)	Section A3.2
Benthic crustacean	Internal External (from water column) External (from water bottom sediment)	Section A3.3
Benthic fish	Internal External (from water column) External (from water bottom sediment)	Section A3.4
Bivalve mollusc	Internal External (from water column) External (from water bottom sediment)	Section A3.5
Sea bird	Internal External (at air/water interface) External (on soil/air interface from source in soil)	Section A3.6
Pelagic crustacean	Internal External (from water column)	Section A3.7
Carnivorous mammal	Internal External (from water column) External (on soil/air interface from source in soil)	Section A3.8

Table 4.2 Terrestrial reference organisms - exposure pathways considered and reference to relevant Look-up tables for DCCs in Appendix 3.

Reference organism	*DCCs derived*	*Reference*
Soil invertebrate (*Collembola*)	Internal External (on the soil/air interface)	Section A3.9
Soil invertebrate (mite)	Internal External (on the soil/air interface) External (100 cm underground)	Section A3.10
Herbivorous mammal (lemming)	Internal External (on the soil/air interface) External (100 cm underground)	Section A3.11
Herbivorous mammal (vole)	Internal External (on the soil/air interface) External (50 cm underground)	Section A3.12
Herbivorous mammal (reindeer)	Internal External (on the soil/air interface)	Section A3.13
Herbivorous bird	Internal External (on the soil/air interface)	Section A3.14
Bird egg	Internal External (on the soil/air interface)	Section A3.15
Carnivorous mammal	Internal External (on the soil/air interface) External (100 cm underground)	Section A3.16
Plant roots	Internal External (at the depth 0-30 cm)	Section A3.17

5 Assessment approach

5.1 Exposure assessment methodology

For the main EPIC assessment, the basic components of information that are required to derive dose rates to organisms are: (i) the activity concentrations of radionuclides in (selected) reference biota and their habitat; (ii) Dose Conversion Coefficients (DCCs) mapping these activity concentrations onto a dose rate and (iii) occupancy factors defining the time spent by biota in various surroundings within their habitats for the parameterisation of external dose calculations.

5.1.1 Deriving total exposure

The whole body absorbed dose rate is used as a measure of the reference organism's exposure to ionising radiation, expressed in units of Gy per year, and is the sum of internal and external absorbed dose rates:

$$\dot{D}^j_{total} = \dot{D}^j_{\text{int}} + \dot{D}^j_{ext} \tag{5.1}$$

where,

$\dot{D}^j_{total}$ is the total absorbed dose rate received by organism *j* (Gy y^{-1}),

$\dot{D}^j_{\text{int}}$ is the internal absorbed dose rate received by organism *j* (Gy y^{-1}),

$\dot{D}^j_{ext}$ is the external absorbed dose rate received by organism *j* (Gy y^{-1}).

It may be appropriate to introduce radiation weighting factors to take account of the differing biological effectiveness of different types of ionising radiation. For this reason, the radiation emission types for each radionuclide have been split into the categories of α, β and γ[3]. Introduction of weighting factors leads to the weighted absorbed dose:

$$\begin{aligned}
\dot{D}^j_{total,weighted} &= \dot{D}^j_{\text{int},weighted} + \dot{D}^j_{ext,weighted} \\
\dot{D}^j_{\text{int},weighted} &= w_\beta \dot{D}^j_{\text{int},\beta} + \dot{D}^j_{\text{int},\gamma} + w_\alpha \dot{D}^j_{\text{int},\alpha} \\
\dot{D}^j_{ext,weighted} &= w_\beta \dot{D}^j_{ext,\beta} + \dot{D}^j_{ext,\gamma} + w_\alpha \dot{D}^j_{ext,\alpha}
\end{aligned} \tag{5.2}$$

where,

w_β and w_α are the radiation weighting factors for beta and alpha radiation, respectively and

the subscripts β, γ, and α denote the contributions to absorbed dose rate from beta particles, gamma ray photons, and alpha particles, respectively.

Contributions from low energy beta particles and alpha particles to external radiation will usually be negligible, but may need to be considered for organisms whose dimensions are of the same order as the range of these radiation types in tissue - typically, in the sub-millimetre range.

For simplicity of explanation, the following two sections describe the methods for calculation of (unweighted) absorbed dose rates to organisms. Extension of the method to calculate weighted absorbed dose rates is described in Section 5.1.4.

5.1.2 Assessment of external exposure

The external dose rate, averaged over different habitats, can be determined by the following equation:

$$\dot{D}^j_{ext} = \sum_z v_z \sum_i C^{ref}_{zi} * DCC^j_{ext,zi} \tag{5.3}$$

where,

[3] This is different to the FASSET approach in which radiation types are categorised as α, lowβ (beta particle radiation with mean particle energies less than 10 keV) and βγ (other beta particles and gamma ray photons), see Brown *et al.* (2003).

v_z is the occupancy factor, i.e. fraction of the time that the organism j expends at a specified location z in its habitat.

C_{zi}^{ref} is the average concentration of the radionuclide i in the reference media of a given location z (Bq kg^{-1} (soil or sediment) or Bq m^{-3} (water)),

$DCC^{j}_{ext,zi}$ is the dose conversion factor for external exposure defined as the ratio between the average activity concentration of the radionuclide i in the reference media corresponding to the location z and the dose rate to the organism j (Gy y^{-1} per Bq kg^{-1} or Bq m^{-3})

5.1.3 Assessment of internal exposure

The internal dose rate (for biota in both aquatic and terrestrial environments) can be derived from the activity concentration in the selected reference organism using the following equation:

$$\dot{D}^{j}_{\text{int}} = \sum_i C_i^j * DCC^{j}_{\text{int},i} \quad (5.4)$$

where,

C_i^j is the average concentration of the radionuclide i in the reference organism j (Bq kg^{-1} fresh weight),

$DCC^{j}_{\text{int},i}$ is the radionuclide-specific dose conversion factor (DCC) for internal exposure defined as the ratio between the average activity concentration of the radionuclide i in the organism j and the dose rate to the organism (Gy y^{-1} per Bq kg^{-1} fresh weight).

If no data are available on the activity concentrations in reference organisms, methodologies are available to allow these values to be estimated. This is discussed in more detail in Chapter 3.

5.1.4 Weighted absorbed dose rate calculation

The final choice of radiation weighting factor for alpha particles will depend on the selection of reference organism, end-point and dose (or dose rate) range. It is considered appropriate that calculations of absorbed dose should be split into low- and high-LET[4] components in order to facilitate the incorporation of a radiation weighting factor once consensus has been achieved.

A provisional recommendation concerning the application of an α-radiation weighting factor in the range of 5-20 was made. Furthermore, a weighting factor of 3 was recommended for application to low energy β. In view of the way in which DCCs have been presented in EPIC, i.e. into components of α, β and γ radiation, it has not been possible to apply a weighting factor for low β in most cases. However, ^{3}H is known to emit a large component of low energy β radiation and earlier studies (e.g. Straume & Carsten, 1993) have shown that a radiation weighting factor in excess of unity might be appropriate for this particular radionuclide.

The weighted internal DCCs for a given radionuclide and reference organism become:

$$\left[DCC^{j}_{\text{int},i,\beta}\right]_w = DCC^{j}_{\text{int},i,\beta} * w_\beta \quad (5.5)$$

$$\left[DCC^{j}_{\text{int},i,\alpha}\right]_w = DCC^{j}_{\text{int},i,\alpha} * w_\alpha \quad (5.6)$$

$$\left[DCC^{j}_{\text{int},i,Total}\right]_w = \left[DCC^{j}_{\text{int},i,\beta}\right]_w + \left[DCC^{j}_{\text{int},i,\alpha}\right]_w + DCC^{j}_{\text{int},i,\gamma} \quad (5.7)$$

where,

$\left[DCC^{j}_{\text{int},i,\beta}\right]_w$; $\left[DCC^{j}_{\text{int},i,\alpha}\right]_w$ and $\left[DCC^{j}_{\text{int},i,Total}\right]_w$ are "weighted" DCCs for β, α and all radiation types respectively. They are specific to radionuclide i and reference organism j.

w_α, w_β are radiation weighting factors.

[4] Linear Energy Transfer (LET) is used as a measure of the rate of energy absorption.

$DCC^{j}_{int,i,\gamma}$ is the DCC for γ radiation for radionuclide i and reference organism j.

The weighted DCCs have been presented as Look-up tables in Appendix 3 of this report. By way of example a w_{α} of 10 has been applied to alpha radiation components. In the exceptional case of tritium, ^{3}H, a weighting factor of 3 has been applied. For all other β, and γ, the radiation weighting factor has been set to unity.

5.2 Interpretation of exposure estimates

There are currently no dose limits in place that can be referred to when evaluating whether biota within Arctic environments are being protected from exposure to ionising radiation. In order to assess the potential consequences of exposures to radiation on non-human biota, arguably, two points of reference may be used. These are (a) natural background doserates and (b) dose rates known to have specific biological effects on individual organisms (Pentreath, 2002). These points will be considered in some detail in the following chapter and possible implications for the development of dose limits for the Arctic, based on these findings, are discussed in Chapter 7.

6 Dose-effect relationships

6.1 General approach

The adopted approach with regards to analyses of dose-effects relationships is to collate and organise data around the reference organism categories defined earlier (Section 2.1) and to focus on dose rates and biological endpoints that are of relevance from the perspective of environmental protection. For this purpose, the compilation of data focused on the effects of chronic radiation exposure at dose rates well below those that are known to cause mortality of organisms. And, from the wide variety of radiation effects reported in the open literature, emphasis was placed upon those which are important for the survival and reproduction of organisms *in the wild*. Furthermore, information was arranged in a form that would facilitate the development of appropriate Arctic dose limits, providing a scientific basis for the regulations in the radiation protection of the environment. To this end, the construction of a preliminary scale of the severity of radiation effects at different levels of chronic exposure was considered useful to aid decision making.

Data concerning dose-effects relationships for radiation effects in reference (or related) Arctic biota available from Russian and other former Soviet Union sources have been collated. The compiled data are concentrated on the effects in radiosensitive species in terrestrial and aquatic ecosystems, such as mammals, fish, and sensitive groups of plants (e.g. pines). Less attention was given to radioresistant species. As stated above, effects data have been organised under "umbrella" end-point categories, namely:

- Morbidity (worsening of physiological characteristics of organisms; effects on immune system, blood system, nervous system, etc.)
- Reproduction (negative changes in fertility and fecundity, resulting in reduced reproductive success)
- Mortality (shortening of lifetime as a result of combined effects on different organs and tissues of the organism)
- Cytogenetic effects (radiation effects on the cellular level)
- Ecological effects (changes in biodiversity, ecological successions, predator-prey relationships)
- Stimulation effects (radiation hormesis, low dose stimulation effects)
- Adaptation effects (responsive adjustments of organisms to the conditions of chronic irradiation)

The biological endpoint "reproductive success" is of particular interest because this tends to be the most radiosensitive endpoint that ultimately influences the viability of a defined population and relates the assessment to the underlying principle of sustainability.

6.2 The EPIC database on radiation effects

In order to underpin the approach outlined above, a data-base in Microsoft ©EXCEL has been constructed. The EPIC database includes data on radiation effects in wild organisms, which were observed from field studies in the northern areas of Russia, including sub-Arctic regions. These areas include the Kyshtym radioactive trace, local areas with enhanced levels of natural radioactivity in Komi Autonomic Republic, and some others. Data on radiation effects in the Low Arctic refer mostly to cold-water fish. The database also includes data from laboratory experiments with boreal organisms, and data from several other relevant experimental studies. Considering the great importance of the radiobiological studies of wildlife in the Chernobyl contaminated areas, these data were also included in the EPIC database. In total, the EPIC database "Radiation effects on biota" contains approximately 1600 records from 435 papers and books. The structure of the database includes the following datasets:

- Radiation effects on terrestrial animals
- Radiation effects on aquatic animals
- Radiation effects on terrestrial plants and herbaceous vegetation
- Radiation effects on soil fauna
- Radiation effects on micro-organisms
- Table of lethal doses

The EPIC database information covers a very wide range of radiation dose rates to wild flora and fauna: from below 10^{-5} Gy d^{-1} up to more than 1 Gy d^{-1}.

Dose reconstructions were made, in some cases, by the authors of the database using data on levels of radioactive contamination in the organism/environment and standard dose derivation methodologies (IAEA, 1976 and 1979; Kryshev & Sazykina, 1990; Kryshev *et al.*, 2002).

6.3 Background dose rates

As considered in Section 5.2, one reference point for assessing the significance of a particular level of radiation exposure may be defined by the natural background radiation. In the Arctic, as everywhere on the Earth, terrestrial and aquatic organisms are exposed to natural sources of ionising radiation, including cosmic rays, radionuclides produced by cosmic ray interactions in the atmosphere, and radiations from naturally-occurring radionuclides, which are ubiquitously distributed in all living and non-living components of the biosphere (Whicker & Schultz, 1982).

The typical dose rates of natural background exposure for different types of organisms in the Arctic are discussed by Sazykina *et al.*, 2003. These dose rates have been derived using data on the activity concentrations of natural radionuclides in the Arctic aquatic ecosystems for several reference organism groups and representative species. The doses have been estimated by the methods described in earlier studies (IAEA, 1976, 1979; Kryshev & Sazykina, 1990,1995; Kryshev *et al.*, 2001,2002), taking into account geometrical characteristics of organisms and ionising radiation sources. Typical annual doses to terrestrial vertebrate under generic conditions have been taken from Whicker & Shultz (1982).

Tables 6.1 and 6.2 present estimates of doses to some aquatic biota from natural background radiation in the Arctic and other regions.

Table 6.1. Estimates of annual doses (mGy/year) to freshwater fish from natural sources of radiation in the Arctic and other regions

Source of radiation	*Arctic*	*Other regions (Whicker, & Schultz, 1982)*
Cosmic	0.24	0.19-0.24
Water	0.00006	0.00004-0.06
Sediments	0-0.27	0-3.2
Internal	0.28	0.32-0.42
Sum of natural sources	0.5-0.8	0.5-3.8

Table 6.2. Assessments of dose rates from natural background exposure for marine biota in the Kara Sea

Internal radiation	
Reference biota	*Dose rate (μGy/day)*
Phytoplankton	0.5-2
Zooplankton	0.6-4
Crustaceans	2-5
Molluscs	2-4
Macrophytes	1-3
Fish	0.6-1
Waterfowls	0.5-1.5
External radiation	
Source of radiation	*Dose rate (μGy/day)*
From water	0.02-0.1
From sediments	0.7-9

6.4 Preliminary relationships between dose rate and effects for chronic low-LET radiation

The EPIC database “Radiation effects on biota” provides the extensive sets of data from Russian/FSU publications, which can substantially enlarge the knowledge of radiobiological effects in northern wildlife. These data were found sufficient to establish dose-effects relationships for northern biota in the terrestrial and aquatic environment as will be discussed in the context of Arctic dose limits later (Section 7.3).

It may additionally be necessary, in the context of management, to develop specific scales documenting the likely effects of radiation exposure for selected reference organisms. An example, based on the EPIC database, is provided in Table 6.3.

Table 6.3 Dose-effects relationships for developing roe of cold-water fish; chronic exposure from radionuclide in aquatic media during the whole period of fish eggs development.

Exposure	*Effects*
Chronic $5x10^{-8}$ Gy d^{-1}	Slight stimulation of salmon's eggs development
Chronic < 10^{-4} Gy d^{-1}	Effects are insignificant
Chronic $(1-2)x10^{-4}$ Gy d^{-1}	First effects appear: some cytogenetic changes in blood of fore-larvae
Chronic $(1-5)x10^{-3}$ Gy d^{-1}	Decrease in survival of eggs, appearance of dead and abnormal embryos, in some cases damaged were 30-50% of eggs
Chronic $3x10^{-2}$ Gy d^{-1}	Considerable decrease in survival of roe, mortality about 50%
Chronic 0.13-0.33 Gy d^{-1}	Practically total death of roe

6.5 Effects of chronic high-LET radiation on wild organisms

In order to revisit the issue of relative biological effectiveness (RBE) and the application of appropriate radiation weighting factors, data pertaining to biota exposure to high-LET, i.e. α-radiation, were treated separately. The effects of high-LET radiation on wildlife, represented in the EPIC database, relate mainly to the areas of enhanced natural radioactivity (U, Th) in Komi Autonomous Region of Russia. The database also includes the results of some experiments with exposure of aquatic organisms to solutions of ^{238}U or ^{232}Th.

The comparison of dose-effects and concentration effects relationships for these radionuclides leads to the conclusion that high chemical toxicity of ^{238}U and ^{232}Th dominates over radiotoxicity. Such alpha-emitting radionuclides, characterized by low specific activity and high chemical toxicity, are therefore not suitable for the purpose of evaluating the radiation weighting factors for high-LET radiation.

6.6 Radiation effects in the Arctic organisms

One of the hypotheses explored within EPIC, which has clear relevance to the derivation of Arctic specific dose limits, is that Arctic flora and fauna manifest effects quite differently following exposure to radiation, compared to similar organisms under temperate conditions. Testing of this hypothesis is difficult because there are very few radiobiological studies that have relevance for the Arctic. Nonetheless, some limited data are available.

For example, fish have been observed to survive for much longer time periods following high dose acute exposures (i.e. approx. 20 Gy) at low temperatures, commensurate with those observed in Arctic environments, compared with higher temperatures, commensurate with those observed in temperate environments (Keiling *et al.,* 1958). On the other hand, other experimental studies have shown that the repair of radiation damage in cells and tissues is not effective at very low temperatures (Kudryashov & Berenfeld, 1982; Kuzin, 1986; Mettler & Upton, 1995).

From a further consideration of general radiobiological laws and peculiarities of metabolic processes in Arctic organisms, several further inferences may be derived. Anticipated impacts of ionising radiation characteristic to Arctic conditions might include:

- Lesions in cooled animals (e.g. poikilothermic or hibernating animals) and plants might be expected to be latent. However, if the organisms become warm, lesions are rapidly revealed.
- Because the development of embryos and young poikilothermic organisms in the Arctic occurs slowly at low temperatures, Arctic organisms may receive much higher doses under conditions of chronic exposure, for a specified dose rate, during the radiosensitive stages of ontogenesis when compared with similar species in the temperate climate.
- Low biodiversity of the Arctic ecosystems provides a more limited potential for compensatory re-placement of damaged species by others.
- Long-distance migrations of many animals in the Arctic may result in mitigated exposure regimes because the animal will spend less time in contact with a localised hot-spot of contamination.

6.7 Summary of dose-effects relationships based on the EPIC database

From information compiled in the EPIC database, provisional dose-effects relation-ships were derived for terrestrial and aquatic animals, and for terrestrial plants. The dose-effects relationships provide the scale of severity of radiation effects at different levels of chronic radiation exposure.

6.7.1 Dose-effects relationships for terrestrial animals

More detailed analysis of the information in the EPIC dataset “Radiation effects on terrestrial animals” made it possible to construct a preliminary scheme of dose – effects relationships for terrestrial animals of northern climatic zones (Sazykina & Kryshev, 2003). These dose-effects relationships are summarized in Table 6.4.

Table 6.4 The relationships between dose rates of chronic radiation exposure and effects of radiation on terrestrial animals

Dose rates of chronic radiation exposure	*Radiation effects on terrestrial animals*
$10^{-5} - 10^{-4}$ Gy d^{-1}	• Recovery of populations after acute accidental exposure • After-effects on progeny born from exposed parents • Some negative changes in blood (α exposure) • Some increase in chromosome aberrations in cells
$10^{-4} - 10^{-3}$ Gy d^{-1}	• Some negative changes in blood (α,β exposure) • After-effects on progeny born from exposed parents (doses to parents >1Gy) • Increase in chromosome aberrations in cells
$10^{-3} - 10^{-2}$ Gy d^{-1}	• Pathology in liver, kidney (radionuclide specific) • Considerable decrease of reproduction potential ($\alpha+\gamma$ exposure), shortening of reproduction period • Some mice species show compensatory increase of reproduction (physiological response to the decrease in population density) • Some life shortening, also higher risk to be captured by predators • Weakening of immune system, increase of infestation with parasites, increase of various infections (α,β,γ exposure) • Negative changes in blood, chronic radiation disease (α,β,γ exposure), cytogenetic effects, increase of embryonic losses
$10^{-2} - 10^{-1}$ Gy d^{-1}	• Sterility, decrease of gonad's mass • Strong infestation with parasites • Osteosarcomes (^{90}Sr), anomalous teeth • Pathology in liver, kidney (radionuclide specific) • Life shortening • Negative changes in blood, chronic radiation sickness (α,β,γ exposure) • After-effects in progeny born from exposed parents • Decrease in some populations, replacement of some populations by those species, which received lower doses, or by more radioresistant species • Cytogenetic effects, increase of embryonic losses
$10^{-1} - 1$ Gy d^{-1}	• Acute radiation sickness • Death of many organisms, decrease of populations
> 1 Gy d^{-1}	• Acute radiation sickness • Lethal dose received within few days

6.7.2 Summary of dose-effects relationships for aquatic organisms.

Table 6.5 relates dose rates to radiation effects on aquatic organisms.

Table 6.5. The relationships between dose rates or acute doses and effects of radiation on aquatic organisms based on the EPIC database (Sazykina & Kryshev, 2003a, 2003b)

Dose rates of chronic radiation exposure	*Radiation effects on aquatic animals*
$10^{-7} – 10^{-5}$ Gy d^{-1}	• No effect or weak stimulation
$10^{-5} – 10^{-4}$ Gy d^{-1}	• No effects on morbidity, fertility or mortality (γ,β exposure) • Suppression of bleak gonads (U) • Some increase in fertility of Daphnia (U, Th) • Slight changes in phagocytic response on infection, some changes in leucocytes (Sr-90, fish) • Some increase in chromosome aberrations in cells (α,γ,β exposure)
$10^{-4} – 10^{-3}$ Gy d^{-1}	• Decrease of immunity, lowering of phagocytic response on infection (Sr-90, fish). • Tendency to the increased mortality from various infections (fish) • Increase of mortality and abnormalities in embryos of trout (long-developed eggs), no effects on short-developed fish eggs (pike) • Some negative changes in male gonads, no noticeable decrease in reproduction (Sr-90, small fish) • Suppression of bleak gonads (U) • Some increase in fertility of Daphnia (U) • Decrease in fertility of Daphnia (Th) • After-effects on fish progeny born from exposed parents (increased level of abnormalities) • Increased levels of chromosome aberrations in cells
$10^{-3} – 10^{-2}$ Gy d^{-1}	• Negative changes in blood, imbalance between different forms of leucocytes (α,β,γ exposure) • Decrease of immunity, lowering of phagocytic response on infection. • Increase of lipidoperoxides content (radiotoxines) in fish liver • Decrease of functional activity and morphological abnormalities in fish gonads (β,γ exposure) • Increase of abnormalities in embryos of fish • Degeneration of fish gonads (U) • Weak stimulation effect on fertility of Daphnia (Sr-90) • Decrease in size of shells of pond snail • After-effects on progeny born from exposed parents (increased levels of abnormalities) • Chronically exposed animals showed higher radioresistance to acute exposure • Cytogenetic effects
$10^{-2} – 10^{-1}$ Gy d^{-1}	• Negative changes in blood, decrease of bacteriostatic capacity of blood • Considerable decrease of immunity, lowering of phagocytic response on infection. • Deterioration of fish eyesight (Sr-90, doses>1,5Gy) • Underdevelopment of male gonads; decrease of gonad's mass; total sterility (fish, frogs) • Morphological abnormalities and underdevelopment of fish ovaries • Increased levels of abnormalities in embryos of fish, increased mortality of fish eggs of some species (peled) • Decrease in fertility of Daphnia (Sr-90) • Increase of fish mortality from various infections

	• Life shortening (fish) • Cytogenetic effects
10^{-1} – 0,5 Gy d^{-1}	• Considerable decrease in fertility of Daphnia • Considerable increase of mortality and abnormalities in embryos of pike • Increased mortality of eggs of pond snail
0.5 - 1 Gy d^{-1}	• All pike embryos had abnormalities, high lethality • Decrease of lifetime of Daphnia
1 – 5 Gy d^{-1}	• Lethal dose is received within several days (fish) • Considerable (up to100%) mortality of fish eggs; pond snail's eggs
5-10 Gy (acute exposure)	• Lethal doses for fish • Increased fecundity of Ostracoda (benthos) • Sterility of scallop • High mortality of fish eggs and eggs of pond snail
100-200 Gy (acute exposure)	• Mortality of some zooplankton species, decrease of biodiversity in zooplankton association.
200-500 Gy (acute exposure)	• Total mortality of zooplankton • Mortality of some phytoplankton species • Stimulation of bacterioplankton

6.7.3 Dose-effects relationships in terrestrial plants and herbaceous vegetation

More detailed analysis of the information in the EPIC database "Radiation effects on terrestrial plants" made it possible to construct a preliminary scheme of dose – effects relationships for plants from northern/temperate climatic zones. These dose-effects relationships for plants are summarized in Table 6.6.

Table 6.6 The relationships between dose rates or acute doses and effects of radiation on terrestrial plants and vegetation (based on EPIC database "Radiation effects on terrestrial plants")

Dose rates/ dose of irradiation	*Radiation effects on plants*
$5x10^{-4}$ –$5x10^{-3}$ Gy d^{-1}	• Cytogenetic effects in chronically exposed populations of trees and herbaceous species growing in contaminated areas. Increased morphological variability in plants. Decreased viability of seeds. (Effects include some burden from acute exposure in the past)
$5x10^{-3}$ – $5x10^{-2}$ Gy d^{-1}	• Cytogenetic effects. Increased morphological variability in plants. • Some decrease in wood growth in coniferous plants (about 10%)
$5x10^{-2}$ –0.1 Gy d^{-1}	• Considerable decrease of wood growth in coniferous trees; sterility of pollen, decreased viability of seeds.
>0.1 Gy d^{-1}	• Considerable damage and death of coniferous trees within few years
0.5-1 Gy (acute)	• Compensatory increase of growth processes (pine), complete recovering of damage to coniferous plants, partial damage in spruce trees
1-5 Gy (acute)	• Moderate damage to coniferous plants: decrease in wood growth, morphological changes in sprouts, needles, seeds. • Cytogenetic effects.
5-10 Gy (acute)	• Considerable damage of crowns in coniferous trees, decrease of wood growth. Decreased production of pollen, sterility. Decreased germination of seeds. Damage to generative organs and sleep-buds (coniferous)
10-20 Gy (acute)	• Sublethal damage to coniferous trees (about 90% of trees died). Death of most growth points, death of seedlings of coniferous trees. • Morphological changes in decidous plants. High level of chromosomal aberrations (coniferous). Infestation of irradiated trees with insects.
20-100 Gy (acute)	• Mass death of coniferous plants. Death of seedlings grown from irradiated seeds (deciduous). High infestation of irradiated trees with insects. Morphological changes of in herbaceous vegetation
100-200 Gy (acute)	• Hard damage to deciduous plants . Displacement of phenophases in herbaceous vegetation . Low survival of seedlings from irradiated seeds (deciduous)
200-400 Gy (acute)	• Full death of seedlings in stage of leave formation (deciduous). • Decrease of species diversity (herbaceous) . Decrease of seed germination and low survival of seedlings (deciduous plants)
>400 Gy (acute)	• Considerable decrease of species diversity in herbaceous communities

7 Criteria and standards for Arctic biota

The dose-effects relationships for low-LET radiation derived from the EPIC database, in coordination with recommendations and achievements from other international programmes/projects are a valuable input to the development of internationally agreed safety guidance for protection of wildlife from ionising radiation. It would be expected that a necessary part of guidance would include standards and criteria. According to risk management terminology, these are distinguished by the following definitions: standards being regulatory or legal limits, either dose limits or environmental concentrations, and criteria referring to levels of exposure above which adverse environmental effects may occur.

7.1 The derivation of dose limits

As stated earlier, no international agreed regulations exist for protecting the natural flora and fauna from detrimental effects of ionising radiation. A main concern for environmental regulations is the establishment of radiation safety standards for biota. Such standards would apply to normal operating activities of industries dealing with technogenic or natural radionuclides, which are associated with a chronic exposure of flora and fauna at comparatively low dose rates (with accumulated doses well below those likely to lead to increased mortality) (IAEA, 1976).

7.2 International developments

There have been several review publications on radiobiological effects in wild nature (IAEA, 1976, 1992; Blaylock & Trabalka, 1978; NCRP, 1991; Polikarpov, 1977, 1998; Turner, 1975; Woodhead, 1984; UNSCEAR, 1996). In most cases, the intention of the authors was to concentrate attention on the effects of chronic low-dose exposures, but these data were very limited. As a result, the existing reviews refer largely to studies of radiation effects from acute exposure at high doses; hence these data are not directly relevant to the environmental concerns. A major problem in the evaluation of the severity of environmental effects and subsequent derivation of standards for non-human organism's exposure has been the lack of available data on effects at low-level chronic radiation in international publications.

In the 1990s, the international reviews of radiation effects on flora and fauna have been published by IAEA (1992) and UNSCEAR (1996). Based on summaries of available radiobiological literature, including some data from Russian sources, these documents provide the following set of preliminary conclusions on the thresholds of observable radiation effects for terrestrial and aquatic biota:

IAEA report (1992, summary):

"Chronic dose rates of 1 mGy d^{-1} to even the most radiosensitive species in terrestrial ecosystems are unlikely to cause measurable detrimental effects in populations and that up to this level adequate protection would therefore be provided".

"*In the aquatic environment it would appear that limiting chronic dose rates to 10 mGy d^{-1} or less to the maximally exposed individuals in a population would provide adequate protection for the population".*

UNSCEAR report (1996, para 264):

"For the most sensitive animal species, mammals, there is little indication that dose rates of 10 mGy d^{-1} to the most exposed individual would seriously affect mortality in the population. For dose rates up to an order of magnitude less (1-2.4 mGy d^{-1}), the same statement could be made with respect to reproductive effects.

For aquatic organisms, the general conclusion was that maximum dose rates of 0.4 mGy h^{-1} (≈10 mGy d^{-1}) to a small proportion of the individuals in aquatic populations and, therefore, lower average dose rates to the whole population would not have any detrimental effects at the population level."

Furthermore, it was stated that for "*the most sensitive plant species, the effects of chronic radiation were noted at dose-rates of 1-3 mGy h^{-1}. It was suggested that chronic dose-rates less than 0.4 mGy h^{-1} (≈10 mGy d^{-1}) would have only slight effects in sensitive plants but would be unlikely to produce significant deleterious effects in the wider range of plants present in natural plant communities."*

The conclusions of the IAEA and UNSCEAR reports specified the ranges of chronic dose rates, which are of concern in the environmental protection of the flora and fauna. None of these dose rate levels were intended as recommendations for radiation protection criteria, although they clearly could have implications for the development of such criteria and standards.

Dose limits have been applied in other situations as exemplified by the approach advocated by the USDoE (2002). The limits used by the USDoE have been established earlier based on the findings of numerous reviews considering the effects of ionising radiation on flora and fauna (e.g. NCRP, 1991; IAEA, 1992) and relate to the protection of populations of wild organisms. A dose limit of 10 mGy d^{-1} is applied to aquatic animals and terrestrial plants and a dose limit of 1 mGy d^{-1} applied to terrestrial animals.

Although these basic recommendations, and in the latter case dose-limits, exist, their applicability directly within the context of EPIC is limited because:

(1) For reasons discussed in the introduction (Section 1.1), there are reasons to believe that Arctic climatic conditions influence the expression of radiation induced effects and, furthermore, that Arctic ecosystems are potentially more vulnerable to contaminants than organisms in other European climatic regions. The dose limits derived for temperate environments may, therefore, be unsuitable for direct application to the Arctic.

(2) The dose limits considered above relate to the protection of populations of wild flora and fauna. In contrast, the approach taken by EPIC focuses on environmentally relevant endpoints at the individual organism level, hence all data collation and subsequent analyses are made at the individual level.

7.3 Developments in EPIC

The key theme for the EPIC project has been to derive dose-effects relationships for a large range of exposures and hence to provide a scale of severity of radiation effects on natural biota following the increase in irradiation levels. Access to such information is important with respect to both environmental protection and the derivation of appropriate dose-standards.

From the information compiled in EPIC, a preliminary scale which maps observed biological effects onto ranges of absorbed dose has been constructed (Table 7.1). Dose-effect relationships have thus been tabulated for the generic groups: terrestrial animals, terrestrial plants and aquatic animals. The table also includes the background dose rate range observed under natural conditions.

Table 7.1 Scale mapping absorbed dose rates onto effect

Absorbed dose rate (Gy d $^{-1}$)	*Effect*
10^{-6} -10^{-5}	Natural radiation background for Arctic/northern organisms
10^{-4} to 5x10^{-4}	Minor cytogenetic effects. Stimulation of the most sensitive species
5x10^{-4} to 1x10^{-3}	Threshold for minor effects on morbidity in sensitive vertebrate animals.
2x10^{-3} to 5x10^{-3}	Threshold for effects on reproductive organs of vertebrate animals, decrease of embryo's survival.
5x10^{-3} to 10^{-2}	Threshold for life shortening of vertebrate animals. Threshold for effects in invertebrate animals. Threshold for effects on growth of coniferous plants.
10^{-2} to 10^{-1}	Life shortening of vertebrate animals; chronic radiation sickness. Considerable damage to coniferous trees.
10^{-1} to 1	Acute radiation sickness of vertebrate animals. Death of coniferous plants. Considerable damage to eggs and larva of invertebrate animals.
> 1	Acute radiation sickness of vertebrate animals; lethal dose received within several days. Increased mortality of eggs and larva of invertebrate animals. Death of coniferous plants, damage to deciduous plants.

A general conclusion can be made, that the threshold for deterministic radiation effects in wildlife (at the individual level) lies somewhere in the range 0.5-1 mGy d^{-1} for chronic low-LET radiation. This is in broad agreement with the conclusions made in the UNSCEAR reports. Having said this, the extrapolation of biological effects observed at one level of biological organisation to a higher level is no simple matter. Although minor effects on morbidity in sensitive vertebrate animals are observed at the dose range specified above, populations of highly productive vertebrate organisms (mice, some ubiquitous fish species) are viable at dose rates in the order of 10 mGy d^{-1}.

The establishment of dose limits may therefore depend not only on the types of organisms that require protection but also on the level of protection, e.g. protection of viable populations versus protection of individuals from a particular radiosensitive species.

The generalised conclusions, within EPIC, regarding the threshold dose rates at which various effects are observed are consistent with earlier studies. From the available information it is, therefore, not possible to justify any Arctic specific dose-standards at the present time. Assumptions of Arctic vulnerability might provide justification for applying an additional safety factor to any derived dose limits, e.g., that standards be set at say a factor of ten lower than those derived for other ecosystems. Having said this, the dataset upon which such a conclusion is drawn is limited in scope and the hypothesis relating to whether there is a unique expression of radiation-induced biological damage under Arctic conditions remains to be properly tested.

Furthermore, the problem of evaluating the appropriate weighting factors for high-LET radiation in the context of wildlife protection is still unsolved. According to the results of the analyses of available data, heavy alpha-emitting radionuclides with very low specific activity and chemical toxicity cannot be used for the purpose of weighting factors estimations, because the bulk of observed effects on biota are associated with chemical toxicity of these elements. It is more appropriate to establish separate safety regulation for these radionuclides (e.g. ^{238}U, ^{232}Th).

As discussed in Section 5.2, background dose rates have been derived for Arctic and/or related ecosystems. This information is summarised in Table 7.2.

It should be noted that background dose rates for Arctic terrestrial flora and fauna are particularly poorly defined and information for freshwater environments is limited to only a few reference organism types.

Table 7.2 Summary of natural background dose rates for Arctic and/ or related ecosystems.

Ecosystem	*Organism*	*Dose rate ($\mu Gy\ d^{-1}$)*
Marine	Phytoplankton[a]	0.5 - 2.1
	Zooplankton[a]	0.6 - 4.1
	Crustaceans[a]	2.7 - 14
	Molluscs[a]	2.7 - 13
	Macrophytes[a]	1.7 - 12
	(Benthic) Fish[a]	1.3 - 10
	Waterfowl[a]	0.5 – 1.6
Freshwater	Fish	1.4 – 2.2
Terrestrial	Generic vertebrate[b]	Circa 3.2

[a] Derived for the Kara Sea – it is assumed that phytoplankton, zooplankton and waterfowl receive all external irradiation from the water column whereas crustaceans, molluscs, macrophytes and benthic fish receive all external irradiation from sediment;

[b] Generic terrestrial vertebrate in a temperate environment (from Whicker & Shultz, 1982).

8 Conclusions and recommendations

8.1 The EPIC approach

Within the frame of the EPIC project, the following major steps were made in the direction of the development of a practical methodology for radiological assessment of Arctic/northern wildlife:

(i) A set of region-representative species have been selected which are characteristic for the marine, freshwater and terrestrial areas of the European Arctic. The selected species satisfy all/most of the selection criteria, they form large populations and their natural areas of geographical distribution cover the greater part of the European Arctic. The contamination of the selected species is studied within radio-ecological monitoring/research programmes, so databases on the radionuclide concentrations are available for most of the selected organisms.

(ii) Site-specific radioecological information has been collated to assess concentration factors (CFs) of radionuclides in Arctic biota.

(iii) Models and computer codes were developed in order to calculate internal and external doses to non-human organisms. Dose-conversion factors have been calculated for a set of reference Arctic organisms and a number of radionuclides.

The EPIC database "Radiation effects on biota" forms a large collection of radiation effects on northern biota covering a very wide range of dose rates to wild flora and fauna: from below 10^{-5} Gy d^{-1} up to more than 1 Gy d^{-1}. A great variety of radiation effects are registered in the EPIC database. These encompass effects from stimulation at low doses up to death from acute radiation syndrome at high doses. Based on information compiled in the EPIC database, preliminary dose-effects relationships were established for terrestrial and aquatic animals of the northern climatic zone and also for terrestrial plants. These dose-effects relationships provide a preliminary scale of severity of radiation effects at increasing levels of chronic radiation exposure. Furthermore, information on background dose rates were derived for selected reference organisms in terrestrial, freshwater and marine environments. Together, these data sets could be used in decision making processes and provide input towards the development of Arctic dose standards.

8.2 Shortcomings of the present assessment methodology

Despite the availability of large data sets, it should be noted that significant information gaps exist. Regarding the transfer of radionuclides in the environment, it has not been possible to derive transfer information for all radionuclide-reference organism combinations. This is especially true in the cases of freshwater and terrestrial environments where data paucity is often great. Even basic information relating to activity concentrations of natural radionuclides in Arctic environments are limited in coverage and thus render the derivation of background dose rates highly uncertain. The existing information concerning the effects of chronic exposure on Arctic wildlife does not cover all groups of sensitive species. For instance, there is a lack of data on large and long-lived Arctic animals, such as seals, polar bears and foxes, which are probably the most radiosensitive animals in Arctic ecosystems. There is also a lack of special experimental studies of those peculiarities in metabolism and biochemical composition of Arctic organisms, which may modify the response to ionising radiation compared with organisms from warmer climatic zones.

Effects of some natural alpha-emitting radionuclides (U, Th) on wildlife demonstrate the complex simultaneous action of chemical toxicity and high-LET radiation. In the consideration of these radionuclides a problem arises in developing a unified methodology for combined assessment for chemical toxicity and radiation on biota. The problem of choosing the appropriate weighting factors for high-LET radiation in the context of wildlife protection is still unsolved.

8.3 Recommendations for future research

There is a requirement to collate further information on natural radionuclides in Arctic environments through field studies. Furthermore, there is a requirement to refine and test existing dynamic models simulating the behaviour and fate of radionuclides in Arctic ecosystems. Empirical data are also required in defining transfer factors for numerous radionuclides and reference organism types. Ideally, data sets should allow statistical information to be derived (e.g. ranges, medians, probability distribution, etc.). Such information is necessary in evolution from an impact assessment to a true environmental risk assessment.

The EPIC database provides a large collection of radiation effects on wildlife under conditions of chronic exposure. At present, radiation impacts in the datasets are given mostly as they appeared in the source publications, i.e. activity concentrations in biota and environment, and/or author's dose estimates. A detailed dose assessment, using modern models for dose-to-biota calculations, is required to provide reliable estimations of dose rates for the EPIC data and make dose reconstructions in cases where only data on activity concentration and effects were available from source publications.

There is a lack of experimental data on radiation effects in typical Arctic organisms; bespoke experimentation is required to determine if extreme Arctic conditions influence the response of biota to ionising radiation exposure.

8.4 Conclusions

The EPIC approach is compatible with those adopted by other assessment systems. EPIC is essentially a single-tiered approach that has a degree of complexity built in which allows realistic impact assessment for the Arctic to be conducted. Within the EPIC system, risk characterisation is only addressed by evaluating dose rates to reference organism in relation to documented dose rate-response relationships. It is envisaged that the EPIC methodology may be used to inform the derivation of recommended standards/limits for the Arctic. With such standards in place the methodology could be used in a compliance situation.
Although basic tools may be available for assessing impacts of ionising radiation on Arctic environments, large areas of data paucity and knowledge gaps are prevalent.

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APPENDIX 1: Transfer factors for terrestrial reference organisms

Concentration ratios (CRs) describing the transfer of radionuclides from air (^{3}H and ^{14}C only) and soil to reference organism groups and representative species. Best estimate (generally mean of observed data) and range are given. For original source data refer to Beresford *et al.*, (2003). Descriptions of allometric and ^{3}H and ^{14}C modelling can be found in Beresford *et al.,* (in press) and Galeriu *et al.,* (2003).

Representative Species	Bq kg^{-1} organism : Bq m^{-3} air		Bq kg^{-1} organism : Bq kg^{-1} soil (dry weight) Best estimate (range)									
	$^{3}H^{a}$	$^{14}C^{a}$	Cs	^{90}Sr	^{99}Tc	^{210}Po	^{226}Ra	Pu	I	Th	U	^{241}Am
Lichen	-	-	7.54 0.13-22.8	6.46 0.22 -42.6	-	0.28 0.01-0.88	0.83 0.48-1.39	-	-	0.27 0.16-0.62	0.20 -	-
All Gymnosperms	-	-	0.95 0.04-5.54	1.33 0.11-3.79	-	-	2.13 (0.01-72.6)x10^{-1}	-	-	0.22 0.17-0.28	0.29 (0.02-116)x10^{-2}	-
Juniperus spp.	-	-	0.51 0.28-1.20	-	-	-	4.26 1.25-7.26	-	-	-	0.30 0.05-0.55	-
Larix / *Picea* spp.	-	-	0.20 0.04-0.51	-	-	3.25x10^{-3} -	5.25x10^{-3} -	-	-	-	1.75x10^{-4} (-)	-
Vaccinium spp	-	-	2.86 0.70-176	0.58 0.03-6.04	-	1.23 0.19-3.17	3.56 (0.06-76.4)x10^{-3}	-	-	0.16 0.02-0.24	0.32 (0.02-75.0)x10^{-2}	-
Salix spp.	-	-	0.51 (0.07-18.1) x10^{-1}	3.35 0.18-10.8	-	8.50x10^{-3} -	1.25x10^{-3} -	-	-	-	1.00x10^{-4} -	-
All Monocotyledons	150 -	890 -	0.98 0.06-18.4	0.35 0.09-1.47	76[b] 10-760	0.44 0.32-0.56	5.66x10^{-3} -	3.40x10^{-4}[b] (0.01-65)x10^{-2}	3.40x10^{-3}[b] (0.34-34.0)x10^{-3}	1.10x10^{-2}[b] (0.11-11.0)x10^{-2}	2.30x10^{-2}[b] (0.23-23.0)x10^{-2}	1.20x10^{-3}[b] (0.01-17.0)x10^{-2}

[a] Estimated using a specific activity model (Galeriu *et al*. 2003).
[b] CR value for grass from IAEA (1994).

Representative Species	Bq kg^{-1} organism : Bq m^{-3} air		Bq kg^{-1} organism : Bq kg^{-1} soil (dry weight) Best estimate (range)									
	^{3}H[a]	^{14}C[a]	Cs	^{90}Sr	^{99}Tc	^{210}Po	^{226}Ra	Pu	I	Th	U	^{241}Am
Herbivorous mammals - all species	-	-	7.01 0.01-76.1	2.89 (0.03-79.6)x10^{-2}	-	4.17 0.40 -14.3	4.77x10^{-2} (0.21-19.5) x10^{-2}	1.01x10^{-3} (-)	-	0.64 (0.21-46.6) x10^{-2}	1.80x10^{-3} (0.12-2.84) x10^{-3}	2.26x10^{-3} -
Herbivorous Mammals - excluding reindeer	-	-	1.03 0.01-76.1	1.09 (0.05-61.8)x10^{-2}	-	-	4.13x10^{-2} (0.21-19.5) x10^{-2}	-	-	7.74x10^{-3} (0.21-1.33) x10^{-2}	-	-
Reindeer	150 -	1340 -	9.91 0.07-45.1	3.48 0.03-8.42	-	4.17 0.40 -14.3	6.07x10^{-2} (0.31-15.9) x10^{-2}	-	-	0.37 0.23-0.47	9.36x10^{-3}[c]	-
Lemmings & Voles	150 -	1340 -	3.49 1.69-4.43	1.87	2.96[c] -	-	6.91x10^{-2} 0.01-0.20	-	3.63x10^{-1}[c] -	7.74x10^{-3} (0.21-1.33) x10^{-2}	2.60x10^{-3} (2.40-2.80) x10^{-3}	-
Carnivorous mammals - *all species*	-	1340 -	2.76 0.10-12.9	0.72 0.12-1.86	-	1.68 1.51-1.85	3.53x10^{-2} (0.43-9.56) x10^{-2}	-	-	5.52x10^{-3} (0.1-1.0) x10^{-2}	7.09x10^{-4} (-)	-
Fox	150 -	1340 -	0.65 0.10-1.68	12.5[c]	0.60[c]	-	4.00x10^{-3} (-)	1.72x10^{-4}	1.66[c]	-	-	1.72x10^{-4}[c]
Herbivorous bird - *all species*	-	-	0.89 0.02-9.05	Data for *Lagopus* spp. only	-	-	3.38x10^{-2} (0.21-19.5) x10^{-2}	-	-	3.89x10^{-4} (3.08-5.44) x10^{-4}	4.98x10^{-4} (4.05-6.76) x10^{-4}	-
Lagopus spp.	150 -	1140 -	0.76 0.02-3.22	3.52x10^{-2} (0.18-22.2) x10^{-2}	-	-	2.53x10^{-2} (0.91-5.07) x10^{-2}	-	-	3.52x10^{-4} -	4.05x10^{-4} -	-
Herbivorous bird -egg	150 -	890 -	6.4x10^{-2}[d] -	-	-	-	-	-	-	-	2.0x10^{-3}[d] -	-

[a] Estimated using a specific activity model (Galeriu *et al*. 2003).

[c] Allometrically derived by Beresford *et al.* (in press).

[d] Estimated from dietary transfer to domestic hen eggs and CR values describing transfer to herbivorous bird whole-body (see Section 7.2.1)

APPENDIX 2: Transfer factors for marine reference organisms

In the process of constructing look-up tables, presenting transfer and uptake data for marine reference organisms, it was deemed appropriate to present data on equilibrium concentration factors. Although the application of such quotients may have a number of limitations as discussed in the main report (Section 4.1.5), the scope, detail and robustness of information required to parameterise, for example, fully dynamic-biokinetic models was not sufficient to allow any alternative approach to be taken at the present time (however desirable).

The recommended data have been derived specifically for Arctic marine environments, whenever possible, although in many cases the values for temperate world-ocean have been employed for lack of regional data. The latter information is extracted from IAEA (2004), in recognition that many of those conducting an assessment may choose to refer to an internationally-sanctioned data-base. Where differences between the data collated in the review conducted within EPIC and the IAEA recommended values were not great, the IAEA values were normally used. In a number of instances, empirical data pertaining to whole body CFs were not available. In such cases, a combination of empirical concentration factors and biokinetic models were used as described elsewhere (Beresford *et al.*, 2003; Brown *et al.*, 2003). The data included in the subsequent look-up tables, therefore, are intended to provide a substantial supplement to the more generic values provided in IAEA (IAEA, 2004).

Unless otherwise stated the values provided in the tables relate to the whole body CF for the organism. The IAEA note (IAEA, 2004) that where reliable information exists for element/organism combinations, in almost every case, the maximum and minimum values observed in the population fall within one order of magnitude of the recommended values. The Agency therefore advises that, except where noted, it can be assumed that CFs vary by one order of magnitude around the recommended value. In view of the compatibility of the EPIC marine transfer tables with the IAEA values, a similar approach is approved here.

Table A2.1 H concentration factors for marine systems (not presented)

There is evidence that the steady-state concentration of tritium in biological tissues approaches, but does not exceed the concentrations in ambient water (Whicker & Schultz, 1982). For this reason the default CF for tritium is normally taken as unity for all marine biota types. This is indeed the approach adopted by the IAEA (IAEA, 2004)

However, there is also some evidence that organically-bound tritium (OBT) may account for cases in which the Tritium/Hydrogen ratio in biota slightly exceeds the ratio in ambient water (Whicker & Schultz, 1982). The fact that higher than expected activity concentrations in marine biota have been observed in environments in which a significant proportion of environmental tritium is present in an organically-bound form, e.g. Cardiff Bay area in the UK, exemplifies the limitations in applying a default unit CF.

For lack of more detailed information on the biological uptake of OBT in marine organisms, a default concentration factor of 1 is taken for H in all cases. These concentration factors may be suitably applicable where ^{3}H is present as tritiated water or water-exchangeable ^{3}H.

Table A2.2 C concentration factors* (l/kg) for marine systems

Reference organism	Bq/kg fresh per Bq/l	Comments
Bacteria	n/a	C-1
Phytoplankton	9 000	C-2
Macroalgae	10 000	C-3
Pelagic crustacean	20 000	C-4
(Bivalve) mollusc	20 000	C-5
Polychaete worm	20 000	C-6
Benthic crustacean	20 000	C-7
Pelagic planktotrophic fish	20 000	C-8
Pelagic carnivorous fish	20 000	C-9
Benthic fish	20 000	C-10
Sea bird	50 000	C-11
Mammal	50 000	C-12

n/a = Not applicable.

*The IAEA (IAEA, 2004) provide specific comments in relation to the derivation of carbon CFs in the accompanying notes to their tabulated recommended values. It is noted that for most elements, CFs are derived by dividing the body concentration of the element (or radioisotope) by the total concentration of the element (or radioisotope) in filtered sweater. If this was carried out for C, the denominator would include dissolved, CO_2, $(CO_3)^{2-}$ HCO_3^- dissolved organic carbon etc. For the purpose of consistency, all values relate to the organic carbon content of seawater.

C-1: No data for bacteria derived. It has been argued, and demonstrably shown (Pröhl *et al.*, 2003) that absorbed doses for bacteria will be essentially determined by the external source represented by the activity concentration in the surrounding medium.
C-2: Value from IAEA (2004).
C-3: Value from IAEA (2004).
C-4: Value from IAEA (2004).
C-5: Value from IAEA (2004).
C-6: This is an estimate. In view of similarities with mollusc in terms of habitat and feeding habits (ingestion of benthic particulate matter), this organism may represent a suitable proxy for the derivation of CFs. Empirical data are required.
C-7: Value from IAEA (2004).
C-8: The value for generic fish derived from IAEA (2004) has been taken to represent pelagic planktotrophic fish.
C-9: The value for generic fish derived from IAEA (2004) has been taken to represent pelagic carnivorous fish.
C-10: The value for generic fish derived from IAEA (2004) has been taken to represent benthic fish.
C-11: This is a rough estimate based on the derivation of information from humans. The carbon content of the body of man is 16 kg (ICRP, 1975). Dividing by the mass of reference man (70 kg), this yields a C concentration of 228.5 g/kg. This value is 2.39 x the C concentration used for fish. Multiplying this value by the CF reported for fish in IAEA (2004) yields a CF of 5×10^4. The application of human data to seabirds is open to question.
C-12: This is a rough estimate based on the derivation of information from humans (see C-12). In view of physiological similarities between mammals the derived CF value might be more appropriately applied to seals than to seabirds.

Table A2.3 Sr concentration factors (l/kg) for marine systems

Reference organism	Bq/kg fresh per Bq/l	Comments
Bacteria	n/a	Sr-1
Phytoplankton	1	Sr-2
Macroalgae	180	Sr-3
Pelagic crustacean	15	Sr-4
(Bivalve) mollusc	10	Sr-5
Polychaete worm	10	Sr-6
Benthic crustacean	15	Sr-7
Pelagic planktotrophic fish	5	Sr-8
Pelagic carnivorous fish	15	Sr-9
Benthic fish	8	Sr-10
Sea bird	940	Sr-11
Mammal	10	Sr-12

n/a = Not applicable

Sr-1: No data for bacteria derived. It has been argued, and demonstrably shown (Pröhl *et al.*, 2003) that absorbed doses for bacteria will be essentially determined by the external source represented.
Sr-2: Value from IAEA (2004).
Sr-3: This value corresponds to ^{90}Sr brown macroalgae sampled from the Kara and Barents Sea areas (Fisher *et al.*, 1999).
Sr-4: Value from the EPIC database for Arctic crustaceans (Beresford *et al.,* 2003).
Sr-5: Value from IAEA (2004).
Sr-6: This is an estimate. In view of similarities with mollusc in terms of habitat and feeding habits (benthic organism ingesting suspended particulate matter), this organism may represent a suitable proxy for the derivation of CFs. Empirical data are required.
Sr-7: Value from the EPIC database for Arctic crustaceans (Beresford *et al.,* 2003).
Sr-8: Value from the EPIC database for Polar Cod (Beresford *et al.,* 2003).
Sr-9: Value from the EPIC database for Cod (Beresford *et al.,* 2003).
Sr-10: Value from the EPIC database for Plaice (Beresford *et al.,* 2003).
Sr-11: Based on the output of a biokinetic model as reported in Brown *et al.*, (2003a).
Sr-12: Value from the EPIC database for Greenland Seal (Beresford *et al.,* 2003).

Table A2.4 Tc concentration factors (l/kg) for marine systems

Reference organism	Bq/kg fresh per Bq/l	Comments
Bacteria	n/a	Tc-1
Phytoplankton	4	Tc-2
Macrolalgae	26 000	Tc-3
Pelagic crustacean	100	Tc-4
(Bivalve) mollusc	300	Tc-5
Polychaete worm	300	Tc-6
Benthic crustacean	1400	Tc-7
Pelagic planktotrophic fish	80	Tc-8
Pelagic carnivorous fish	80	Tc-8
Benthic fish	80	Tc-8
Sea bird	870	Tc-9
Mammal	20	Tc-10

n/a = Not applicable

Tc-1: No CF data for bacteria have been derived. It has been argued, and demonstrably shown (Pröhl *et al.*, 2003) that absorbed doses for bacteria will be essentially determined by the external source represented.
Tc-2: Based on IAEA (2004)
Tc-3: Based on a mean value for brown seaweeds for 4 European marine areas (Hurtgen *et al.*, 1988; Masson *et al.*, 1995; Brown *et al.*, 1999).
Tc-4: Value from the EPIC database for shrimp (Beresford *et al.,* 2003).
Tc-5: Value from the EPIC database for mussels (Beresford *et al.,* 2003).
Tc-6: This is an estimate. In view of similarities with mollusc in terms of habitat and feeding habits (benthic organism ingesting suspended particulate matter), this organism may represent a suitable proxy for the derivation of CFs. Empirical data are required.
Tc-7: Value from the EPIC database for crab (Beresford *et al.,* 2003).
Tc-8: Based on IAEA (2004) derived from data from the English Channel (IPSN, 1999) – for generic fish.
Tc-9: Based on the output of a biokinetic model as reported in Brown *et al*. (2003a).
Tc-10: Based on the average of 2 biokinetic model as reported in Brown *et al*. (2003a).

Table A2.5 I concentration factors (l/kg) for marine systems

Reference organism	Bq/kg fresh per Bq/l	Comments
Bacteria	n/a	I-1
Phytoplankton	800	I-2
Macroalgae	400	I-3
(Pelagic) crustacean	3	I-4
(Bivalve) mollusc	10	I-5
Polychaete worm	10	I-6
Benthic crustacean	3	I-7
Pelagic planktrophic fish	9	I-8
Pelagic carnivorous	9	I-8
Benthic fish	9	I-8
Wading bird	880	I-9
Mammal	8	I-10

n/a = Not applicable

I-1: No data for bacteria derived. It has been argued, and demonstrably shown (Pröhl *et al*., 2003) that absorbed doses for bacteria will be essentially determined by the external source represented.
I-2: Value from IAEA (2004). The recommended value was derived using stable element data.
I-3: Data for brown seaweed reported in Holm *et al.* (1994). It should be noted that Holm *et al*. (1994) reported large variations in ^{131}I concentrations between red (mean = 48 800), green (CF = 921) and brown seaweed (CF = 418). This may account for the discrepancy observed with the IAEA recommended value which presumably pertains to all 3 seaweed groups.
I-4: Value from IAEA (2004) for crustaceans (presumably benthic in most cases). The IAEA notes that there are few recent I CF data for crustaceans and little to support or refute the concentration of 1 mg/kg (d.w.) used in the derivation of the recommended value.
I-5: Value from IAEA (2004) derived using stable element data.
I-6: This is an estimate. In view of similarities with mollusc in terms of habitat and feeding habits (ingestion of benthic particulate matter), this organism may represent a suitable proxy for the derivation of CFs. Empirical data are required.
I-7: Value from IAEA (2004). The IAEA notes that there are few recent I CF data for crustaceans and little to support or refute the concentration of 1 mg/kg (d.w.) used in the derivation of the recommended value.
I-8: Value from IAEA (2004) for generic fish.
I-9: Based on the output from a biokinetic model as reported in Brown *et al*. (2003a).
I-10: Based on the output from a biokinetic model as reported in Brown *et al*. (2003a).

Table A2.6 Cs concentration factors (l/kg) for marine systems

Reference organism	Bq/kg fresh per Bq/l	Comments
Bacteria	n/a	Cs-1
Phytoplankton	20	Cs-2
Macroalgae	75	Cs-3
Pelagic crustacean	35	Cs-4
(Bivalve) mollusc	50	Cs-5
Polychaete worm	50	Cs-6
Benthic crustacean	150	Cs-7
Pelagic planktotrophic fish	100	Cs- 8
Pelagic carnivorous fish	80	Cs-9
Benthic fish	100	Cs-10
Sea bird	580	Cs-11
Mammal	70	Cs-12

n/a = Not applicable

Cs-1: No CF data for bacteria have been derived. It has been argued, and demonstrably shown (Pröhl *et al.*, 2003) that absorbed doses for bacteria will be essentially determined by the external source represented.
Cs-2: Based on IAEA (1985) and IAEA (2004). These values in turn are based on 2 references Styron *et al*. (1976) and Heldal *et al*. (2001).
Cs-3: This value is based on mean of values cited in 2 publications (Holm *et al*, 1994) and Fisher *et al.* (1999) for brown macroalgae. Brown macroalgae has been selected as the reference type in this case owing to the fact that it exhibits the highest uptake. Brown seaweeds are more common in northern marine environments and are often sampled in monitoring work although they are normally not consumed by humans.
Cs-4: Value from the EPIC database for shrimp (Beresford *et al.,* 2003).
Cs-5: Value from the EPIC database for mussel (Beresford *et al.,* 2003).
Cs-6: This is an estimate. In view of similarities with mollusc in terms of habitat and feeding habits (benthic organism ingesting suspended particulate matter), this organism may represent a suitable proxy for the derivation of CFs. Empirical data are required.
Cs-7: Value from the EPIC database for crab (Beresford *et al.,* 2003).
Cs-8: Value from the EPIC database for Polar Cod (Beresford *et al.,* 2003).
Cs-9: Value from the EPIC database for Cod (Beresford *et al.,* 2003).
Cs-10: Value from the EPIC database for Plaice (Beresford *et al.,* 2003).
Cs-11: Value from the EPIC database for Gull (Beresford *et al.,* 2003).
Cs-12: Value from the EPIC database for Greenland Seal (Beresford *et al.,* 2003).

Table A2.7 Po concentration factors (l/kg) for marine systems

Reference organism	Bq/kg fresh per Bq/l	Comments
Bacteria	n/a	Po-1
Phytoplankton	70 000	Po-2
Macroalgae	1000	Po-3
Pelagic crustacean	45 000	Po-4
(Bivalve) mollusc	60 000	Po-5
Polychaete worm	16 000	Po-6
Benthic crustacean	37 000	Po-7
Pelagic planktotrophic fish	3 330	Po-8
Pelagic carnivorous fish	600	Po-9
Benthic fish	5 330	Po-10
Sea bird	39 000	Po-11
Mammal	21 000	Po-12

n/a = Not applicable.

Po-1: No data for bacteria derived. It has been argued, and demonstrably shown (Pröhl *et al*., 2003) that absorbed doses for bacteria will be essentially determined by the external source represented.
Po-2: Value from IAEA (2004).
Po-3: Value from IAEA (2004). No new information has been collated on the uptake of Po by macroalgae following IAEA-TECDOC-211 (IAEA, 1978). However, it should be noted that information for European marine environments has been published by McDonald *et al*. (1992) and that the mean value derived from this study coincide exactly with the figure recommended by the IAEA.
Po-4: Value from the EPIC database for shrimp (Beresford *et al.,* 2003).
Po-5: Value from the EPIC database for mussel (Beresford *et al.,* 2003).
Po-6: These data are for whole annelids sampled in the Baltic Sea (Skwarzec & Falkowski, 1988).
Po-7:
Po-8: Value from the EPIC database for Polar Cod (Beresford *et al.,* 2003).
Po-9: Value from the EPIC database for Cod (Beresford *et al.,* 2003).
Po-10: Value from the EPIC database for Plaice (Beresford *et al.,* 2003).
Po-11: Based on the output from a biokinetic model as reported in Brown *et al*. (2003a). A single compartmental model for retention of Po in man has been used.
Po-12: Value from the EPIC database for Greenland Seal (Beresford *et al.,* 2003).

Table A2.8 Ra concentration factors (l/kg) for marine systems

Reference organism	Bq/kg fresh per Bq/l	Comments
Bacteria	n/a	Ra-1
Phytoplankton	2000	Ra-2
Macroalgae	100	Ra-3
Pelagic crustacean	100	Ra-4
(Bivalve) mollusc	100	Ra-5
Polychaete worm	100	Ra-6
Benthic crustacean	100	Ra-7
Pelagic planktotrophic fish	100	Ra-8
Pelagic carnivorous fish	100	Ra-8
Benthic fish	100	Ra-8
Sea bird	520	Ra-9
Mammal	25	Ra-10

n/a = Not applicable.

Ra-1: No data for bacteria derived. It has been argued, and demonstrably shown (Pröhl *et al.*, 2003) that absorbed doses for bacteria will be essentially determined by the external source represented.
Ra-2: Value from IAEA (2004).
Ra-3: The IAEA report (2004) that no new information has been collated on the uptake of Ra to macroalgae following IAEA-TECDOC-211 (IAEA, 1978).
Ra-4: Value from IAEA (2004).
Ra-5: The IAEA state (2004) that this value was derived from information which did not include CFs for lamellibranch or gastropod molluscs. The application of this CF value to bivalve molluscs must therefore be viewed with caution.
Ra-6: This is an estimate. In view of similarities with mollusc in terms of habitat and feeding habits (benthic organism ingesting suspended particulate matter), this organism may represent a suitable proxy for the derivation of CFs. Empirical data are required.
Ra-7: Value from IAEA (2004). The IAEA report (2004) that no new information has been collated on the uptake of Ra to crustaceans following IAEA-TECDOC-211 (IAEA, 1978).
Ra-8: This is the value for generic fish derived from IAEA (2004).
Ra-9: Based on the output of a biokinetic model as reported in Brown *et al.* (2003a). The appropriateness of using elimination rates derived from retention factors for man (ICRP-30, parts 1-4) is of some concern.
Ra-10: Based on the output of a biokinetic model as reported in Brown *et al.* (2003a).

Table A2.9 Th concentration factors (l/kg) for marine systems

Reference organism	Bq/kg fresh per Bq/l	Comments
Bacteria	n/a	Th-1
Phytoplankton	40 000	Th-2
Macroalgae	200	Th-3
Pelagic crustacean	1000	Th-4
(Bivalve) Mollusc	1000	Th-5
Polychaete worm	1000	Th-6
Benthic crustacean	1000	Th-7
Pelagic planktotrophic fish	600	Th-8
Pelagic carnivorous fish	600	Th-8
Benthic fish	600	Th-8
Sea bird	65	Th-9
Mammal	6*	Th-10

n/a = Not applicable
* Concentration ratio.

Th-1: No data for bacteria derived. It has been argued, and demonstrably shown (Pröhl *et al.*, 2003) that absorbed doses for bacteria will be essentially determined by the external source represented.
Th-2: Value from IAEA (2004)
Th-3: Value from IAEA (2004)
Th-4: Value from IAEA (2004) for crustaceans (mainly benthic). It should be noted that additional data pertaining to Th CFs for crustaceans were not found to supplement a value first derived in the 1970s (IAEA, 1978).
Th-5: Value from IAEA (2004). The derivation of this value is somewhat unclear as the technical report provides only the information that "no CF data for lamellibranch or gastropods molluscs were located".
Th-6: This is an estimate. In view of similarities with mollusc in terms of habitat and feeding habits (benthic organism ingesting suspended particulate matter), this organism may represent a suitable proxy for the derivation of CFs. Empirical data are required.
Th-7: Value from IAEA (2004). It should be noted that additional data pertaining to Th CFs for crustaceans were not found to supplement a value first derived in the 1970s (IAEA, 1978).
Th-8: Value from IAEA (2004) for generic fish.
Th-9: Based on the output of a biokinetic model as reported in Brown *et al.* (2003a).
Th-10: Based on the average of 2 biokinetic model outputs as reported in Brown *et al.* (2003a). In the case of both models (model using allometrically derived excretion rate and multi-compartmental excretion model), the concentration ratio at 10 y, as oppose to the (equilibrium) CF, was used in the derivation of this value.

Table A2.10 U concentration factors (l/kg) for marine systems

Reference organism	Bq/kg fresh per Bq/l	Comments
Bacteria	n/a	U-1
Phytoplankton	20	U-2
Macroalgae	50	U-3
Pelagic crustacean	10	U-4
Mollusc	30	U-5
Polychaete worm	30	U-6
Benthic crustacean	10	U-7
Pelagic planktotrophic fish	1	U-8
Pelagic carnivorous fish	1	U-8
Benthic fish	1	U-8
Sea bird	3	U-9
Mammal	0.05*	U-10

n/a = Not applicable
* Concentration ratio.

U-1: No data for bacteria derived. It has been argued, and demonstrably shown (Pröhl *et al.*, 2003) that absorbed doses for bacteria will be essentially determined by the external source represented.
U-2: Value from IAEA (2004).
U-3: This is a mean value derived for 3 European marine areas taken from McDonald *et al.* (1992).
U-4: Value from IAEA (2004) for crustaceans (mainly benthic). It should be noted that additional data pertaining to U CFs for crustaceans were not found to supplement a value first derived in the 1970s (IAEA, 1978).
U-5: Value from IAEA (2004). Value is for Lamellibranch or bivalve molluscs
U-6: This is an estimate. In view of similarities with mollusc in terms of habitat and feeding habits (benthic organism ingesting suspended particulate matter), this organism may represent a suitable proxy for the derivation of CFs. Empirical data are required.
U-7: Value from IAEA (2004). It should be noted that additional data pertaining to U CFs for crustaceans were not found to supplement a value first derived in the 1970s (IAEA, 1978).
U-8: Value from IAEA (2004) for generic fish.
U-9: Based on the output of a biokinetic model as reported in Brown *et al*. (2003a).
U-10: Based on the average of 2 biokinetic model outputs as reported in Brown *et al*. (2003a). In the case of the multi-compartmental excretion model, the concentration ratio at 10 y, as oppose to the (equilibrium) CF, was used in the derivation of this value.

Table A2.11 Pu concentration factors (l/kg) for marine systems

Reference organism	Bq/kg fresh per Bq/l	Confidence	Comments
Bacteria	n/a	n/a	Pu-1
Phytoplankton	20 000	Medium	Pu-2
Macroalgae	4 650	High	Pu-3
Pelagic crustacean	300		Pu-4
Mollusc	150	Medium	Pu-5
Polychaete worm	150	Low	Pu-6
Benthic Crustacean	300	Medium	Pu-7
Pelagic planktotrophic fish	<200	Medium	Pu-8
Pelagic carnivorous fish	140	Medium	Pu-9
Benthic fish	<200	Medium	Pu-10
Sea bird	540	Low	Pu-11
Mammal	400	Medium	Pu-12

n/a = Not applicable

Pu-1: No data for bacteria derived. It has been argued, and demonstrably shown (Pröhl *et al*., 2003) that absorbed doses for bacteria will be essentially determined by the external source represented.
Pu-2: Value from IAEA (2004).
Pu-3: Value pertains to brown macroalgae and is based on 4 references (Fisher *et al*., 1999; Germain *et al*., 2000; Holm *et al*., 1991 and Holm *et al.* 1994) covering 3 European marine waters.
Pu-4: Value from the EPIC database for generic crustaceans (Beresford *et al.,* 2003).
Pu-5: Value from the EPIC database for mussels (Beresford *et al.,* 2003).
Pu-6: This is an estimate. In view of similarities with mollusc in terms of habitat and feeding habits (benthic organism ingesting suspended particulate matter), this organism may represent a suitable proxy for the derivation of CFs. Empirical data are required.
Pu-7: Value from the EPIC database for generic crustaceans (Beresford *et al.,* 2003).
Pu-8: Value from the EPIC database for Polar Cod (Beresford *et al.,* 2003).
Pu-9: Value from the EPIC database for Cod (Beresford *et al.,* 2003).
Pu-10: Value from the EPIC database for Plaice (Beresford *et al.,* 2003).
Pu-11: Based on the output of a biokinetic model as reported in Brown *et al.* (2003a). It should be noted that this value is only obtained after an equilibration period of approximately 10 years. Shorter contaminant contact times will lead to concomitantly lower concentration ratios.
Pu-12: Value from the EPIC database for "Sea mammals" (Beresford *et al.,* 2003).

Table A2.12 Am concentration factors (l/kg) for marine systems

Reference organism	Bq/kg fresh per Bq/l	Comments
Bacteria	n/a	Am-1
Phytoplankton	20 000	Am-2
Macroalgae	8 000	Am-3
Pelagic crustacean	400	Am-4
Bivalve mollusc	20 000	Am-5
Polychaete worm	700	Am-6
Benthic crustacean	500	Am-7
Pelagic planktotrophic fish	100	Am-8
Pelagic carnivorous fish	100	Am-8
Benthic fish	100	Am-8
Sea bird	310	Am-9
Mammal	5*	Am-10

n/a = Not applicable
* Concentration ratio.

Am-1: No data for bacteria derived. It has been argued, and demonstrably shown (Pröhl *et al*., 2003) that absorbed doses for bacteria will be essentially determined by the external source represented.
Am-2: Value from IAEA (2004).
Am-3: Value from IAEA (2004). IAEA have derived a value for brown seaweed based on 4 references mainly dealing with European coastal environments.
Am-4: Value from IAEA (2004) for crustacean (mainly benthic). The CF value for Am was assumed to be the same as for Cf – a radionuclide for which experimental data were available.
Am-5: Value from the EPIC database for mussel (Beresford *et al.,* 2003). It should be noted that this values is considerably higher than the IAEA (2004) recommended value of 1000 and should be treated with some caution.
Am-6: This is an estimate. In view of similarities with mollusc in terms of habitat and feeding habits (benthic organism ingesting suspended particulate matter), this organism may represent a suitable proxy for the derivation of CFs. Empirical data are required.
Am-7: Value from the EPIC database for lobster (Beresford *et al.,* 2003
Am-8: Value from IAEA (2004) for generic fish.
Am-9: Based on the output of a biokinetic model as reported in Brown *et al.* (2003a). It should be noted that this value is only obtained after an equilibration period of approximately 10 years. Shorter contaminant contact times will lead to concomitantly lower concentration ratios.
Am-10: This is a Concentration ratio based on the output of 2 biokinetic models as reported in Brown *et al.* (2003a). This value was derived for a simulation period of 10 years at which time the system had not reached equilibrium. A period of several hundred years is required for the system to truly equilibrate.

APPENDIX 3: Weighted DCCs for reference organisms

3.1 Pelagic planktotrophic fish

Table A3.1.1: Description

Habitat	Representative species	Reference dimension (cm) of adult	Shape
Pelagic	Polar cod (*Boreogadus saida*)	15 × 3 × 1.5	ellipsoid

Table A3.1.2: DCCs (Artificial radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg (w.w.)	**External** (from water column), Gy a^{-1} Bq^{-1} m^3
Sr-90	9.77E-07	1.29E-11
Y-90	3.98E-06	7.39E-10
Tc-99	5.10E-07	3.86E-13
I-129	3.38E-07	1.06E-10
I-131	9.95E-07	1.88E-09
Cs-137	1.29E-06	2.80E-09
Cs-134	1.03E-06	7.65E-09
Pu-239	2.64E-04	2.56E-13
Am-241	2.81E-04	1.11E-10

Table A3.1.3: DCCs (Natural radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg (w.w.)	**External** (from water column), Gy a^{-1} Bq^{-1} m^3
H-3	8.61E-08	0.00E+00
C-14	2.50E-07	2.78E-17
K-40	2.47E-06	9.54E-10
U-238	2.15E-04	2.58E-12
Th-234	3.81E-06	7.58E-10
U-234	2.44E-04	3.51E-12
Th-230	2.40E-04	3.62E-12
Ra-226	2.46E-04	2.99E-11
Rn-222	9.91E-04	9.23E-09
Pb-210	2.04E-07	1.20E-11
Bi-210	1.85E-06	1.17E-10
Po-210	2.73E-04	4.14E-14
Th-232	2.03E-04	2.70E-12
Ra-228	2.27E-06	4.84E-09
Th-228	2.78E-04	1.18E-11
Ra-224	1.37E-03	8.10E-09

3.2 Pelagic carnivorous fish

Table A3.2.1: Description

Habitat	Representative species	Reference dimension (cm) of adult	Shape
Pelagic	Cod (*Gadus morhua*)	50 ×10 × 6	ellipsoid

Table A3.2.2: DCCs (Artificial radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg (w.w.)	**External** (from water column), Gy a^{-1} Bq^{-1} m^3
Sr-90	9.90E-07	4.18E-13
Y-90	4.55E-06	1.70E-10
Tc-99	5.10E-07	1.08E-17
I-129	3.71E-07	7.36E-11
I-131	1.20E-06	1.68E-09
Cs-137	1.61E-06	2.50E-09
Cs-134	1.78E-06	6.90E-09
Pu-239	2.64E-04	6.92E-13
Am-241	2.81E-04	9.70E-11

Table A3.2.3: DCCs (Natural radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg (w.w.)	**External** (from water column), Gy a^{-1} Bq^{-1} m^3
H-3	8.61E-08	0.00E+00
C-14	2.50E-07	0.00E+00
K-40	2.69E-06	7.38E-10
U-238	2.15E-04	9.04E-13
Th-234	4.32E-06	2.49E-10
U-234	2.44E-04	1.44E-12
Th-230	2.40E-04	2.15E-12
Ra-226	2.46E-04	2.73E-11
Rn-222	9.93E-04	7.85E-09
Pb-210	2.08E-07	8.50E-12
Bi-210	1.95E-06	1.99E-11
Po-210	2.73E-04	3.77E-14
Th-232	2.03E-04	1.33E-12
Ra-228	2.92E-06	4.19E-09
Th-228	2.78E-04	9.52E-12
Ra-224	1.38E-03	7.13E-09

3.3 Benthic crustacean

Table A3.3.1: Description

Habitat	Representative species	Reference dimension (cm) of adult	Shape
Benthic	Crab (*Cancer pagurus*)	10 × 10 × 5 (total size), 5×5×3 (body size without coat)	ellipsoid

Table A3.3.2: DCCs (Artificial radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External** (from water column), Gy a^{-1} Bq^{-1} m^3	**External** (from bottom sediment), Gy a^{-1} Bq^{-1} kg
Sr-90	9.78E-07	4.36E-12	6.54E-09
Y-90	4.19E-06	2.56E-10	3.84E-07
Tc-99	5.09E-07	1.39E-13	2.08E-10
I-129	3.43E-07	8.42E-11	3.29E-08
I-131	1.02E-06	1.76E-09	5.14E-07
Cs-137	1.34E-06	2.62E-09	7.54E-07
Cs-134	1.13E-06	7.18E-09	2.02E-06
Pu-239	2.64E-04	8.52E-13	6.47E-11
Am-241	2.81E-04	1.02E-10	2.72E-08

Table A3.3.3: DCCs (Natural radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External** (from water column), Gy a^{-1} Bq^{-1} m^3	**External** (from bottom sediment), Gy a^{-1} Bq^{-1} kg
H-3	8.61E-08	0.00E+00	0.00E+00
C-14	2.50E-07	1.26E-17	1.89E-14
K-40	2.53E-06	7.93E-10	4.74E-07
U-238	2.15E-04	1.17E-12	5.14E-10
Th-234	3.99E-06	3.30E-10	3.79E-07
U-234	2.44E-04	1.78E-12	7.16E-10
Th-230	2.40E-04	2.42E-12	8.16E-10
Ra-226	2.46E-04	2.84E-11	1.09E-08
Rn-222	9.91E-04	8.23E-09	4.45E-06
Pb-210	2.05E-07	9.36E-12	2.45E-09
Bi-210	1.88E-06	3.98E-11	5.97E-08
Po-210	2.73E-04	3.92E-14	1.99E-11
Th-232	2.03E-04	1.56E-12	5.98E-10
Ra-228	2.40E-06	4.39E-09	2.32E-06
Th-228	2.78E-04	1.01E-11	3.27E-09
Ra-224	1.37E-03	7.43E-09	3.86E-06

3.4 Benthic fish

Table A3.4.1: Description

Habitat	Representative species	Reference dimension (cm) of adult	Shape
Benthic	Plaice (*Pleuronectes platessa*)	25 × 20 × 3	ellipsoid

Table A3.4.2: DCCs (Artificial radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External** (from water column), Gy a^{-1} Bq^{-1} m^3	**External** (from bottom sediment), Gy a^{-1} Bq^{-1} kg
Sr-90	9.88E-07	4.66E-12	6.99E-09
Y-90	4.43E-06	5.94E-10	8.91E-07
Tc-99	5.10E-07	6.14E-15	9.21E-12
I-129	3.60E-07	1.69E-10	3.29E-08
I-131	1.13E-06	3.50E-09	5.29E-07
Cs-137	1.51E-06	5.18E-10	7.85E-07
Cs-134	1.54E-06	1.43E-08	2.06E-06
Pu-239	2.64E-04	1.90E-12	6.47E-11
Am-241	2.81E-04	2.04E-10	2.72E-08

Table A3.4.3: DCCs (Natural radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External** (from water column), Gy a^{-1} Bq^{-1} m^3	**External** (from bottom sediment), Gy a^{-1} Bq^{-1} kg
H-3	8.61E-08	0.00E+00	0.00E+00
C-14	2.50E-07	1.16E-23	0.00E+00
K-40	2.64E-06	1.59E-09	3.77E-07
U-238	2.15E-04	2.70E-12	5.14E-10
Th-234	4.20E-06	7.30E-10	4.26E-08
U-234	2.44E-04	3.98E-12	7.16E-10
Th-230	2.40E-04	5.08E-12	8.16E-10
Ra-226	2.46E-04	5.64E-11	1.09E-08
Rn-222	9.92E-04	1.65E-08	3.98E-06
Pb-210	2.07E-07	1.89E-11	2.45E-09
Bi-210	1.92E-06	8.18E-11	0.00E+00
Po-210	2.73E-04	7.80E-14	1.99E-11
Th-232	2.03E-04	3.36E-12	5.98E-10
Ra-228	2.73E-06	8.78E-09	2.15E-06
Th-228	2.78E-04	2.04E-11	3.27E-09
Ra-224	1.37E-03	1.48E-08	3.60E-06

3.5 Bivalve mollusc

Table A3.5.1: Description

Habitat	Representative species	Reference dimension (cm) of adult	Shape
Benthic	Common mussels (*Mutilus edulis*), Scallops (*Pecten maximus*)	5 × 3 × 2.5 (total size); 3.2 × 2 × 1.5 (body)	ellipsoid

Table A3.5.2: DCCs (Artificial radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External** (from water column), Gy a^{-1} Bq^{-1} m^3	**External** (from bottom sediment), Gy a^{-1} Bq^{-1} kg
Sr-90	9.75E-07	1.48E-11	2.23E-08
Y-90	4.07E-06	6.50E-10	9.76E-07
Tc-99	5.09E-07	1.49E-12	2.23E-09
I-129	3.39E-07	1.06E-10	3.29E-08
I-131	9.97E-07	1.88E-09	5.47E-07
Cs-137	1.30E-06	2.79E-09	8.04E-07
Cs-134	1.05E-06	7.64E-09	2.07E-06
Pu-239	2.64E-04	1.54E-12	6.47E-11
Am-241	2.81E-04	1.11E-10	2.72E-08

Table A3.5.3: DCCs (Natural radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External** (from water column), Gy a^{-1} Bq^{-1} m^3	**External** (from bottom sediment), Gy a^{-1} Bq^{-1} kg
H-3	8.61E-08	0.00E+00	0.00E+00
C-14	2.50E-07	2.54E-14	3.81E-11
K-40	2.50E-06	9.37E-10	6.36E-07
U-238	2.15E-04	2.38E-12	5.14E-10
Th-234	3.88E-06	6.81E-10	8.95E-07
U-234	2.44E-04	3.28E-12	7.16E-10
Th-230	2.40E-04	3.46E-12	8.16E-10
Ra-226	2.46E-04	3.00E-11	1.09E-08
Rn-222	9.91E-04	9.12E-09	5.14E-06
Pb-210	2.05E-07	1.17E-11	2.45E-09
Bi-210	1.86E-06	1.08E-10	1.62E-07
Po-210	2.73E-04	4.14E-14	1.99E-11
Th-232	2.03E-04	2.54E-12	5.98E-10
Ra-228	2.31E-06	4.80E-09	2.58E-06
Th-228	2.78E-04	1.16E-11	3.27E-09
Ra-224	1.37E-03	8.04E-09	4.26E-06

3.6 Sea bird

Table A3.6.1: Description

Habitat	Representative species	Reference dimension (cm) of adult	Shape
Islands	Gull (*Larus spp.*)	15×11×8 (body); 21×16×11 (including feather)	ellipsoid

Table A3.6.2: DCCs (Artificial radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External** (from semi-infinite source in water), Gy a^{-1} Bq^{-1} m^3	**External** (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2
Sr-90	9.88E-07	5.82E-13	0.00E+00
Y-90	4.54E-06	5.98E-11	0.00E+00
Tc-99	5.10E-07	1.56E-15	0.00E+00
I-129	3.73E-07	2.93E-11	4.14E-07
I-131	1.19E-06	7.95E-10	9.53E-06
Cs-137	1.59E-06	1.17E-09	1.36E-05
Cs-134	1.77E-06	3.27E-09	3.72E-05
Pu-239	2.64E-04	2.62E-13	1.86E-09
Am-241	2.81E-04	4.50E-11	6.08E-07

Table A3.6.3: DCCs (Natural radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External**, (on the water/air interface, from semi-infinite source in water), Gy a^{-1} Bq^{-1} m^3	**External,** (on the soil/air interface, from semi-infinite source in soil), Gy a^{-1} Bq^{-1} kg
H-3	8.61E-08	0.00E+00	0.00E+00
C-14	2.50E-07	2.77E-23	0.00E+00
K-40	2.68E-06	3.49E-10	3.16E-07
U-238	2.15E-04	3.19E-13	5.88E-11
Th-234	4.31E-06	1.00E-10	3.55E-08
U-234	2.44E-04	5.50E-13	1.51E-10
Th-230	2.40E-04	9.40E-13	3.59E-10
Ra-226	2.46E-04	1.30E-11	9.51E-09
Rn-222	9.92E-04	3.71E-09	3.35E-06
Pb-210	2.08E-07	3.77E-12	1.11E-09
Bi-210	1.94E-06	8.55E-12	0.00E+00
Po-210	2.73E-04	1.79E-14	1.68E-11
Th-232	2.03E-04	5.50E-13	1.77E-10
Ra-228	2.91E-06	1.99E-09	1.81E-06
Th-228	2.78E-04	4.43E-12	2.45E-09
Ra-224	1.38E-03	3.40E-09	3.04E-06

3.7 Pelagic crustacean

Table A3.7.1: Description

Habitat	Representative species	Reference dimension (cm) of adult	Shape
Pelagic	Northern shrimp (*Pandalus borealis*)	7 × 1.5 × 1.5	ellipsoid

Table A3.7.2: DCCs (Artificial radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg (w.w.)	**External** (from water column), Gy a^{-1} Bq^{-1} m^3
Sr-90	9.67E-07	2.31E-11
Y-90	3.72E-06	1.00E-09
Tc-99	5.08E-07	2.13E-12
I-129	3.34E-07	1.11E-10
I-131	9.57E-07	1.92E-09
Cs-137	1.24E-06	2.85E-09
Cs-134	9.23E-07	7.76E-09
Pu-239	2.64E-04	1.92E-12
Am-241	2.81E-04	1.13E-10

Table A3.7.3: DCCs (Natural radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg (w.w.)	**External** (from water column), Gy a^{-1} Bq^{-1} m^3
H-3	8.61E-08	0.00E+00
C-14	2.50E-07	1.95E-14
K-40	2.39E-06	1.04E-09
U-238	2.15E-04	3.12E-12
Th-234	3.58E-06	9.88E-10
U-234	2.44E-04	4.17E-12
Th-230	2.40E-04	4.10E-12
Ra-226	2.46E-04	3.02E-11
Rn-222	9.91E-04	9.60E-09
Pb-210	2.03E-07	1.30E-11
Bi-210	1.80E-06	1.69E-10
Po-210	2.73E-04	4.19E-14
Th-232	2.03E-04	3.16E-12
Ra-228	2.11E-06	5.01E-09
Th-228	2.78E-04	1.24E-11
Ra-224	1.37E-03	8.34E-09

3.8 Carnivorous mammal

Table A3.8.1: Description

Habitat	Representative species of carnivorous mammal	Reference dimension (cm) of adult	Shape
Islands	Harp Seal *(Phoca groenlandica)*	170×45×40	ellipsoid

Table A3.8.2: DCCs (Artificial radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External** (from water column), Gy a^{-1} Bq^{-1} m^3	**External,** on the soil/air interface (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2
Sr-90	9.90E-07	6.84E-19	0.00E+00
Y-90	4.71E-06	1.29E-11	0.00E+00
Tc-99	5.10E-07	0.00E+00	0.00E+00
I-129	4.25E-07	1.92E-11	1.51E-07
I-131	1.96E-06	9.24E-10	6.86E-06
Cs-137	2.70E-06	1.40E-09	9.84E-06
Cs-134	4.77E-06	3.90E-09	2.69E-05
Pu-239	2.64E-04	2.06E-13	1.10E-09
Am-241	2.81E-04	4.70E-11	4.18E-07

Table A3.8.3: DCCs (Natural radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External** (from water column), Gy a^{-1} Bq^{-1} m^3	**External**, on the soil/air interface (from semi-infinite source in soil), Gy a^{-1} Bq^{-1} kg
H-3	8.61E-08	0.00E+00	0.00E+00
C-14	2.50E-07	0.00E+00	0.00E+00
K-40	3.00E-06	4.29E-10	2.09E-07
U-238	2.15E-04	1.75E-13	2.17E-11
Th-234	4.48E-06	6.88E-11	2.39E-08
U-234	2.44E-04	4.02E-13	8.20E-11
Th-230	2.40E-04	9.38E-13	2.32E-10
Ra-226	2.46E-04	1.52E-11	6.88E-09
Rn-222	9.96E-04	4.58E-09	2.26E-06
Pb-210	2.13E-07	3.22E-12	5.84E-10
Bi-210	1.96E-06	2.04E-13	0.00E+00
Po-210	2.73E-04	2.16E-14	1.13E-11
Th-232	2.03E-04	4.84E-13	1.08E-10
Ra-228	4.71E-06	2.40E-09	1.22E-06
Th-228	2.78E-04	5.06E-12	1.72E-09
Ra-224	1.38E-03	4.41E-09	2.05E-06

3.9 Soil invertebrate (*Collembola spp.*)

Table A3.9.1: Description

Depth in soil/depth burrow, cm	Proposed reference organism	Reference dimension (cm) of adult	Shape
Mainly in litter layer	*Collembola* spp.	0.5×0.1×0.1	ellipsoid

Table A3.9.2: DCCs (Artificial radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg (w.w.)	**External**, on the soil/air interface (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2
Sr-90	6.36E-07	0.00E+00
Y-90	6.08E-07	0.00E+00
Tc-99	4.47E-07	0.00E+00
I-129	3.12E-07	6.40E-07
I-131	4.15E-07	1.04E-05
Cs-137	5.95E-07	1.51E-05
Cs-134	2.06E-07	4.14E-05
Pu-239	2.61E-04	5.06E-09
Am-241	2.78E-04	5.55E-07

Table A3.9.3: DCCs (Natural radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External**, on the soil/air interface (from the semi-infinite source in soil), Gy a^{-1} Bq^{-1} kg
H-3	8.61E-08	0.00E+00
C-14	2.41E-07	0.00E+00
K-40	7.00E-07	3.76E-07
U-238	2.14E-04	4.76E-10
Th-234	8.18E-07	4.24E-08
U-234	2.42E-04	6.70E-10
Th-230	2.37E-04	7.76E-10
Ra-226	2.43E-04	1.09E-08
Rn-222	9.68E-04	3.97E-06
Pb-210	1.93E-07	2.30E-09
Bi-210	6.02E-07	0.00E+00
Po-210	2.70E-04	1.98E-11
Th-232	2.02E-04	5.59E-10
Ra-228	4.35E-07	2.15E-06
Th-228	2.74E-04	3.22E-09
Ra-224	1.34E-03	3.60E-06

3.10 Soil invertebrate (Mites)

Table A3.10.1: Description

Depth in soil/depth burrow, (cm)	Proposed reference organism	Reference dimension (cm) of adult	Shape
100	Mites (the suborder *Oribatida* (oribatid or beetle, mites) of the order Acariformes	0.3×0.04	Flattened sphere

Table A3.10.2: DCCs (Artificial radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External**, on the soil/air interface (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2	**External,** in soil at the depth 100 cm (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2
Sr-90	3.74E-07	0.00E+00	0.00E+00
Y-90	2.46E-07	0.00E+00	0.00E+00
Tc-99	3.54E-07	0.00E+00	0.00E+00
I-129	2.92E-07	6.42E-07	0.00E+00
I-131	2.08E-07	1.04E-05	9.22E-10
Cs-137	4.22E-07	1.51E-05	4.19E-09
Cs-134	8.95E-08	4.14E-05	1.60E-08
Pu-239	2.55E-04	5.17E-09	3.95E-14
Am-241	2.70E-04	5.56E-07	0.00E+00

Table A3.10.3: DCCs (Natural radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External**, on the soil/air interface (from the semi-infinite source in soil), Gy a^{-1} Bq^{-1} kg	**External,** in soil at the depth 100 cm, (from the infinite source in soil), Gy a^{-1} Bq^{-1} kg
H-3	8.61E-08	0.00E+00	7.50E-14
C-14	2.25E-07	0.00E+00	2.51E-08
K-40	3.13E-07	3.77E-07	3.12E-06
U-238	2.10E-04	4.99E-10	5.07E-06
Th-234	4.69E-07	4.26E-08	4.09E-06
U-234	2.37E-04	6.98E-10	7.48E-06
Th-230	2.33E-04	8.00E-10	7.08E-06
Ra-226	2.38E-04	1.09E-08	7.63E-06
Rn-222	9.31E-04	3.97E-06	6.86E-05
Pb-210	1.90E-07	2.39E-09	2.58E-08
Bi-210	2.77E-07	0.00E+00	1.69E-06
Po-210	2.63E-04	1.99E-11	1.03E-05
Th-232	1.99E-04	5.82E-10	4.23E-06
Ra-228	2.27E-07	2.15E-06	6.88E-06
Th-228	2.67E-04	3.25E-09	1.09E-05
Ra-224	1.29E-03	3.60E-06	8.91E-05

3.11 Small herbivorous mammal (Lemming)

Table A3.11.1: Description

Depth in soil/depth burrow, (cm)	Proposed reference organism	Reference dimension (cm) of adult	Shape
100	Collared Lemming (*Lemus dicrostonyx*)	[1]14×5.5×6.3 [2]8.8×3.4×3.9	Ellipsoid

[1]Actual volume; [2]Size of effective homogeneous ellipsoid (for dose calculation)

Table A3.11.2: DCCs (Artificial radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External,** on the soil/air interface (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2	**External,** in soil at the depth 100 cm (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2
Sr-90	9.81E-07	0.00E+00	0.00E+00
Y-90	4.28E-06	0.00E+00	0.00E+00
Tc-99	5.10E-07	0.00E+00	0.00E+00
I-129	3.47E-07	5.35E-07	0.00E+00
I-131	1.04E-06	9.82E-06	9.38E-10
Cs-137	1.37E-06	1.42E-05	4.29E-09
Cs-134	1.21E-06	3.89E-05	1.64E-08
Pu-239	2.64E-04	2.34E-09	4.00E-14
Am-241	2.81E-04	5.82E-07	0.00E+00

Table A3.11.3: DCCs (Natural radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External,** on the soil/air interface (from the semi-infinite source in soil), Gy a^{-1} Bq^{-1} kg	**External,** in soil at the depth 100 cm (from the infinite source in soil), Gy a^{-1} Bq^{-1} kg
H-3	8.61E-08	0.00E+00	0.00E+00
C-14	2.50E-07	0.00E+00	4.56E-15
K-40	2.56E-06	3.45E-07	7.93E-07
U-238	2.15E-04	1.03E-10	1.20E-09
Th-234	4.07E-06	3.86E-08	3.34E-07
U-234	2.44E-04	2.10E-10	1.81E-09
Th-230	2.40E-04	4.18E-10	2.44E-09
Ra-226	2.46E-04	1.02E-08	2.85E-08
Rn-222	9.92E-04	3.66E-06	8.27E-06
Pb-210	2.06E-07	1.32E-09	9.47E-09
Bi-210	1.89E-06	0.00E+00	4.08E-08
Po-210	2.73E-04	1.83E-11	3.93E-11
Th-232	2.03E-04	2.21E-10	1.58E-09
Ra-228	2.48E-06	1.97E-06	4.40E-06
Th-228	2.78E-04	2.66E-09	1.01E-08
Ra-224	1.37E-03	3.31E-06	7.45E-06

3.12 Small herbivorous mammal (Vole)

Table A3.12.1: Description

Depth in soil/depth burrow, (cm)	Proposed reference organism	Reference dimension (cm) of adult	Shape
50	Vole (*Microtus* spp)	[1]10.3×4×4.9 [2]6.6×2.6×3.3	Ellipsoid

[1]Actual volume; [2]Size of effective homogeneous ellipsoid (for dose calculation)

Table A3.12.2: DCCs (Artificial radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External,** on the soil/air interface (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2	**External,** in soil at the depth 100 cm (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2
Sr-90	9.78E-07	0.00E+00	0.00E+00
Y-90	4.17E-06	0.00E+00	0.00E+00
Tc-99	5.09E-07	0.00E+00	0.00E+00
I-129	3.42E-07	5.62E-07	0.00E+00
I-131	1.01E-06	9.90E-06	6.63E-08
Cs-137	1.33E-06	1.44E-05	1.79E-07
Cs-134	1.11E-06	3.94E-05	5.42E-07
Pu-239	2.64E-04	2.59E-09	3.78E-12
Am-241	2.81E-04	5.71E-07	1.09E-13

Table A3.12.3: DCCs (Natural radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External,** on the soil/air interface (from the semi-infinite source in soil), Gy a^{-1} Bq^{-1} kg	**External,** in soil at the depth 100 cm (from the infinite source in soil), Gy a^{-1} Bq^{-1} kg
H-3	8.61E-08	0.00E+00	0.00E+00
C-14	2.50E-07	0.00E+00	1.81E-13
K-40	2.52E-06	3.52E-07	8.38E-07
U-238	2.15E-04	1.27E-10	1.52E-09
Th-234	3.97E-06	3.95E-08	4.17E-07
U-234	2.44E-04	2.41E-10	2.21E-09
Th-230	2.40E-04	4.43E-10	2.72E-09
Ra-226	2.46E-04	1.03E-08	2.91E-08
Rn-222	9.91E-04	3.74E-06	8.53E-06
Pb-210	2.05E-07	1.40E-09	1.01E-08
Bi-210	1.87E-06	0.00E+00	5.61E-08
Po-210	2.73E-04	1.86E-11	4.02E-11
Th-232	2.03E-04	2.42E-10	1.83E-09
Ra-228	2.38E-06	2.01E-06	4.54E-06
Th-228	2.78E-04	2.73E-09	1.06E-08
Ra-224	1.37E-03	3.38E-06	7.64E-06

3.13 Large herbivorous mammal

Table A3.13.1: Description

Proposed reference organism	Reference dimension (cm) of adult	Shape
Reindeer (*Rangifer tarandus*)	200×19×32	ellipsoid

Table A3.13.2: DCCs (Artificial radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg (w.w.)	**External,** on the soil/air interface (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2
Sr-90	9.90E-07	0.00E+00
Y-90	4.70E-06	0.00E+00
Tc-99	5.10E-07	0.00E+00
I-129	4.13E-07	2.49E-07
I-131	1.65E-06	8.37E-06
Cs-137	2.25E-06	1.19E-05
Cs-134	3.54E-06	3.25E-05
Pu-239	2.64E-04	1.44E-09
Am-241	2.81E-04	5.33E-07

Table A3.13.3: DCCs (Natural radionuclides)

Nuclides	**Internal,** Gy a^{-1} Bq^{-1} kg	**External,** on the soil/air interface (from the semi-infinite source in soil), Gy a^{-1} Bq^{-1} kg
H-3	8.61E-08	0.00E+00
C-14	2.50E-07	0.00E+00
K-40	2.89E-06	2.59E-07
U-238	2.15E-04	3.39E-11
Th-234	4.47E-06	2.94E-08
U-234	2.44E-04	1.08E-10
Th-230	2.40E-04	2.88E-10
Ra-226	2.46E-04	8.15E-09
Rn-222	9.94E-04	2.78E-06
Pb-210	2.11E-07	8.08E-10
Bi-210	1.96E-06	0.00E+00
Po-210	2.73E-04	1.39E-11
Th-232	2.03E-04	1.37E-10
Ra-228	4.00E-06	1.50E-06
Th-228	2.78E-04	2.07E-09
Ra-224	1.38E-03	2.52E-06

3.14 Herbivorous bird

Table A3.14.1: Description

Proposed reference organism	Reference dimension (cm) of adult	Shape
Willow ptarmigan or willow grouse *(Lagopus lagopus)*	[1]25×17×13 [2]14×9.4×7.2	ellipsoid

[1]Actual volume; [2]Size of effective homogeneous ellipsoid (for dose calculation)

Table A3.14.2: DCCs (Artificial radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg (w.w.)	**External**, on the soil/air interface (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2
Sr-90	9.87E-07	0.00E+00
Y-90	4.53E-06	0.00E+00
Tc-99	5.10E-07	0.00E+00
I-129	3.69E-07	3.84E-07
I-131	1.17E-06	9.44E-06
Cs-137	1.56E-06	1.34E-05
Cs-134	1.67E-06	3.68E-05
Pu-239	2.64E-04	1.79E-09
Am-241	2.81E-04	6.07E-07

Table A3.14.3: DCCs (Natural radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External,** on the soil/air interface (from the semi-infinite source in soil), Gy a^{-1} Bq^{-1} kg
H-3	8.61E-08	0.00E+00
C-14	2.50E-07	0.00E+00
K-40	2.67E-06	3.08E-07
U-238	2.15E-04	5.31E-11
Th-234	4.29E-06	3.47E-08
U-234	2.44E-04	1.42E-10
Th-230	2.40E-04	3.47E-10
Ra-226	2.46E-04	9.33E-09
Rn-222	9.92E-04	3.27E-06
Pb-210	2.08E-07	1.06E-09
Bi-210	1.93E-06	0.00E+00
Po-210	2.73E-04	1.64E-11
Th-232	2.03E-04	1.70E-10
Ra-228	2.85E-06	1.77E-06
Th-228	2.78E-04	2.40E-09
Ra-224	1.37E-03	2.97E-06

3.15 Egg from ground nesting bird

Table A3.15.1: Description

Proposed reference organism	Reference dimension (cm) of adult	Shape
Red Grouse (*Lagopus lagopus scoticus*) egg	4.6×3.2×3.2	ellipsoid

Table A3.15.2: DCCs (Artificial radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg (w.w.)	**External**, on the soil/air interface (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2
Sr-90	9.78E-07	0.00E+00
Y-90	4.18E-06	0.00E+00
Tc-99	5.09E-07	0.00E+00
I-129	3.42E-07	5.89E-07
I-131	1.01E-06	1.00E-05
Cs-137	1.33E-06	1.47E-05
Cs-134	1.11E-06	4.00E-05
Pu-239	2.64E-04	3.01E-09
Am-241	2.81E-04	5.59E-07

Table A3.15.3: DCCs (Natural radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External,** on the soil/air interface (from the semi-infinite source in soil), Gy a^{-1} Bq^{-1} kg
H-3	8.61E-08	0.00E+00
C-14	2.50E-07	0.00E+00
K-40	2.53E-06	3.61E-07
U-238	2.15E-04	1.70E-10
Th-234	3.98E-06	4.05E-08
U-234	2.44E-04	2.95E-10
Th-230	2.40E-04	4.84E-10
Ra-226	2.46E-04	1.05E-08
Rn-222	9.91E-04	3.82E-06
Pb-210	2.05E-07	1.50E-09
Bi-210	1.88E-06	0.00E+00
Po-210	2.73E-04	1.91E-11
Th-232	2.03E-04	2.78E-10
Ra-228	2.39E-06	2.06E-06
Th-228	2.78E-04	2.82E-09
Ra-224	1.37E-03	3.46E-06

3.16 Carnivorous mammal (burrowing)

Table A3.16.1: Description

Depth in soil/depth burrow (cm)	Proposed reference organism	Reference dimension (cm) of adult	Shape
100	Arctic fox *(Alopex lagopus)*	54×11×18	Ellipsoid

Table A3.16.2: DCCs (Artificial radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External**, on the soil/air interface (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2	**External**, in soil at the depth 100 cm (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2
Sr-90	9.90E-07	0.00E+00	0.00E+00
Y-90	4.64E-06	0.00E+00	0.00E+00
Tc-99	5.10E-07	0.00E+00	0.00E+00
I-129	3.95E-07	2.97E-07	0.00E+00
I-131	1.39E-06	8.92E-06	1.02E-09
Cs-137	1.88E-06	1.27E-05	4.64E-09
Cs-134	2.55E-06	3.46E-05	1.77E-08
Pu-239	2.64E-04	1.58E-09	4.37E-14
Am-241	2.81E-04	5.73E-07	0.00E+00

Table A3.16.3: DCCs (Natural radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External**, on the soil/air interface (from the semi-infinite source in soil), Gy a^{-1} Bq^{-1} kg	**External,** in soil at the depth 100 cm (from the infinite source in soil), Gy a^{-1} Bq^{-1} kg
H-3	8.61E-08	0.00E+00	0.00E+00
C-14	2.50E-07	0.00E+00	0.00E+00
K-40	2.77E-06	2.80E-07	6.03E-07
U-238	2.15E-04	4.02E-11	3.91E-10
Th-234	4.40E-06	3.17E-08	1.34E-07
U-234	2.44E-04	1.20E-10	7.53E-10
Th-230	2.40E-04	3.13E-10	1.50E-09
Ra-226	2.46E-04	8.68E-09	2.24E-08
Rn-222	9.93E-04	2.99E-06	6.48E-06
Pb-210	2.10E-07	9.08E-10	5.77E-09
Bi-210	1.96E-06	0.00E+00	5.25E-09
Po-210	2.73E-04	1.50E-11	3.11E-11
Th-232	2.03E-04	1.50E-10	8.27E-10
Ra-228	3.39E-06	1.62E-06	3.44E-06
Th-228	2.78E-04	2.21E-09	7.53E-09
Ra-224	1.38E-03	2.72E-06	6.02E-06

3.17 Plant roots

Table A3.17.1: Description

Depth in soil/depth burrow (cm)	Proposed reference organism	Reference dimension (cm) of adult	Shape
0 - 30	Plant roots (Fine leaved grass) (*Vaccinium myrtillus*)	29×0.0035×0.0035	ellipsoid

Table A3.17.2: DCCs (Artificial radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg (w.w.)	**External,** mean value at the depth 0-30 cm (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2
Sr-90	1.95E-07	0.00E+00
Y-90	8.83E-08	0.00E+00
Tc-99	2.36E-07	0.00E+00
I-129	2.80E-07	1.86E-07
I-131	9.31E-08	2.56E-06
Cs-137	3.45E-07	3.97E-06
Cs-134	3.42E-08	1.10E-05
Pu-239	2.64E-04	1.09E-08
Am-241	2.81E-04	1.06E-07

Table A3.17.3: DCCs (Natural radionuclides)

Nuclide	**Internal,** Gy a^{-1} Bq^{-1} kg	**External,** from the infinite source in soil, Gy a^{-1} Bq^{-1} kg
H-3	8.61E-08	0.00E+00
C-14	2.13E-07	3.71E-08
K-40	1.23E-07	3.30E-06
U-238	2.15E-04	6.80E-09
Th-234	2.90E-07	4.27E-06
U-234	2.44E-04	8.67E-09
Th-230	2.40E-04	7.67E-09
Ra-226	2.46E-04	3.09E-08
Rn-222	9.79E-04	1.33E-05
Pb-210	1.92E-07	2.39E-08
Bi-210	1.12E-07	1.85E-06
Po-210	2.73E-04	4.29E-11
Th-232	2.03E-04	6.66E-09
Ra-228	1.37E-07	6.97E-06
Th-228	2.78E-04	1.65E-08
Ra-224	1.34E-03	1.45E-05

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