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Update of the MARINA Project on the radiological exposure of the European Community from radioactivity in North European marine waters

Annex F: Assessment of the Impact of Radioactive Substances on Marine Biota of North European Waters

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Directorate-General Environment
Directorate C – Health and environment
Unit C.4 – Radiation protection

2002

Marina II

ASSESSMENT OF THE IMPACT OF RADIOACTIVE SUBSTANCES ON MARINE BIOTA OF NORTH EUROPEAN WATERS

Report of Working Subgroup D*

By

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This report, nevertheless, remains the responsibility of the authors.

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Glossary of Terms

The following terms have been adopted or modified from: IAEA International basic safety standards (1996), IAEA Safety Glossary (2000), NRPB (1998), Environment Agency (2001), Berkeley National Laboratory glossary and ecological literature.

Absorbed dose. Quantity of energy imparted by *ionising radiation* to unit mass of matter such as tissue. Unit *gray*, symbol Gy. 1 Gy = 1 joule per kilogram; also 1 rad = 0.01 Gray.

Activity. Attribute of an amount of a *radionuclide.* Describes the rate at which transformations occur in it. Unit *Becquerel*, symbol Bq. 1 Bq =1 transformation per second.

Acute exposure. Exposure received within a short period of time. Normally used to refer to exposure of sufficiently short duration that the resulting *dose* can be treated as instantaneous (e.g. less than an hour). Usually contrasted with *chronic exposure.*

Alpha particle (alpha radiation). A positively charged particle (a ^{4}He nucleus) made up of two neutrons and two protons. It is the least penetrating of the three common forms of radiation, being stopped by a sheet of paper.

Aquatic Biota. Plant or animal life living in or on water.

Background radiation. The exposure of organisms to radiation naturally existing in the environment.

Becquerel (Bq). See *activity*.

Benthic organisms. Animals and plants living on or within the bottom sediments of an aquatic ecosystem.

Beta particle. An electrically charged elementary particle (electron or positron), emitted during the decay of some radioactive elements. The mass of electron is 1/1836 of that of a proton.

Bioaccumulation. The capacity of organisms to accumulate in their bodies some contaminants in higher concentrations through dietary intake or directly from the environment.

Biota. Plant and animal life of a particular region.

Chronic exposure. Exposure persisting in time.

Community. An assemblage of populations of different species within a specified location in space and time.

Concentration factor for aquatic organism. The ratio of radionuclide concentration in an aquatic organism to that in water.

Cosmic Rays. High energy *ionising radiation* from space.

Cytogenetic damage. Damage to chromosomes that can be detected on the microscopic level.

Decay of a radionuclide. The process of spontaneous transformation of a *radionuclide.* The decrease in the activity of a radioactive substance.

Demersal fish. Fish inhabiting the deeper layers of water column.

Deterministic effect. A *radiation* effect for which generally a threshold level of dose exists, above which the severity of the effect is greater for a higher dose.

Dose assessment. Assessment of the *dose(s)* to an individual or group of organisms.

Dose. A measure of the energy deposited by *radiation* in a target.

Dose rate. Dose delivered over a specified unit of time.

Electron. An elementary particle with low mass, 1/1836 that of a *proton*, and unit negative electric charge. Positively charged *electrons*, called positrons, also exist. See also *beta particle.*

Equivalent dose. The quantity obtained by multiplying the *absorbed dose* by a radiation weighting factor to allow for the differing effectiveness of the various types of *ionising radiation* in causing harm to organism.

Fertility. The number of fertilized eggs produced in a given time in sexually reproducing plants and animals.

Gamma ray. A discrete quantity of electromagnetic energy without mass or charge emitted by a *radionuclide.* Gamma rays are high-energy electromagnetic photons similar to X-rays. They are highly penetrating and several inches of lead or several feet of concrete are necessary to shield against them.

Gray (Gy). See absorbed dose.

Ion. Electrically charged atom or grouping of atoms.

Ionisation. The process by which a neutral atom or molecule acquires an electric charge and become an ion.

Ionising radiation. *Radiation* that produces *ionisation* in matter. Examples are *alpha particles, beta-particles, gamma rays, X-rays* and *neutrons.*

Linear energy transfer (LET). A measure of how, as a function of distance, energy is transferred from radiation to the exposed matter. *Radiation* with high LET is normally assumed to comprise of protons, neutrons and alpha particles (or other particles of similar or greater mass). *Radiation* with low LET is assumed to comprise of photons (including *X-rays* and *gamma rays*), electrons and positrons.

Morbidity. A decline in well-being due to a worsening of the physiological characteristics of the organism, e.g. effects on the immune system, blood system, nervous system, etc.

Naturally occurring radionuclides. *Radionuclides* that occur naturally in significant quantities on Earth.

Pelagic organisms. Animals and plants living in water column of marine ecosystem. Pelagic organisms are distinct from *benthic* organisms. Phytoplankton, zooplankton, planktivorous fish are examples of pelagic organisms.

Phytoplankton. Passive or weakly motile suspended small plants (mostly microscopic algae). The plant subgroup of plankton.

Plankton. Small organisms which are passively suspended in water column.

Poikilotermic animals. Animals, which are unable to maintain the body temperature at a constant level. The body temperature of a poikilotermic animal follows the temperature of the environment. E.g. fish, molluscs, crustaceans, frogs are poikilotermic organisms.

Population. Group of individuals of a particular species inhabiting a specified territory.

Proton. An elementary particle with unit positive charge, stable nucleus of a hydrogen atom.

Rad. Unit of absorbed dose of ionising radiation equal to an energy of 100 ergs per gram of irradiated material.

Radiation (ionising). Refers to alpha particles, beta particles, photons (gamma rays or x-rays), high-energy electrons, and any other particles capable of producing ions.

Radiation weighting factors (w_r). Defined as multipliers of absorbed dose used to account for the relative effectiveness of different types of radiation in inducing health effects.

Radioecological assessment. Includes the analysis of radionuclide accumulation and transfer in the biotic components of the environment. Complex radioecological assessment includes also *radiological assessment* for non-human organisms.

Radiological assessment for non-human organisms. Includes assessment of doses received by organisms and analysis of biological effects of radiation. Assessment is aimed at providing information that forms the basis of a decision whether the radiological situation is satisfactory or not.

Relative Biological Effectiveness (RBE). Ratio of the absorbed dose of a reference radiation (normally gamma rays or X rays) required to produce a level of biological response to the absorbed dose of the radiation of concern required to produce the same level of biological response, all other conditions being kept constant.

Stochastic Effects. Effects for which the probability of occurrence is a function of dose, without threshold, but the severity of the effects is independent of dose.

Zooplankton. Weakly motile suspended small animals (mostly invertebrates). The animal subgroup of plankton.

Executive Summary

The objectives of work

The primary objective of the MARINA II study is to provide input from the European Commission to the work of OSPAR RSC in implementing the OSPAR Strategy with regard to radioactive substances and the work of the European Commission in respect of this Strategy. The OSPAR Strategy places particular emphasis on the radiological impacts on man and biota and requires contracting parties to develop further scientific tools for assessing radiation exposure and risk especially to marine organisms. Consequently a sub-group in the MARINA II Study was established to address the radiological aspects relating to biota and this chapter presents the results of the work of that sub-group.

Methodology for assessing doses and radiation impact on marine biota

At present, no internationally agreed criteria, or guidance, exist for assessing the impact of environmental radiation on flora and fauna.

An assessment methodology has been identified, in the present report, for the estimation of doses and radiation impact on marine biota, based on the current 'state-of-the-art' in the dosimetry of non-human organisms, and available information of the effects of chronic radiation exposure on aquatic organisms. The methodology includes the following components: identification of biological endpoints of concern; selection of region-specific organisms for assessment; adaptation of dosimetric models for dose calculations and, radiological assessment for marine biota.

The biological endpoints of concern

There are significant differences between the radiation protection of man, and the non-human biotic environment, in relation to the definition of the biological endpoints of concern. For humans the concern is on the potential impairment of health in any individual resulting from inherited or somatically acquired mutations. In the environment the concern is on the maintenance of the integrity of ecosystems and component populations of different species, which, in turn, depends on the survival and reproduction of individual organisms in the populations.
Four umbrella endpoints have been proposed to be inclusive of relevant effects at the level of individual organisms (FASSET Project, 2001):

- **Morbidity** (a decline in well-being due to a worsening of the physiological characteristics of the organisms, e.g., effects on the immune system, blood system, nervous system, etc.);

- **Reproduction** (negative changes in fertility and fecundity resulting in reduced reproductive success, i.e. reduced production of reproductively competent individuals in the following generations);

- **Cytogenetic effects** (cytological and genetic changes in tissues) and,

- **Mortality** (shortening of lifetime because of the combined effects on different organs and tissues of the organism).

During normal operating conditions, both in the nuclear industry and in other industries dealing with natural radionuclides, the radioactive waste management activities (inclusive of authorised releases directly to the environment) are associated with chronic exposure of flora and fauna at comparatively low dose rates.

Dose-effect relationships

To evaluate the possible harm to biota, the dose rates to organisms inhabiting the industry-impacted marine areas in the OSPAR region, have been compared with the available information on the effects of radiation in aquatic organisms.

Comprehensive reviews on the effects of ionising radiation on non-human organisms provide the following general conclusions on the range of chronic dose rates, which are of practical interest in the radiological assessment for aquatic and coastal organisms (including sea birds and marine mammals):

NCRP report (1991):
"It appears that a chronic dose rate of no greater than 10 mGy day^{-1} (1 rad day^{-1}) to the maximally exposed individual in a population of aquatic organisms would ensure protection for the population. If modeling and/or dosimetric measurements indicate a level of 2.5 mGy day^{-1}, then a more detailed evaluation of the potential ecological consequences to the endemic population should be conducted" (page 62, conclusions);

IAEA report (1992):
"In the aquatic environment it would appear that limiting chronic dose rates to 10 mGy day^{-1} or less to the maximally exposed individuals in a population would provide adequate protection for the population" (page 53, summary);

UNSCEAR report (1996):
*"Overall consideration of the data available for the effects of chronic irradiation on aquatic organisms has led to the conclusion that dose rates up to 10 mGy day^{-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"***(**para 176);

"*For the most sensitive animal species, mammals, there is little indication that dose rates of 10 mGy day^{-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 day^{-1}), the same statement could be made with respect to reproductive effects" (conclusions, p.59)* .

In the terrestrial environment harmful effects to animals are not expected at dose rates below 1 mGy day^{-1}.

None of the above cited dose rate levels were intended as recommendations for radiation protection criteria although they clearly could have implications for the development of such criteria.

To provide an understanding of natural normal levels of radiation exposure of marine biota, the natural background exposure has been estimated for the representative marine organisms.

Selection of region-representative marine organisms

It is practically impossible to perform radioecological assessment for every species from the thousands inhabiting the waters of the North-East Atlantic. This problem has been solved by selecting a limited set of region-specific organisms, which have been used as representative marine organisms in this radioecological assessment. The report presents the criteria for, and a selection of, the region-specific organisms for the OSPAR marine region. The selected representative species satisfy most, or all, of the selection criteria; they form large populations, and their natural areas of geographical distribution cover the whole or the greater part of the OSPAR region.

The set of region-representative organisms includes molluscs (mussel and winkle/limpet), large crustaceans (crab and lobster), fish (cod and plaice). The contamination of the region-specific species is studied within radioecological monitoring/research programmes; databases on the concentrations of radionuclides are available for these organisms. Some preliminary assessments were made for seafood-eating coastal birds and seals; however, these organisms are not the subjects of systematic radioecological monitoring.

In the radiological assessment, the use of region-specific organisms throughout the whole OSPAR region offers the possibility to compare the doses to biota at different locations of the North-East Atlantic. However, there are some shortcomings that may affect the comparisons, such as: the representativeness of organisms within the existing monitoring programs; frequency of sampling and differences in type of exposures among the organisms.

Dose assessment to marine biota in the OSPAR region

In the MARINA II Update study, dose rates to representative marine organisms have been calculated using the existing dosimetric approaches; adaptations were made to take into account the sizes and habits of the region-specific organisms. Doses from both external and internal pathways have been estimated, as well as total dose rates to the representative organisms.

To account the differences in the relative biological efficiency of α-, β-, and γ- radiation, a radiation weighting factor (w_r) of 20 has been selected for α-emitting radionuclides as a very conservative assumption, and a factor of 1 for other radionuclides.

Dose assessments to marine biota have been made for the selected representative areas of the OSPAR region:

- Coastal areas in the vicinity of nuclear reprocessing plants (Sellafield, UK; Cap de la Hague, France);
- Near coastal zone of nuclear power plant (Ringhals NPP in Sweden);
- Coastal zones in the vicinity of non-nuclear plants, characterized by discharges of enhanced levels of natural radionuclides (phosphate plant at Whitehaven, UK; offshore oil installations in the North Sea);

- Remote marine areas with low levels of man-made radioactivity, which are considered as relatively non-contaminated waters in the OSPAR region (Barents Sea, North-Norwegian coastal waters).

Real data of measurements of radionuclide concentrations in the marine biota, seawater and sediments have been used for 'dose-to-biota' estimates. This information has been obtained in the course of routine/research monitoring programmes. The environmental data for dose assessment has been compiled by the Working Group B within the frame of the MARINA II Project; these include databases from BNFL and MAFF/CEFAS; Nord-Cotentin database; data from the AMAP programme, and journal publications. The assessments were made for the periods extending from the early 1980s to the late 1990s.

Average dose rates (in Gray per day) to site-specific organisms have been calculated for each year of observations, using a computer code linked with databases. Uncertainties in dose rates associated with the scattering of monitoring data were estimated to be about one order of magnitude.

The results of dose assessment to marine biota

During the assessment period, dose rates to representative organisms within the OSPAR region varied within a very broad range from about 10^{-9} Gy day^{-1} in the remote, relatively 'clean' areas up to about 10^{-4} Gy day^{-1} in the industry-impacted zones (values weighted by w_r).

Among the marine zones affected by the nuclear industry, the highest dose rates to marine biota were estimated for the **Sellafield coastal area** impacted by the BNFL nuclear reprocessing plant. The dose rates to representative organisms that inhabit the Sellafield coastal waters are shown in Figure 1, demonstrating the gradual decrease of radiation exposure to biota during the assessment period (1986-2001).

Molluscs (mussel, winkle) were found to be the most exposed group among the assessed marine organisms, as a result of high accumulation of many radionuclides in their tissues. The contribution of different radionuclides to the dose rates to molluscs is shown in Figure 2.

Crustaceans (crab, lobster) were found to receive somewhat lower radiation exposures than molluscs; dose rates to fish were lower than those to crustaceans. The contribution of different radionuclides to the dose rates to fish is given in Figure 3.

Preliminary estimations of the exposure of seafood-eating birds, inhabiting the vicinity of Sellafield, have revealed that dose rates to this group of near-sea organisms were closer to those to molluscs and higher than those to fish. Preliminary estimations for grey seals indicated that dose rates were approximately the same as for large fish.

During the assessment period (1986-2001), the estimated dose rates to marine biota in the vicinity of Sellafield were found to be even lower than the levels suggested in the literature at which effects on aquatic organisms at a population level would be unlikely (UNSCEAR 1996, IAEA 1992). A gradual decrease in dose rates was found during the assessment period, although the exposure to marine organisms at Sellafield from man-made sources remained

higher than that of the same species in the remote, relatively ’clean’ areas within the OSPAR region (Barents Sea).
Doses to marine biota at the **Cap de la Hague coastal area** in France, affected by the nuclear reprocessing plant, were somewhat lower than those at Sellafield, with a gradual decrease in the dose rates throughout the assessment period 1982-1997 (see Figure 4).

Estimated dose rates to marine biota due to artificial radionuclides in the vicinity of a nuclear power plant (**Ringhals NPP in Sweden**) were very low during recent years (1997-2000), amounting to a minor addition to natural background.

Regarding non-nuclear industry-impacted zones, the radiation exposure to marine biota in 1991-1999 was estimated in the vicinity of the phosphate plant at **Whitehaven (UK**) where raw minerals with enhanced levels of naturally occurring radioactive material (NORM) were processed until 1992. At the beginning of the assessment period, the estimated radiological impact to marine biota from a big phosphate plant was found to be comparable with that from a large nuclear reprocessing plant at Sellafield. In the recent years the additional dose rates to marine biota at Whitehaven (from NORM) were of the same order of magnitude as the natural background.

The radiation impact on marine biota in the vicinity of **offshore oil installations in the North Sea** is associated mainly with the elevated concentrations of radium isotopes released with produced waters[1] from oil platforms. Presently there exist no monitoring data but model estimations indicate that the radiation exposure of marine biota in the immediate proximity of oil platforms may be enhanced, especially in the local zones with slow water currents. Accurate evaluation of this impact is a task for further investigation.

Dose rates due to man-made radionuclides in the marine areas of the OSPAR region remote from sources of radionuclide discharges (e.g. **Barents Sea**) are negligible compared with the natural background.

Radioecological situation in marine ecosystems of the OSPAR region

Figure 5 shows the estimated dose rates to molluscs from exposure to radionuclides at the selected locations within the OSPAR region.

All estimated dose rates to marine biota within the OSPAR region are below the lower boundary of the zone of deterministic effects on the health and reproduction of marine organisms.

Conclusion

According to the **available information** and the dose assessment for the selected industry-impacted locations in the OSPAR region, there is no identifiable impact on populations of marine biota from radioactive discharges.

The methodology for determining the impact of radioactivity on marine biota is still under development. In the future, the methodology of radiological assessment to natural biota will

[1] Produced water is the description given to the large quantity of contaminated water produced when pumping oil and gas from the wells.

be improved following the development of scientific knowledge on the dose-effect relationships in marine organisms.

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FASSET Project (2001). Framework for Assessment of Environmental Impact. Progress Report 1 (covering the period 1.11.2000 – 31.10.2001). A Project within the EC 5th Framework Programme

IAEA. International Atomic Energy Agency (1992). *Effects of Ionizing Radiation on Plants and Animals at Levels Implied by Current Radiation Protection Standards*. Technical Report Series N. 332, IAEA, Vienna, Austria

NCRP. National Council on Radiation Protection and Measurements (1991). *Effects of Ionizing Radiation on Aquatic Organisms*. NCRP Report N 109, NCRP, Bethesda, Maryland

UNSCEAR. United Nations Scientific Committee on the Effects of Atomic Radiation. (1996). *Effects of Radiation on the Environment,* Annex to *Sources and Effects of Ionising Radiation* (1996 Report to the General Assembly, with one Annex), Scientific Committee on the Effects of Atomic radiation, UN, New York

Figure 1 **Radiation exposure of marine biota in the Sellafield coastal area (Cumbrian waters, UK). Man-made radionuclides**

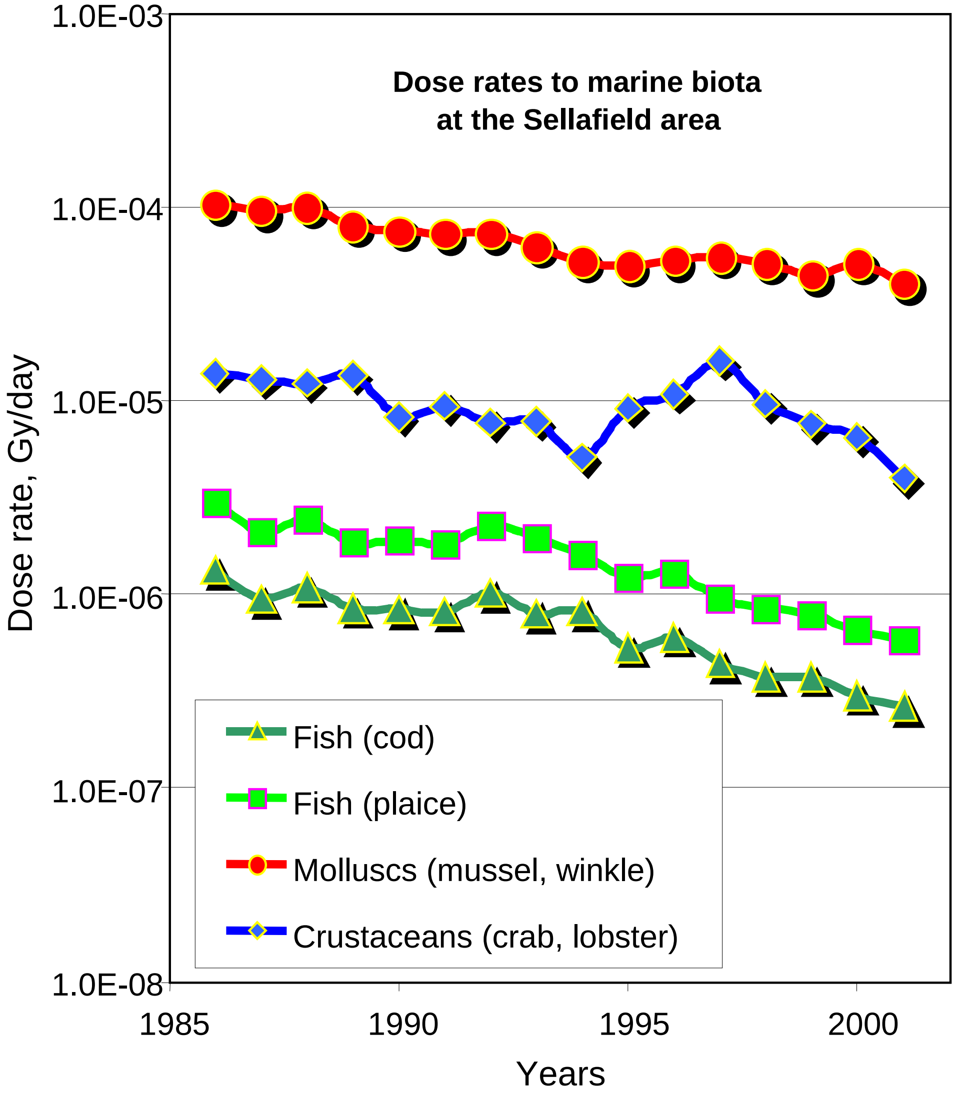
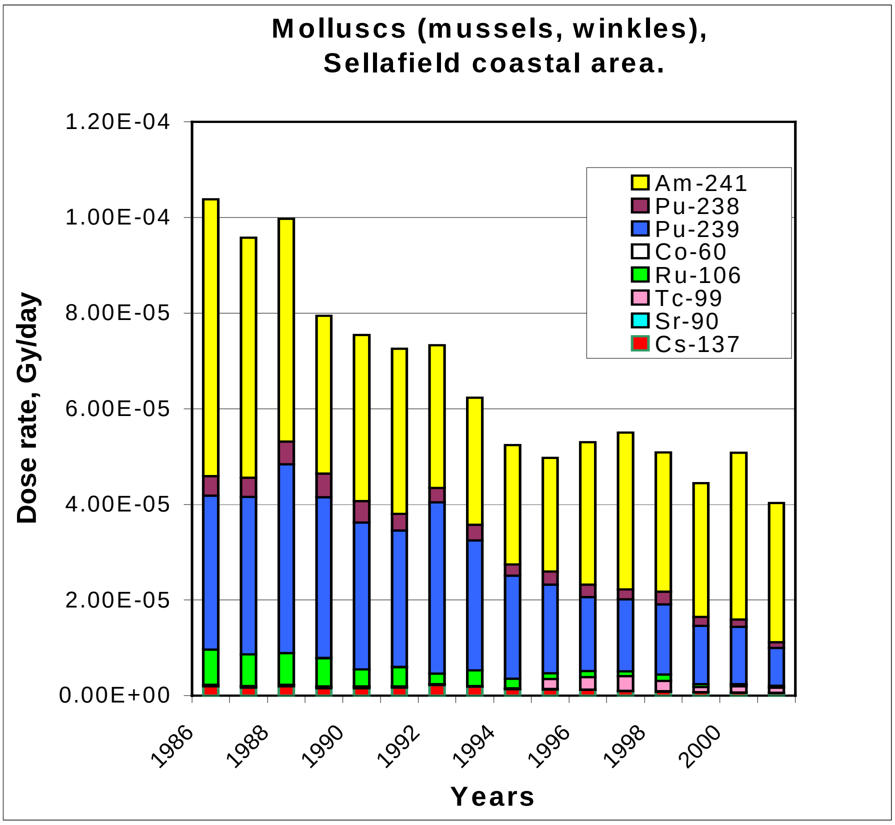


Figure 2 **Sellafield coastal area, UK. Contribution of different radionuclides to the radiation exposure of molluscs in 1986-2001; detailed figure for the year 1999**



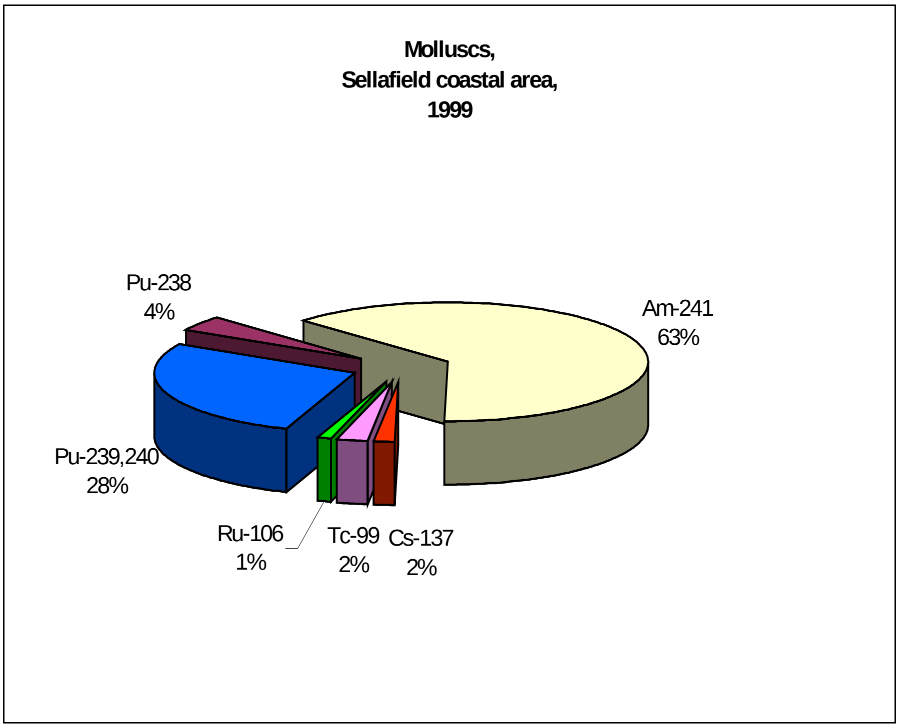


Figure 3 **Sellafield coastal area, UK. Contribution of different radionuclides to the radiation exposure of fish (cod) in 1986-2001; detailed figure for the year 1999**

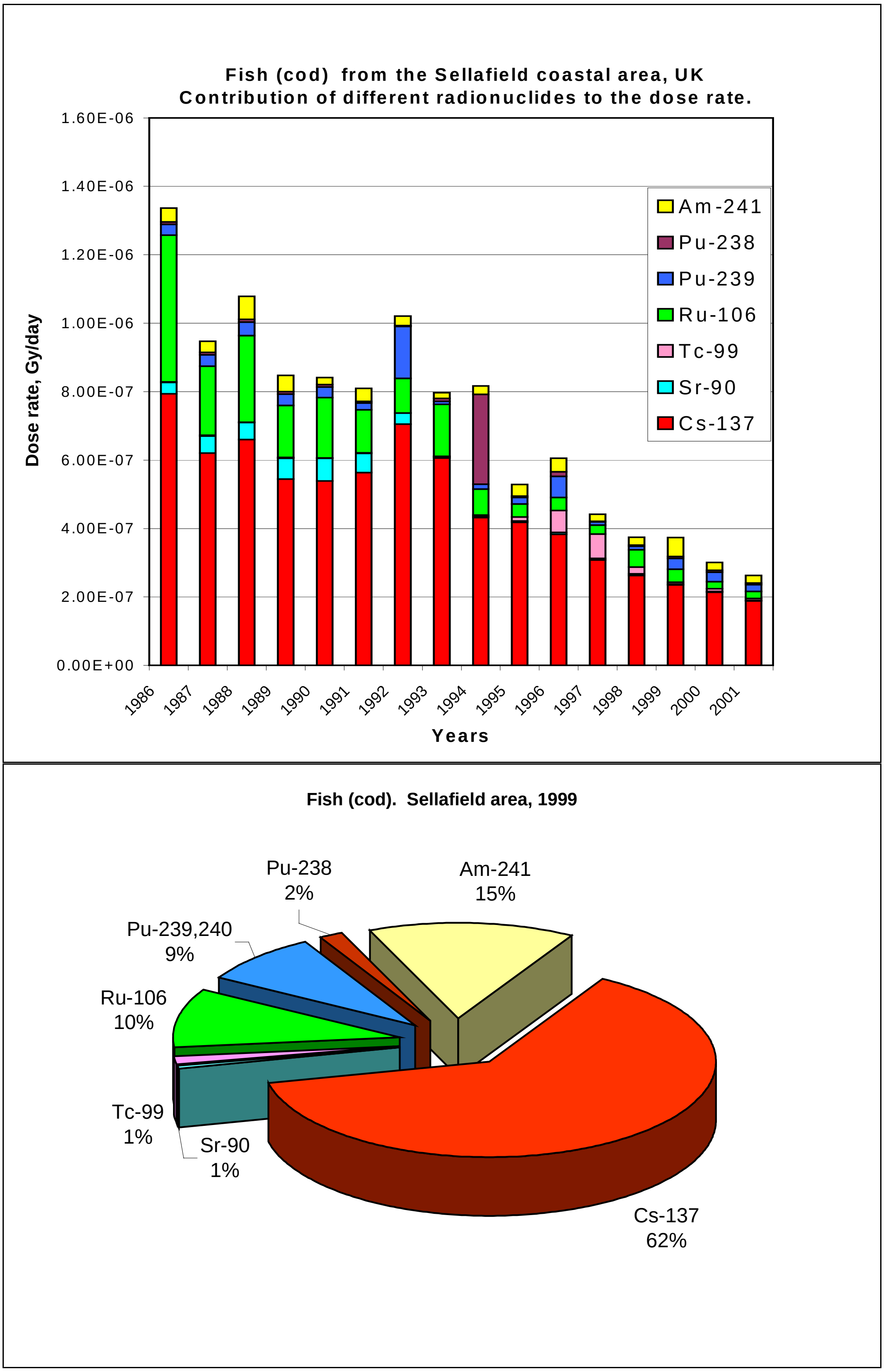


Figure 4 **Radiation exposure of marine biota at the Cap de la Hague coastal area (France) due to man-made radionuclides. *Data on alpha-emitters were available only for Patella molluscs (limpets)**

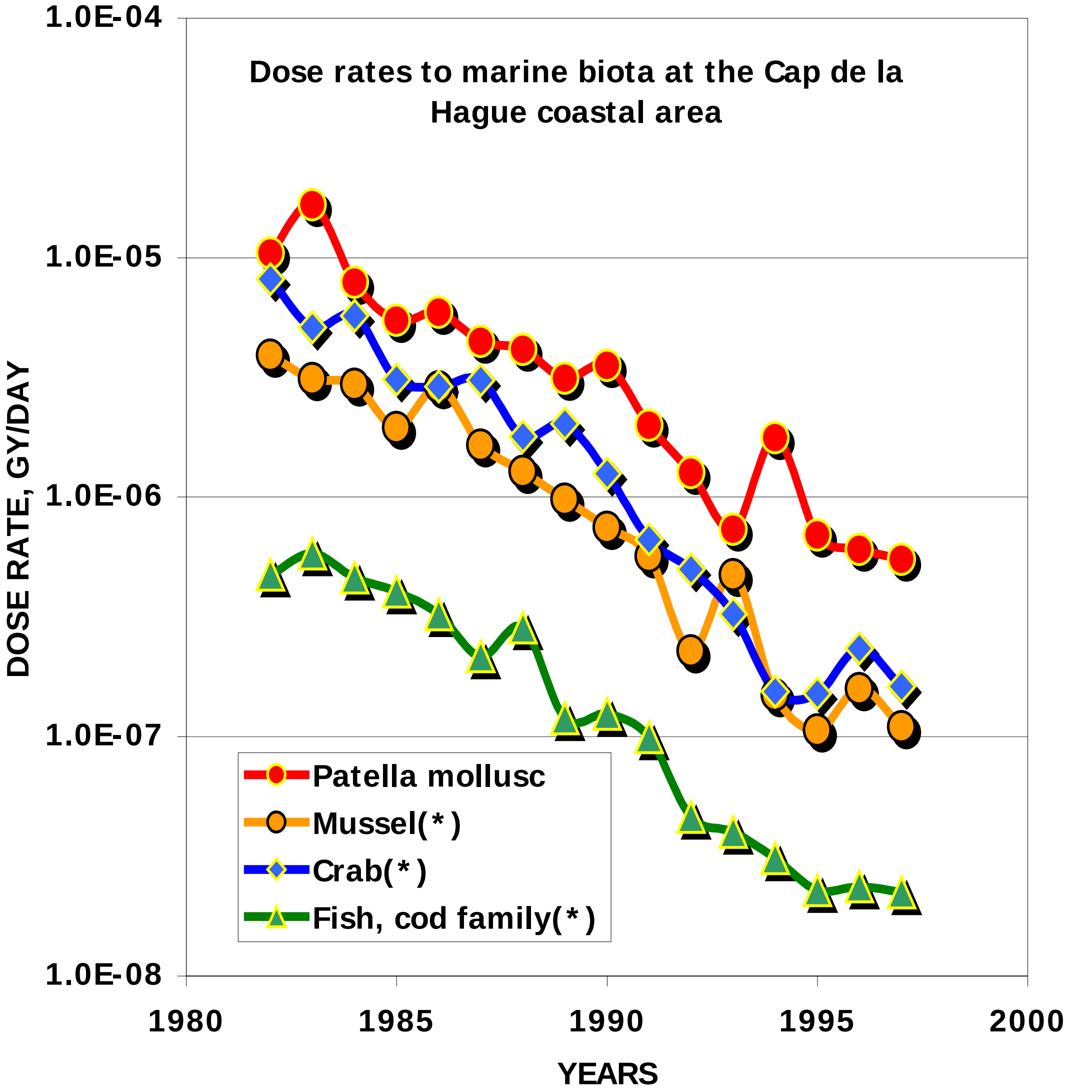
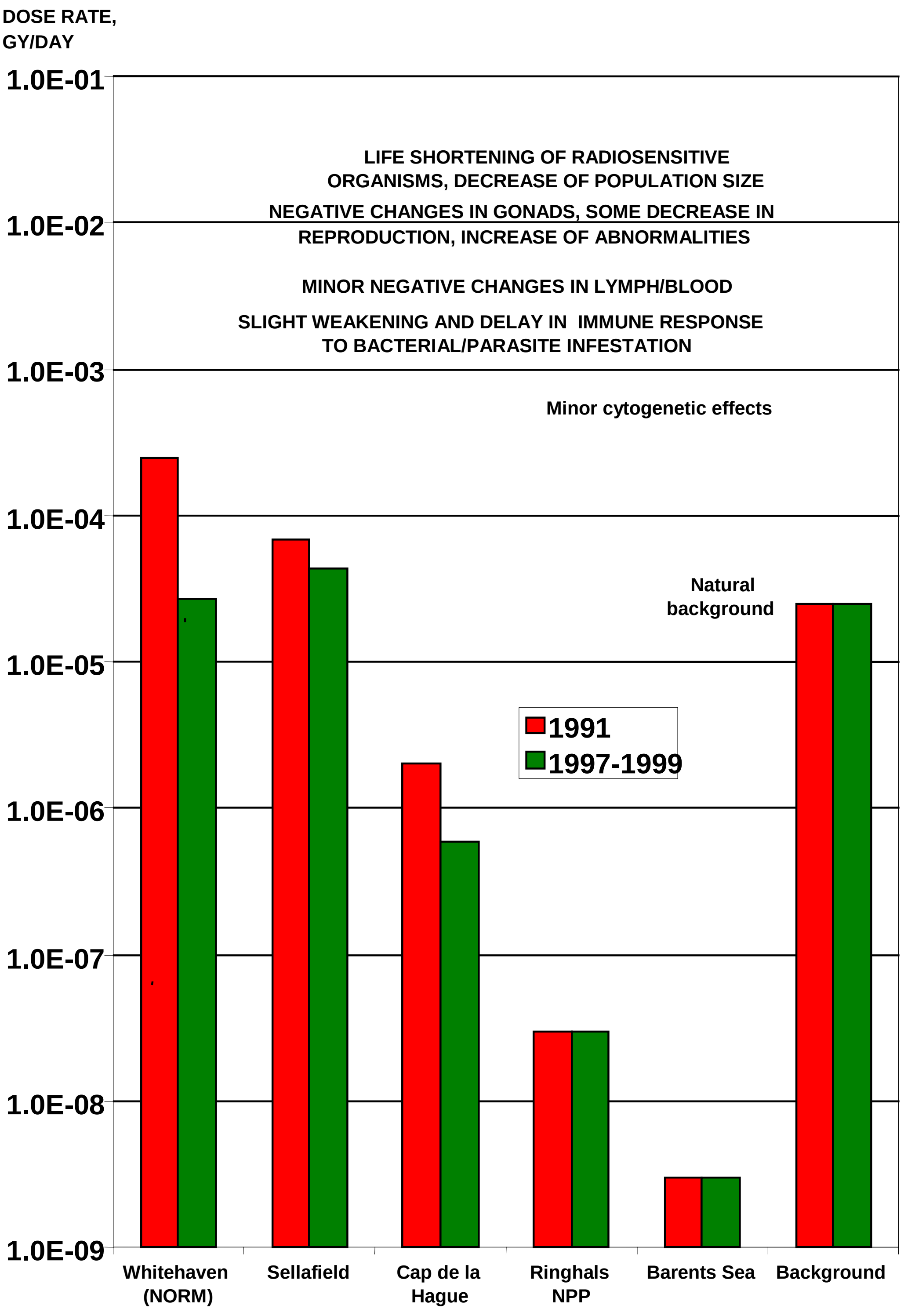


Figure 5 **Radiation exposure of molluscs in the OSPAR region (additional exposure above natural radiation background)**



Note: Presented are annual average values of dose rates to molluscs at different locations of the OSPAR region; values for molluscs near Ringhals NPP are upper estimates of dose rates.

1 Introduction

There is a growing international interest of specialists and the public in establishing a regulatory framework for protection of the environment from the effects of ionising radiation. Until the recently, the international position concerning the radiation protection of biota was based on the ICRP statement that "… if man is adequately protected then other living things are also likely to be sufficiently protected" (ICRP, 1977. 1991). However, *Homo sapiens* represents only one biological species, whereas the biosphere consists of millions of species, differing considerably from man by their size, lifespan, habitat, habits and radiosensitivity. The living conditions for non-human organisms in the natural ecosystems are not comparable with the conditions of human life, and the radiation doses to non-human organisms may be orders of magnitude different from the exposure of humans.

The Rio Declaration on Environment and Development (UNCED, 1992a) and the Convention on Biological Diversity (UNCED, 1992b) provided an internationally agreed concept of "sustainable development", including requests for environmental protection, the conservation of biodiversity, and the maintenance of ecosystems and the ecological processes essential for the healthy functioning of the biosphere. For industries, which may release hazardous wastes to the environment, an environmental impact assessment for both humans and the environment is an established practice (EIA Directive 85/337/EEC amended by 97/11/EC). There is a growing consensus that from ethical, legal and scientific perspectives, specific radiation protection standards are needed for the environment *per se*, with a focus on the ecological consequences from detrimental effects of ionising radiation.

The problems of the radiation exposure of marine biota in northern European waters, and the possible consequent biological impacts, were not addressed in the report of the original MARINA project (MARINA I, 1990). The subject did arise, however, at the associated seminar held in Bruges, Belgium in June 1989, and a short paper, outlining the, then, state-of-the-art in the approach to dose assessment for aquatic organisms, was included in the seminar proceedings (Woodhead & Pentreath, 1989).

The new MARINA Update project, besides dealing with the assessment of radiation exposure to the human population, established a subgroup (subgroup D[*]) with the specific task of assessing the dose rates to, and estimating the possible radiobiological effects on, representative non-human organisms, inhabiting the marine waters of the North-East Atlantic within the OSPAR area. The present report summarizes the methodology and results of this radiological assessment.

2 Approaches for protecting flora and fauna from ionising radiation

At present, the European Union regulations (Directive 96/29/EURATOM Basic Safety Standards) regarding the protection of the environment from ionising radiation are based on the ICRP approach (ICRP, 1977, 1990) and Basic Safety Standards (IAEA, 1996) with exclusive consideration of protection of humans from exposure. The environment is mainly considered as a pathway for radionuclide transfer to man. No internationally agreed criteria, or guidance, exist for assessing the impact of environmental radiation on flora and fauna.

In recent years, considerable international efforts have been undertaken to develop scientifically correct and practically acceptable methodologies for assessing the possible impact on the environment from the effects of increased exposure to ionising radiation, and, thus, to provide a basis for the protection of the non-human biotic environment.

Several relevant international documents have been prepared: OSPAR Strategy with regard to Radioactive substances (1998); UNSCEAR Report (1996), IAEA TECDOC 1091 (1999), and others. Preliminary ideas and views on the problem have been discussed in recent publications (Larsson et al., 1996; Pentreath, 1998, 1999; Pentreath and Woodhead, 2000; Howard, 2000; Strand et al., 2000; Kryshev, Sazykina, 1998; Sazykina, Kryshev, 1999a,b); publications and reports of the EULEP/EURADOS/UIR Joint Concerted Action (1997-1999). Two special International Congresses have been organized in Stockholm (1996) and Ottawa (1999). In addition, the IAEA has organized several specialists' meetings to discuss the principles of the protection of the environment from the effects of ionising radiation (IAEA, working materials, 1997-2001).

Two innovative EC projects commenced in 2000: FASSET (Framework for Assessment of Environmental Impact) and EPIC (Environmental Protection from Ionising Contaminants in the Arctic), which are directed towards the development of appropriate methodologies to provide for environmental protection from radiation; the project activities include the preparation of databases on dose-effect relationships, the selection of reference biota, and the development of dose assessment models, as well as the application of the methodologies to the extreme Arctic environment.

In 2000, the ICRP organized a special Task Group with the aim to develop a policy and suggest a framework for the environmental protection from radiation hazards based on scientific and ethical principles. The new policy, and the conceptual framework, should feed into the ICRP's next set of recommendations. The Task Group will report their findings in 2003.

The U.S. Department of Energy (DOE) has been active in developing frameworks and guidance for demonstrating protection of the environment from the effects of ionising radiation. DOE currently has in place an interim standard approach for the protection of aquatic organisms (U.S. DOE, 2000), and has considered dose rate standards for both aquatic and terrestrial biota. The DOE technical standard assumes upper limits for the protection of plants and animals at the following absorbed dose rates: for aquatic animals, 1 rad day^{-1} (10 mGy day^{-1}); for terrestrial plants, 1 rad day^{-1} (10 mGy day^{-1}); and for terrestrial animals, 0.1 rad day^{-1} (1 mGy day^{-1}). The approach used in the U.S. technical standard applies these dose limits to representative, rather than maximally exposed, individuals in given populations of plants and animals.

2.1 Existing scientific recommendations for protecting the aquatic wildlife from the effects of ionising radiation

During normal operating conditions, in both the nuclear industry and other industries dealing with natural radionuclides, the radioactive waste management activities (inclusive of authorised releases directly to the environment) are associated with a consequent 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). Even in the areas contaminated by radiation accidents, high dose rates leading to the lethal exposure of the flora and fauna have only been observed within a short period immediately after the release of the radionuclides.

There have been many reviews of the available radiobiological literature from the viewpoint of its utility for providing a basis for assessing the possible impacts of chronic, low-level irradiation arising from radionuclide contamination of the environment (see, e.g., Polikarpov, 1966; Turner, 1975; IAEA, 1976; 1988; 1992; Blaylock & Trabalka, 1978; Woodhead, 1984; Anderson & Harrison, 1986; NCRP, 1991; Rose, 1992; UNSCEAR, 1996). In most cases, the declared intention was to concentrate on the data generated by studies at chronic, low dose rates, but this relevant material was found to be rather limited. Inevitably, therefore, the reviews included some data obtained from experiments to determine the acute effects of short-term exposures at high dose rates (and usually, therefore, high doses); while not directly relevant to the majority of environmental concerns, these data were used as a basis for informed extrapolations.

The later and the most comprehensive reviews on the effects of ionising radiation on non-human organisms provided the following general conclusions on the range of chronic dose rates which provide adequate protection for populations of aquatic organisms:

NCRP report (1991):

"It appears that a chronic dose rate of no greater than 10 mGy day^{-1} (1 rad day^{-1}) to the maximally exposed individual in a population of aquatic organisms would ensure protection for the population. If modeling and/or dosimetric measurements indicate a level of 2.5 mGy day^{-1}, then a more detailed evaluation of the potential ecological consequences to the endemic population should be conducted" (page 62, conclusions).

IAEA report (1992):

"*In the aquatic environment it would appear that limiting chronic dose rates to 10 mGy day^{-1} or less to the maximally exposed individuals in a population would provide adequate protection for the population"* (page 53, summary);

UNSCEAR report (1996, para 176):

"Overall consideration of the data available for the effects of chronic irradiation on aquatic organisms has led to the conclusion that dose rates up to 10 mGy day^{-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".

"For the most sensitive animal species, mammals, there is little indication that dose rates of 10 mGy day $^{-1}$ 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 day $^{-1}$),

the same statement could be made with respect to reproductive effects" (conclusions, p.59).
In the terrestrial environment the harmful effects to animals are not expected at dose rates below 1 mGy day^{-1}.

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.

The above-cited conclusions of the NCRP, IAEA and UNSCEAR make it possible to evaluate a range of chronic dose rates, which are of practical interest in the radiological assessment of marine organisms:

- Dose rates in the range 1-10 mGy day^{-1} are considered as the levels at which minor radiation effects on the morbidity, fertility and fecundity of individual aquatic animals begin to become apparent first in laboratory studies, and, at higher exposure, in natural populations;

- At average dose rates above 2.5 mGy day^{-1} to aquatic organisms NCRP recommended to consider a more detailed evaluation for the most vulnerable populations;

- Average dose rates higher than 10 mGy day^{-1} are assumed to be harmful to populations of aquatic organisms.

In this report the recommendations of the NCRP (1991), IAEA (1992) and UNSCEAR (1996) reports are used for the evaluation of the possibility of detrimental effects of radiation on populations of marine organisms within the OSPAR area.

It should be noted, however, that the currently available information concerning the effects of chronic exposure on aquatic wildlife is very limited; for instance, there is no data on marine mammals, which probably are the most radiosensitive animals in marine ecosystems. The marine mammals can be considered in the same way as the great majority of terrestrial mammals, i.e. by informed extrapolation from the available data on effects in mammals.

Polikarpov (1977, 1998, 2001) has generalized the available information into a conceptual scheme of the effects of chronic exposures to ionising radiation, based on changes in the most radiosensitive organisms, populations and ecosystems. The scheme includes the following categories:

(a) the 'Uncertainty' zone (below the lowest natural ionising radiation background level);
(b) the 'Radiation well-being zone' (natural ionising radiation background range);
(c) the 'Physiological masking zone' (0.005–0.1 Gy y^{-1}); in this zone minor cytogenetic, physiological and morbid effects can be observed; however the scale of effects does not significantly exceed the natural range of variability in physiological functions of organisms;

(d) the ‘Ecological masking zone’ (0.1-0.4 Gy y^{-1}); in this zone a variety of radiation effects can be registered on the organism's level; significant masking of these effects in ecosystems occurs due to natural selection, variability of ecological conditions etc.;

(e) the ‘Zone of damage to communities/ecosystems’ (>>0.4 Gy y^{-1}); in this zone obvious radiation effects are registered, including increased mortality of organisms, elimination of some species, impoverishment of ecosystems;

(f) the ‘Radiation threshold for lethality of the biosphere’ (>>MGy y^{-1}).

The scheme, as proposed by Polikarpov, provides a general view on the range of bio-ecological effects of radiation; it allows any estimate of the incremental dose rate from contamination in the environment to be placed into context so that an approximate indication of its significance may be obtained.

Estimates of the dose rates to aquatic biota in the most contaminated sites of the world (areas of Kyshtym and Chernobyl radiation accidents; areas of historical releases of radionuclides) demonstrate that dose rates about 10 mGy day^{-1} were characteristic for the exposure of biota in these highly contaminated water bodies (Blaylock, Trabalka, 1978; Sokolov et al., 1994; UNSCEAR, 1996; Kryshev et al., 1998; Kryshev & Sazykina, 1995, 1998).

2.2 RBE and radiation weighting factors

The magnitude of harmful effects, caused by ionising radiation depends not only on absorbed dose, but also on the type of ionising particles, produced by the decay of a radionuclide. The α-, β-, and γ-radiation differ from each other by penetrating capacity, particle size, energy, and by their ability to produce ions in biological tissues. The alpha particles are known to have the highest ionising effect in biological tissues per unit of absorbed dose.

To account for the different quality of radiation the concept of relative biological effectiveness is employed. The relative biological effectiveness (RBE) is defined as the ratio of dose required to achieve a specific biological effect from a standard radiation (typically gamma rays) to that required for the same end point from different types of radiation. The value of the RBE is thus expressed as a ratio of two different radiation doses required to producing the same effect.

$$RBE = D_l/D_h;$$

where *D* is the adsorbed dose in tissue to produce a specific effect and *l* and *h* refer to the low-LET standard and the test high-LET radiation. This interpretation tacitly assumes that the energy distribution throughout the irradiated system is uniform, and has no consequence on the measurement of effects.

The values of RBE can be experimentally estimated for different types of radiation. It is practically impossible to obtain experimental values of RBE for a great number of possible endpoints and every type of organisms. Instead, a simple set of radiation weighting factors is employed. The radiation weighting factors (w_r) are defined as multipliers of absorbed dose used to account for the relative effectiveness of different types of radiation in inducing health effects (ICRP, 1991; IAEA, 1996). The value of

w_r for a given type of radiation is derived from available values of RBE. The equivalent dose is calculated by multiplying the absorbed dose by the radiation weighting factor.

A special problem in radiobiology of non-human organisms is the establishment of appropriate radiation weighting factors between equal absorbed doses of α-, β,- and γ-radiation. Up to now, there are no officially established values for the radiation weighting factors for organisms other than man.

UNSCEAR (1996) has proposed that a radiation weighting factor (w_r) of 5 for alpha particles is, perhaps, appropriate for non-human biota, based on the approach that deterministic effects are of greater importance for wildlife than stochastic effects. Based on experimental data, Kocher and Trabalka (2000) suggested that the weighting factors for deterministic effects of alpha radiation are within the range from 5 to 10. A weighting factor of 20 for alpha particles is suggested in a number of publications (e.g., Woodhead, 1984; Blaylock et al., 1993; Environment Agency, 2001).

Regarding beta radiation, a radiation weighting factor of 3 has been proposed for tritium (Environment Canada, 2000; Environment Agency, 2001); UNSCEAR (1996) has made a general recommendation to use a radiation weighting factor of 1 for all beta emitters.

Efforts are being undertaken within current EC Projects (FASSET and EPIC) to evaluate experimentally derived RBE values for various relevant endpoints and dose rates for biota in order to develop radiation weighting factors appropriate for environmental protection.

As a very conservative default for the purpose of this assessment, it seems reasonable to apply a radiation weighting factor of 20 to the absorbed dose from α-particles and a factor of 1 for beta- and gamma- radiation, and to quantify the biologically equivalent dose in the unit of Gy, weighted by w_r.

3 Endpoints of concern in radiation protection of wildlife

There are some significant differences between the radiation protection of man on one hand, and the biotic environment on the other, in relation to the definition of the biological endpoints of concern. Besides taking into account deterministic effects for humans the concern is on the potential impairment of health in any individual resulting from inherited or somatically acquired mutations.

Human ethics requires, that each individual person should be protected, and the dose limit established for the general public (1 mSv $year^{-1}$) is assumed to provide an acceptable degree of protection for individual members of the human population.

Within the biosphere, populations of individual wild organisms (more or less self-sustaining sub-sets of individual species) become grouped together as interacting communities that, together with the inanimate physical and chemical components of the environment, constitute ecosystems. Natural ecosystems are complex organizations, in which (usually) many individual plant and animal species combine to accumulate solar energy and facilitate the circulation of the essential chemical elements that are required for the continued existence of themselves and their ecosystem. The maintenance of the integrity of ecosystems, in turn, depends on the survival and reproduction of healthy component populations.

The natural law is not focused on the survival of an individual wild organism, i.e., the survival of biological species, communities and ecosystems is generally not dependent on the survival of single plants or animals. It may be concluded, therefore, that protection of the environment means the protection of the normal overall functioning of populations, communities and natural ecosystems, even if a few individual organisms are damaged by radiation.

The damage produced by radiation in wild plants and animals can be registered, in principle, at each of the increasingly complex levels of the biological hierarchy: atoms, molecules, cells, tissues/organs, organisms, populations, ecosystems, and the biosphere. This immediately raises the question: what level of biological hierarchy is to be selected as the most appropriate, or representative, for the purpose of assessing harm to the natural environment from the effects of ionising radiation?

Initially, all of the known effects of radiation occur at the atomic level within molecules. The numerous molecular effects of ionisation are accumulated and possibly amplified by biochemical pathways and may lead to the damage of genetic information, cells, tissues/organs, and abnormalities in metabolism; these effects may then express themselves at the level of individual organism. If the radiation damage results in a decrease in the survival potential of organisms (life shortening, a reduction of the reproductive success, a reduction of competitive activity, etc.), this could in turn influence the maintenance of the exposed population as a whole. The scale of population effects is strongly dependent on the number of damaged individuals in the population. Effects at the population level can, in turn, be transformed to effects at the community and ecosystem level via disturbances in the evolutionary balance in the trophic relations between species.

Because it is impossible to consider every radiation effect in all of the extant species of plant and animal, some broad (umbrella) endpoints have to be selected; indeed, not all of the available radiobiological information is relevant to the evaluation of the possible environmental consequences of any incremental radiation exposure arising from human activities.

The initial effects of radiation, as observed at the molecular level, are generally of little use for decision makers because it is difficult to interpret them in terms of their consequent effects at the organism level. However, the mechanistic information on radiation effects at the molecular and cellular level is important and, in addition to the epidemiological studies, can facilitate the interpretation of effects occurring at the organism level.

On the other hand, a quantitative evaluation of dose-effect relationships at the population, community and ecosystem levels is also a difficult task because there exist strong (presently unquantified) and complex non-linear interactions between the

biological components, as well as special compensatory mechanisms for maintaining the integrity of the system.
From the practical point of view, the most applicable information for which dose-effect relationships could be derived is that which relates to the level of individual organism. The term “individual organism” here refers to a typical “reference” organism of a given type/species, whose response to radiation exposure is to be assessed.

A radiobiological endpoint has been defined as a consequence of the absorption of radiation that has relevance for the health of the individual organism and that may, therefore, have implications for the population (FASSET, 2001).

The biological endpoints are to be measurable at an organism level. The endpoints of special importance are those referring to key characteristics of the survival capacity of the population, i.e., mortality and reproduction.

According to the suggestions of the FASSET Project (FASSET, 2001), four umbrella endpoints are assumed to be inclusive of all relevant effects at the level of individual organisms:

- Morbidity (a decline in well-being due to a worsening of the physiological characteristics of the organism, e.g., effects on the immune system, blood system, nervous system, etc.);

- Reproduction (negative changes in fertility and fecundity resulting in reduced reproductive success, i.e. reduced production of reproductively competent individuals in the following generations);

- Cytogenetic effects (cytological and genetic changes in tissues (including the gonads of the organisms); and,

- Mortality (shortening of lifetime because of combined effects on different organs and tissues of the organism).

It should be understood, that these defined categories of umbrella endpoints are mutually dependent, e.g. effects on morbidity can lead to worsening of reproduction success, to early death, etc.

4 The procedure for assessing the radiological impact on marine biota

The procedure for radioecological assessment for biota includes the following steps:

- Selection of region-representative organisms for a given geographical area;

- Estimation of dosimetric factors (normalized dose rates) for representative organisms resulting from a unit contaminaton of organisms, and also from a unit contamination of environment (seawater and sediments);

- Assessment of actual/potential doses to representative organisms of a given geographic area, based on actual/predicted data of environmental contamination with radionuclides;
- Comparison of actual/potential dose rates to representative organisms with existing data on harmful effects of radiation, using such endpoints as morbidity, mortality, reproduction and cytogenetic effects;

- Conclusions on the radioecological state of biota in a given geographical area.

5 Selection of region-specific organisms for radioecological assessment (North-European waters)

It is practically impossible to perform radioecological assessment for every species from the thousands of species inhabiting the waters of the North-East Atlantic. This problem can be solved by selecting a limited set of region-specific organisms, which are to be used as representative marine organisms in radioecological assessment.

This section presents the criteria for, and a preliminary selection of, the region-specific organisms for the OSPAR marine region.

5.1 Criteria for selecting region-specific organisms in a given geographical area

The selection of region-specific organisms in a given geographical area for the radioecological assessment is based on the following basic criteria (EPIC, 2001b):

- Ecological (position in ecosystem);
- Availability for monitoring;
- Dosimetric (critical pathways of exposure);
- Radiobiological (sensitivity to radiation) and,
- Recovery potential of populations.

5.1.1 Ecological criteria

The ecological criteria allow the selection of the region-specific organisms among the dominant species at each trophic level of the ecosystem.

The ecological criteria are based on the statement that the appropriate reference organisms for assessment are the dominant representatives of basic trophic levels of the marine ecosystem. These species carry out the major energy/material flows in the ecosystem, and the well-being of dominant species is vitally important for the well-being of the whole ecosystem (Begon et al., 1986). As a rule, one reference organism per trophic level may be selected.

5.1.2 Monitoring criteria

The monitoring criteria allow the selection of the region-specific organisms among the wide spread species available for radionuclide analysis.

Radioecological assessment is closely linked with the monitoring of the region-specific organisms, including measurements of radionuclide concentrations in the organisms.

Taking into account the monitoring purposes, it is practical to select the region-specific organisms (within each trophic level) from the following groups of species:

- Typical, numerous and wide spread species in the investigated area;
- Species which can be easily collected (microscopic-size organisms are not suitable);
- Species which can be easily identified; and,
- Species of commercial importance which are monitored because of importance to man.

The dominant representatives of basic food chains selected from ecological criteria, satisfy most monitoring conditions. Also organisms, which are known to be natural accumulators of radionuclides, are the most suitable for radioecological assessment because they demonstrate the highest levels of biological transfer of radionuclides and would, therefore, be likely to receive the highest dose rates from internal sources.

The only exceptions are phytoplankton and bacteria, which are too small to be properly collected for radionuclide analysis. Endangered or rare species are also not suitable for the screening assessment, because they are not available for routine radionuclide analysis.

5.1.3 Dosimetric criteria

The dosimetric criteria provide a set of characteristic types of region-specific organisms, based on critical pathways of radiation exposure.

Radiation exposure of biota in the contaminated marine environment is associated with the following major pathways:

- internal exposure from radionuclides incorporated within organisms;
- external exposure from water, bottom sediments, and biofoulings;
- external exposure from radionuclides adsorbed on the organism’s surfaces.

It is proposed to define a “critical group” of organisms for each possible pathway of exposure. Representatives from each “critical group” may be selected as the region-specific organisms. The following critical groups of organisms can be distinguished in the aquatic ecosystem:

- bottom-dwelling organisms (critical pathway - external exposure);
- organisms, accumulating specific radionuclides (critical pathway - internal exposure).

In the dosimetric calculations it is essential to estimate the contribution of α-, β-, and γ-emitters to the dose to the whole organism, as well as to the dose to its organs and tissues. Taking into account the differences in penetration capacity for α-, β- and γ-

radiation, the dosimetric calculations are to be performed for region-specific organisms of different size groups. The set of region-specific organisms should include both relatively small organisms (critical group for α- and β-emitters), whose organs may be comparable in size to the path lengths of α- and β-particles, as well as relatively large organisms (critical group for γ-emitters), which can absorb higher γ-radiation doses.

5.1.4 Biological radiosensitivity criterion

The biological radiosensitivity criterion allows the selection of the region-specific organisms among the sensitive species in the ecosystem and excludes from consideration the most radioresistant organisms.

The biological species forming the ecosystem vary considerably in respect to their sensitivity to ionising radiation. It is well known that many lower organisms are rather resistant to radiation. For example, bacteria, planktonic algae, bottom invertebrates are several orders of magnitude less sensitive to radiation exposure as compared with fish or mammals (IAEA, 1976, 1979; NCRP,1991; UNSCEAR, 1996).

It is inexpedient to select the organisms for radioecological assessment among very radioresistant species, because they certainly will not be damaged at the radiation levels, which may be expected in the marine environment from authorized releases. For the purposes of radioecological assessment the region-specific organisms should be chosen among relatively radiosensitive groups of organisms in an ecosystem.

5.1.5 Criterion of the recovery potential of populations

Biological species differ considerably in their capacity to recover at the population level when some individual organisms are damaged. In general, the recovery capacity depends on the number of progeny produced by individual organisms per unit of time, and also on the period of development of the organisms (time to reproductive maturity).

It is not sensible to perform a detailed radiological assessment for species with very high recovery potential. This is because, if such organisms were to be damaged by radiation, the losses would be rapidly recovered by the reproduction of remaining organisms. Instead, the species with relatively low recovery potential are good candidates for the region-specific organisms in radioecological assessment. So, the low recovery potential can be used as a criterion for revealing the most vulnerable species of biota in a given geographical area.

If a biological species satisfies all, or most, of the above criteria, such a species could be considered as a candidate for the list of region-specific organisms in a given geographical area.

For the purposes of radioecological assessment it is proposed to exclude some groups of marine organisms from the list of region-specific organisms. These are:

- Bacteria;
- Phytoplankton;

- Small zooplankton.

It is assumed, that the above listed groups of organisms are not suitable for the specific purposes of the radioecological assessment because of: a) difficulties in sampling very small organisms of one species for the radionuclide analyses; b) relatively high resistance to radiation when compared with other species (UNSCEAR, 1996); c) small sizes and short individual lifetimes, which prevent organisms from receiving high doses of radiation; and, d) high biological productivity, which means rapid recovery of populations. Thus, these groups of organisms are unlikely to be damaged at existing/expected levels of radioactive contamination of the OSPAR region. It should be stressed, however, that the above listed groups of organisms play a great role in the functioning of marine ecosystems, and their damage by any toxicant can have serious implications for the whole ecosystem.

The potential candidates for the region-specific organisms can be selected from the following broad categories of marine biota:

- Fish;
- Molluscs;
- Large crustaceans;
- Soft benthos;
- Seabirds;
- Marine mammals;
- Macrophytes.

In the present report, macrophytes are not considered: aquatic plants are known to be more radioresistant than animals, and dose assessment for plants is reasonable only in case of accidental contamination. Soft benthos is not considered in the present report because of non-sufficient data on benthos contamination, and lack of detailed information on radionuclides distribution within bottom sediments.

5.2 Region-specific marine organisms in the OSPAR region

Among thousands of biological species inhabiting the marine waters of the North-East Atlantic, only a few species, listed below, were selected as region-specific representative organisms for radiological assessment.

The selected species satisfy all/most of the selection criteria, they form large populations, and their natural areas of geographical distribution cover the whole or the greater part of the OSPAR region.

The contamination of the selected species is studied within radioecological monitoring/research programmes, so databases on the concentrations of radionuclides are available for most of the selected organisms.

In the radiological assessment, the use of region-specific organisms throughout the whole OSPAR region provides an advantageous possibility to compare on a unified basis the doses/effects to biota in different local sites of the North-East Atlantic region.

5.2.1 Region-specific fish in the OSPAR marine region

In the present study (MARINA II Update) it is proposed to consider a set of region-specific fish species, representing the most typical commercial fish in the OSPAR region. Region-specific fish species are divided into several groups according to their trophic/size/habitat type, see Table 1.

A few typical representatives in each trophic/size/habitat group are listed in the column 'Representative species' (Table 1); one species of each type is a recommended representative organism for dose assessments, see column 'Recommended organism'.

Size/weight characteristics of the region-specific fish given in Table 1 refer to a typical adult specimen of the recommended organism. It should be noted, however, that in the absence of the recommended organism in any local place within the OSPAR region, the assessment can be made for other representative species of the same trophic/size/habitat type.

The proposed list of fish covers almost all typical geometrical forms of fish inhabiting the OSPAR marine region. The proposed forms allow the calculation of dosimetric factors (dose rates per unit concentration of radionuclide) applicable to any specific radiological assessment of fish exposure in the OSPAR region. They also, incidentally and quite usefully, show the influence of fish size on the dose rate received from internal sources and the influence of the external sources, particularly the sediments.

For the assessment of external radiation exposure additional information is needed on the environmental behaviour of fish. The default values of percentage of time, which fish spend near the sea bottom or in the water column are presented in Table 2.

5.2.2 Region-specific molluscs in the OSPAR region

Molluscs are important representatives of the marine biota in dose assessment due to the fact that they:

- accumulate many radionuclides with high concentration factors;
- have close contact with bottom sediments where a number of radionuclides are accumulated and provide a source of external exposure; and,
- have natural shielding covers, which in some cases provide protection from external exposure, but in other cases the shells themselves may become an additional source of radiation exposure to organisms due to high accumulation of radionuclides.

Two types of commercially important molluscs are typical for the OSPAR region: Bivalve molluscs and Gastropod molluscs.

The characteristics of the region-specific molluscs are given in Table 3.

5.2.3 Region-specific crustaceans in the OSPAR region

Large crustaceans are a commercially important group of marine biota in the OSPAR region.

Two main types of crustaceans can be considered as region-specific organisms – crabs and pelagic shrimps. These organisms are exposed to radiation from different pathways, thus providing a range of possible dose rates from each pathway of exposure.

Table 4 presents the main size/weight characteristics of the region-specific large crustaceans.

5.2.4 Region-specific marine mammals and seabirds in the OSPAR region

Marine mammals and seabirds belong to the radiosensitive types of biota in the marine environment.

The common seal (*Phoca vitulina*) is recommended as the region-specific sea mammal in the OSPAR region, with a typical ellipsoidal size of 150 x 40 x 40 cm, and a weight of 120 kg.

A seabird of the *Larus* genus (common gull) is recommended as the region-specific seabird, with a typical ellipsoidal body size of 15 x 11 x 8 cm, overall dimensions (including feather) 21 x 16 x 11 cm, average density of body tissues 0.8 g cm^{-3}, density of feather layer 0.33 g cm^{-3}, and weight 0.6 kg (Woodhead, 1986).

5.3 Ecological links of region-specific organisms with other species in the marine ecosystems of the OSPAR region

Biological species in the marine ecosystems represent an evolutionary selected set of inter-linked organisms.

Populations of different species form trophic chains, where organisms of higher trophic levels feed on organisms of lower trophic levels. In general, the dose assessment for biota does not require a detailed knowledge of the trophic position of reference organisms.

However, in the assessment of radiation effects in biota, it is necessary to consider the possibility of indirect effects of radiation associated with a distortion of the ecological balance (or trophic links) between species in the ecosystem. Simple examples of indirect effects of radiation are as follows: a) a ‘prey’ population is more seriously damaged by radiation than a ‘predator’ population, the number of prey organisms decreases, and, as a consequence, the number of predators also decreases because of lack of food; b) a ‘predator’ population is more seriously damaged by radiation than the ‘prey’ population, the number of predators decreases, and as a consequence, the population of prey rapidly increases in number, this results in the depression of other prey species competing for the same food and space resources.

6 Methods for dose assessment to region-specific marine biota

The assessment of dose rates to marine biota (both pelagic and benthic) is an important, and necessary, tool in the evaluation of the impact of radionuclides released into the environment.

In the marine environment, dose rates to biota originate from external irradiation due to the presence of radionuclides in the water column and bottom sediments, and from internal irradiation owing to the uptake and assimilation of radionuclides by the biota.

6.1 The ‘state-of-the-art’ in the dose assessment to aquatic organisms

Initially, the development of dose assessment methods for marine biota was closely linked with the management of deep sea disposals of radioactive wastes, estimation of the potential damage from the underwater nuclear tests, and evaluation of damage to biota associated with historical releases from nuclear fuel reprocessing plants into the marine environment.

These considerations drove the dosimetric approach in the direction of a generic assessment using reference organisms that: showed a range of size forms; showed a range of radiosensitivities (on the basis of the available information); showed a range of bio-accumulation capacities; and, occupied different environmental niches.

The reference organisms, although they might bear a resemblance, were not meant to represent particular, identifiable species. It was assumed that this approach would provide a reasonable assessment of the general range of dose rates that would be experienced in a contaminated environment. In order to simplify the dosimetric calculations, the target geometries were reduced to spheres, or ellipsoids with differing ratios between the axes. The characteristics of the reference organisms, used in previous assessments, are set out in Table 5, and the basis for their selection is given in more detail in (Pentreath & Woodhead, 1988).

With the assumptions of uniform radionuclide distribution in the bodies of the organisms at levels defined by equilibrium concentration factors (CF), and uniform distributions of radionuclides in the sediments at levels defined by equilibrium distribution coefficients (k_d), these models were used to estimate the dose rate factors per unit concentration in water (Bq m^{-3}) for a wide range of radionuclides that might be present in radioactive wastes (Pentreath & Woodhead, 1988). These dose rate factors were not, however, applied to the estimation of the dose rates that might have existed in the marine waters of northern Europe at the time of the original MARINA I assessment (MARINA I, 1990).

A similar set of reference geometries and environmental niches was considered in (Blaylock et al., 1993) with the following modifications: small crustaceans were replaced by small insects/ larvae of the same size; large crustaceans were replaced by small fish, again of the same size.

Amiro (1997) proposed an even more conservative dosimetric approach of assuming some generic, non-identified organisms to be exposed to maximum possible levels from potential internal and external sources. This approach is intended for simple screening of potential exposure for assessments where consideration of specific target organisms is either impossible or not required.

Mathematical methods for dosimetry in non-human organisms were developed based on achievements in medical dosimetry (Radiation Dosimetry, 1956; Brownell et al., 1968; Berger, 1968, 1971; Ellet & Humes, 1971), and also on methods developed in the engineering dosimetry of radiation shielding (Engineering, 1968; Gusev et al., 1989). The adaptation of dosimetric models for calculating doses to aquatic organisms has been made in a number of publications (Adams, 1968; Woodhead, 1970, 1973a, 1979, 1984; IAEA, 1976, 1979,1988; Pentreath & Woodhead, 1988).

6.2 Adaptation of dosimetric methods to regional dose assessment for marine biota

For the specific purposes of the OSPAR regional radioecological assessment, a generic approach with the use of non-identified reference organisms is not suitable; in the regional assessment the actual doses and effects are estimated for real organisms based on site-specific data on the environmental contamination in the investigated region.

Dose calculations have been carried out for the selected region-specific representatives of the marine biota in the North European marine waters – the OSPAR marine region. Doses from both external and internal pathways are estimated, as well as total dose rates to the representative organisms.

In the MARINA Update report, dose rates to marine organisms are calculated using the existing dosimetric approaches, outlined in the above listed publications; adaptations were made to take into account the sizes and habits of the region-specific organisms.

6.2.1 Input data in the dose assessment for biota

Input data are required for the calculation of doses to biota; in particular, the concentrations of radionuclides in the biota and the abiotic marine environment (water, sediments). These data are derived using the datasets from both analyses of the monitoring information, and radionuclide transport modeling in marine ecosystems.

In some cases, the available monitoring data on radionuclide distribution are not sufficient for dose assessment for biota. Some data have, therefore, to be reconstructed from the well-known correlations between the activity levels in water and consequent equilibrium concentrations in the sediments (K_d) and biota (CF).

6.2.2 Quantities and units in the dose assessment for biota

Marine organisms have great differences in their average lifetimes, so the most appropriate quantity in any dose assessment is the estimation of dose rates (dose per unit time). If required, one can switch to doses by integrating the dose rate over the lifespan or some other relevant period of the life of the organism (e.g. the period of embryonic development).

Taking into account the fact that the lifespans of the selected reference organisms range from months to years, the appropriate units for dose rates are in Gy day^{-1}.

The activity concentrations of radionuclides in water are given in Bq m^{-3} or in Bq L^{-1}; in organisms, in Bq kg^{-1} of fresh weight; and, in bottom sediments, in Bq kg^{-1} of natural (wet) weight.

6.2.3 Calculation of radiation doses to marine organisms from incorporated radionuclides

An important characteristic in calculations of internal dose to marine organisms is the relation between the linear dimensions of organisms and maximum path lengths of ionising particles in tissues (IAEA, 1976). This characteristic enables one to estimate the relative importance of alpha, beta and gamma radiation from internal and external sources.

Assessment of dose from incorporated alpha emitters

Most alpha emitters are sources of non-relativistic energies (up to 10 MeV). Alpha particles are characterized by high ionising, and low penetrating, power - their paths in materials are essentially straight. The path lengths of alpha particles in air and biological tissue are of the order of a few centimeters and several tens of micrometers, respectively.

Since the dimensions of the reference marine organisms are large compared with the path lengths of alpha particles, the actual body shapes become unimportant for dosimetric calculations. The dose rate to a larger aquatic organism (and component organs and tissues with dimensions greater than ~0.5 mm) is then effectively equal to $D_\alpha(\infty)$, the specific dose rate within the infinite volume of a uniformly contaminated absorbing material, and the value of $D_\alpha(\infty)$ (Gy day^{-1}) can be found using the following formula (IAEA, 1976; Loevinger et al., 1956)

$$D_\alpha(\infty) = 1.38 \cdot 10^{-8} \cdot \overline{E}_\alpha C_{org}, \qquad (1)$$

where $\overline{E}_\alpha$ is the average energy of alpha particles per decay of the particular radionuclide (MeV), and C_{org} is the activity concentration of the radionuclide within the organism, organ or tissue (Bq kg^{-1} wet weight).

Assessment of dose from incorporated beta emitters

Beta radiation is electron/positron radiation arising from the decay of nuclei. As beta particles interact with matter, they lose energy, decelerate and scatter. A special feature of the beta radiation from a particular radionuclide is the continuous character of its spectrum, because beta particles emitted by nuclei possess different initial energies from zero to a certain maximum value. A significant characteristic of the beta spectrum is the average energy of beta particles per decay.

Fast beta particles lack a strongly defined path, but can be characterized by the maximum path corresponding to the maximum energy E_0 of the beta spectrum. The highest-energy particles with an energy of about 3.5 MeV, can travel a distance of ≥10 mm in biological tissue. The average range for the beta particles from the decay of a particular radionuclide is approximately 20% of the maximum range corresponding to the beta particles with the maximum energy, E_0.

In the region-specific representative organisms considered here, such as molluscs, crustaceans, fish, etc. (i.e., with size greater than 1 cm), the contribution to the dose rate due to uniformly distributed beta emitters is taken to be equal to $D_\beta(\propto)$, which is the dose rate within an infinite volume of an absorbing material uniformly contaminated with the beta emitter (IAEA, 1976, 1979):

$$D_\beta(\infty) = 1.38 \cdot 10^{-8} \cdot \overline{E}_\beta C_{org} , \qquad (2)$$

where $D_\beta(\propto)$ is dose rate in Gy day^{-1}; $\overline{E_\beta}$ is the average energy of beta particles per decay of the particular radionuclide (MeV), and, C_{org} is the concentration of the beta emitter in the organism, (Bq kg^{-1} wet weight).

In some special cases, the dose to small critical organs within the organisms need to be calculated, and detailed dose rate distribution is required. The basic equation in the dosimetry of beta radiation is the Loevinger formula for the distribution of dose around a point source, derived from a mathematical analysis of experimental data (Loevinger et al.,1956; Engineering, 1968; Gusev et al., 1989; IAEA, 1979). The determination of dose from incorporated beta emitters breaks down into two stages. At the first stage, the dose from a point source of beta particles is determined and at the second stage the distribution of dose from volume sources of beta radiation is obtained by integrating the doses from elementary point sources. The beta-radiation dose rate distribution in aquatic organisms of arbitrary shape is rather difficult to determine by direct integration of the dose function from a point source. Consequently, the organisms/organs are approximated by spheres, cylinders, or other elementary geometric figures in the dose calculations (IAEA, 1976, 1979). For the purpose of evaluating the possible radiobiological effects in some organisms (especially small fish and molluscs), the considerable extent of accumulation of certain radionuclides in organs/tissues should be taken into account, as this may lead to a non-uniform distribution of dose rate within the body resulting in higher exposure of critical organs (e.g., gonads, liver). For a restricted number of region-specific organisms, detailed calculations of dose rate distribution can be performed provided that additional experimental information on the radionuclide distribution in different organs is available.

Assessment of dose from incorporated gamma emitters

The average dose rate from incorporated gamma emitters can be calculated using the following equation (Loevinger et al., 1956; Engineering, 1968; Gusev et al., 1989)

$$\overline{D}_{\gamma,\mathrm{int}} = 8.64 \cdot 10^4 \cdot C_{org} \cdot \rho \cdot \Gamma_\delta \cdot \overline{g};$$
$$\overline{g} = \frac{1}{V}\int_V g_P dV; \quad where \quad g_P = \int_V \frac{\exp(-\mu_{eff}\, r)}{r^2} dV; \qquad (3)$$

where $\overline{D}_{\gamma,\mathrm{int}}$ is the dose rate , Gy day^{-1}; Γ_δ is the kerma radiation constant of a radionuclide, (Gy m^2)(s Bq)$^{-1}$; C_{org} is the concentration of the radionuclide in the organism, Bq kg^{-1} wet weight; ρ is the density of the biological material, kg m^{-3}; $\overline{g}$ is the average geometric factor, m; g_P is the geometric factor at point *P*; V is the body volume, m^3; μ_{eff} is the effective attenuation factor of the biological tissue/water, m^{-1}; coefficient 8.64x10^4 is the number of seconds in a day.

In radiation dosimetry, the kerma Γ_δ (Gy m^2 s^{-1}Bq^{-1}) is a standard dose constant, characteristic for each radionuclide; it is defined by the formula (Engineering, 1968; Gusev et al., 1989):

$$\Gamma_\delta = \frac{1.602 \cdot 10^{-13}}{4\pi \cdot w} \cdot \sum_{i=1}^{m} E_{0i} \cdot n_{\gamma i} \cdot \mu_{tr,i}^{air}(E_{0i}); \qquad (4)$$

where E_{0i} is the energy of photon of the i-th energy group emitted by the radionuclide, MeV (1 MeV=1.602x10^{-13} J); *m* – total number of energy groups of photons emitted by the radionuclide; $n_{\gamma i}$ is the fraction of photons emitted with energy E_{oi}; $\mu_{tr,i}^{air}(E_{0i})$ is the energy absorption coefficient in the standard media (air) , m^2 kg^{-1}; w=1 J kg^{-1} Gy^{-1}. Standard Γ_δ values are tabulated for a point source in the air, for biological tissues and water $\Gamma_\delta^{wat} = \frac{\mu_{tr}^{wat}}{\mu_{tr}^{air}} \Gamma_\delta \approx 1.09 \cdot \Gamma_\delta$.

The value of the geometric factor $\overline{g}$, appearing in the Eq.(3), can be calculated analytically for simple symmetrical figures, such as sphere, plate, cylinder, truncated cone, etc. (Loevinger et al., 1956; Engineering, 1968; IAEA, 1976; Gusev et al., 1989).

For a sphere, the average geometric factor throughout the spherical volume accounts for 0.75 of the geometric factor g_o at the center of the sphere, i.e.

$$\overline{g}_{sph} = \frac{3}{4} g_0 = \frac{3}{4} \cdot \frac{4\pi}{\mu_{eff}} (1 - \exp(-\mu_{eff} R)); \qquad (5)$$

where R is the radius of the sphere, m.

For cylinders of different size, the average geometric factors are tabulated in (Loevinger et al., 1956; IAEA, 1976).

The calculation of geometric factors for volumes of arbitrary shape is a complicated task and it is solved with the use of computer codes.

For the purposes of medical dosimetry, detailed numerical calculations have been performed by the Monte-Carlo method, which provided values of the absorbed fractions of energy in different volumes containing gamma-emitting radioactive substances (Brownell, Ellet & Reddy, 1968; Ellet & Humes, 1971). In these calculations the following modification of the Eqs.(3) and (4) was used:

$$\overline{D}_{\gamma,\text{int}} = 1.38 \cdot 10^{-8} \cdot C_{org} \sum_i E_i n_i \Phi_i(E_i) \approx 1.38 \cdot 10^{-8} \cdot C_{org} \cdot \overline{E}_\gamma \cdot \Phi(\overline{E}_\gamma); \qquad (6)$$

where $\Phi(E) = \dfrac{\textit{photon energy absorbed in the volume}}{\textit{photon energy emitted by the source}}$ is the photon absorbed fraction within a target volume.

The $\Phi(E_\gamma)$ values were obtained for a range of emitted photon energies E_γ from 0.02 to 2.75 MeV; geometrical models considered were spheres and ellipsoids of different shapes (flat, thick and elongated ellipsoids) with masses ranging from 1 g up to 200 kg, (unit density tissue), containing the uniformly distributed gamma-emitter (Brownell et al., 1968; Ellet & Humes, 1971).

The approach (6) was successfully adopted for the dosimetry of aquatic biota (IAEA, 1988; Pentreath & Woodhead, 1988; Blaylock et al., 1993; Woodhead, 2000).

For very large organisms (walrus, whale) a simplified assumption can be used, i.e., that the dose rate within the organism is equal to $D_\gamma(\infty)$, the dose rate within the infinite volume of an absorbing material uniformly contaminated with the gamma emitter. The value of $D_\gamma(\infty)$, Gy day^{-1} can be calculated from formula (6), taking Φ=1 (Brownell et al., 1968; Ellet & Humes, 1971; Pentreath & Woodhead, 1988; Blaylock et al., 1993):

$$D_\gamma(\infty) = 1.38 \cdot 10^{-8} \, \overline{E}_\gamma \cdot C_{org}. \qquad (7)$$

6.2.4 External irradiation

The sources of external irradiation of marine biota are as follows:

- irradiation from contaminated water and bottom sediments;
- irradiation from contaminated overgrowths of macroalgae or accumulations of molluscs; and,
- irradiation from radionuclides adsorbed onto the surfaces of organisms.

For large organisms the predominant external irradiation pathway can be from gamma-radiation, and to a lesser extent from beta-particles. For small organisms (phytoplankton, small zooplankton, fish eggs), the doses from alpha- and beta-emitters adsorbed on their surfaces may be important in the external dosimetry.

Exposure from water

In the assessment of external dose, water is considered as an infinite source of uniformly distributed radionuclides.

External exposure from alpha and beta emitters uniformly distributed in the water column may be significant only for the outer surfaces of the selected region-specific marine organisms because of short paths of α- and β- particles in water and biological tissues.

The dose rate to the surface layer (skin) of organisms from alpha and beta emitters distributed in water column can be estimated as 0.5 $D_\alpha(\infty)$ (for alpha emitters) and 0.5 $D_\beta(\infty)$ (for beta emitters), where $D(\infty)$ is calculated from Eqs. (1) or (2) at the radionuclide concentration in water.

External gamma-radiation dose rate $D^W_{\gamma,ext}$ to aquatic organisms from a gamma emitter of average energy E_γ uniformly distributed in the water column is calculated as:

$$D^{wat}_{\gamma,ext} = D^{wat}_\gamma(\infty) - D^{wat}_\gamma(V_{org}); \tag{8}$$

where $D^{wat}_\gamma(\infty)$ and $D^{wat}_\gamma(V_{org})$ are calculated from Eq. (7) and Eq. (3) or Eq. (6) respectively; both values are calculated from the radionuclide concentration in water.

External exposure from bottom sediments

The bottom sediments are represented as a layer of infinite thickness with uniformly distributed activities of radionuclides.
The dose rate at the surface of bottom sediments from γ-radiation can be estimated as $0.5\,D_\gamma(\infty)$ (IAEA, 1976).

6.2.5 Calculation of total dose rates to the region-specific organisms

Radiological dose conversion factors (internal and external exposure) were calculated with a computer code for each of the region-specific organisms, represented by the appropriate geometric model, for different radionuclides, see Appendix A. The radioactive decay data used in calculations were taken from the ICRP Publication 38 (ICRP, 1983).

Dose conversion factors for internal exposure are calculated on the assumption of a unit radionuclide concentration in the organism 1 Bq kg^{-1} wet weight. Dose conversion factors for external exposure from water are calculated, using a unit radionuclide concentration in the water 1 Bq L^{-1}. Dose conversion factors for external exposure from sediments are calculated, using a unit radionuclide concentration in sediments 1 Bq kg^{-1} wet weight.

The total dose rate to the i-th region-specific organism from a given radionuclide can be calculated by the formula:

$$D^i{}_{tot} = w_r \cdot [DCF^i{}_{\text{int}} \cdot C^i{}_{org} + DCF^i{}_{wat} \cdot C_{wat} + DCF^i{}_{sed} \cdot C_{sed}]; \tag{9}$$

where D^i_{tot} is the total dose rate to reference organism;

w_r is the radiation weighting factor for the given radiation (alpha, beta or gamma exposure);

$DCF^i_{\text{int}}, DCF^i_{wat}, DCF^i_{sed}$ are calculated dose conversion factors for internal and external exposure; $C^i_{org}, C_{wat}, C_{sed}$ are the radionuclide concentrations in the i-th organism, water, and sediments, respectively.

In an ideal situation, measured concentrations of the radionuclides are available for the organism, water and sediment; this makes it possible to use Eq. (9) directly. In the worst case, when only data on radionuclide concentrations in water are available, the radionuclide concentrations in the organism and sediments can be reconstructed using appropriate concentration factors (CF) and K_d values (IAEA, 1985). It should be noted, however, that concentration factors and K_d values are variable from site to site, and the uncertainty associated with employing default values of CF and K_d can be rather large.

In the present approach, the radiation weighting factors for α- and β-radiation are not included in the tabulated dose conversion factors (see Appendix A), the reason being that the values of these factors for non-human biota are not yet established in the official documents.

7 Dose assessment to marine biota in the industry-impacted zones of the North-East Atlantic

This chapter presents the results of dose assessment to natural marine biota in some representative, industry-impacted sites of the OSPAR region.

Assessment of radiation exposure to marine organisms has been performed, based on the methodology and dose conversion factors outlined in the previous sections of this report. Real data on the radioactive contamination of the marine environment were used for dose estimates, which were obtained in the course of routine/research monitoring programmes carried out in 1980s-1990s. The input data on the radioactivity of marine environment in the OSPAR region has been compiled by the Working Group B within the present MARINA II study ; the sources of data included databases from BNFL and MAFF/CEFAS, the Nord-Cotentin database; data from the AMAP programme; and, journal publications.

The following data were used as input information in the dose assessment to marine biota:

- Measured activity concentrations of artificial or natural radionuclides in the key representatives of marine organisms in a particular marine area;

- Measured activity concentrations of radionuclides in sea water and sediments in a particular marine area.

As far as possible, site-specific species of organisms were considered; however, the existing monitoring databases are not specially adapted for the dose-to-biota assessment, therefore some data in the databases represent values averaged by broad categories of organisms (e.g. ‘fish’, ‘shellfish’), and for some organisms data are missing. As a rule, the routine monitoring measurements include the radionuclide analysis of edible parts of organisms only, without consideration of different organs and tissues.

The dose assessment to marine biota has been performed based on the assumption of a uniform distribution of radionuclides within organism; the results, therefore, are averaged dose rates to the whole body of the organism.

Dose assessments to marine biota have been made for the following industry-impacted areas of the OSPAR region:

- Coastal areas in the vicinity of nuclear reprocessing plants (Sellafield, UK; Cap de la Hague, France);
- Near coastal zone of nuclear power plant (Ringhals NPP in Sweden);
- Coastal zones in the vicinity of non-nuclear plants, characterized by discharges of enhanced levels of natural radionuclides (phosphate plant at Whitehaven, UK; oil fields in the North Sea);
- Remote marine areas with low levels of man-made radioactivity, which are considered as relatively 'clean' waters (Barents Sea, Norwegian coastal waters).

Dose rates to site-specific organisms were calculated for each year of observations, using a computer code connected with databases.

To provide a basis for comparison in this dose assessment, estimated values for natural background exposure of the selected organisms have been taken from literature. Taking into account that living organisms have been exposed to natural background radiation during the entire period of biological evolution, the background dose rates to biota are considered as normal, i.e. not having a negative impact on the safety of organisms.

To evaluate the possible harm to biota, the dose rates to organisms, inhabiting the industry-impacted marine areas were compared with the available information on the 'dose-effect' relationships for aquatic organisms.

7.1 Background exposure of marine organisms from natural sources of radiation

The background exposure of marine organisms comprises cosmic radiation and exposure from natural radionuclides dispersed in water, present in sediments, and accumulated in living organisms.

The typical concentrations of natural radionuclides in sea water and representative organisms are summarized in Table 6. The summary of dose rates to marine organisms from natural background radiation is presented in Table 7.

7.2 Contamination in the remote marine areas of the OSPAR region

In addition to the natural radioactivity of seawater, there exists some global contamination of the World Ocean with artificial radionuclides.

Two main sources are fallout from nuclear weapon tests, and the operation of nuclear reactors including the concomitant processing of the spent fuel. The contamination of the remote zones in the OSPAR region provides an indication of the levels of man-made background within the OSPAR area.

The Barents Sea and the northern part of the Norwegian Sea can be considered as relatively clean areas in the OSPAR region remote from intensive industrial activity.

The current man-made radioactivity in the Barents Sea is characterized by trace concentrations of ^{137}Cs, ^{90}Sr, ^{99}Tc, $^{239,240}Pu$.

The activity concentrations of artificial radionuclides and dose rates to representatives of marine biota in the Barents Sea are summarized in Table 8 and Table 9.

The additional dose rates to marine biota from artificial radionuclides in the Barents Sea are extremely low in comparison with the exposure from natural radioactivity, so no harm can be expected from those minor dose rates.

8 Radiological impact on marine biota from nuclear industry

8.1 Sellafield area: dose rates to marine biota

The coastal area impacted by the Sellafield nuclear reprocessing plant is located at the east coast of the Irish Sea, UK. The scheme of the Sellafield coastal area is shown in Figure1.

The ‘Sellafield Coastal Area’ extends 15 km north and south of Sellafield from St. Bees Head to Selker and 11 km offshore; most of the fish and shellfish consumed by the most exposed group is taken from this area. Specific surveys are carried out in the smaller ‘Sellafield Offshore Area’ where experience has shown that good catch rates may be obtained. This area consists of a rectangle, one nautical mile (1.8 km) wide by two nautical miles (3.6 km) long, situated south of the pipelines with the long side parallel to the shoreline; it averages about 5 km from the pipeline outlet (MAFF & SEPA, 1999).

The dose assessment to marine biota in the vicinity of Sellafield was performed, using monitoring data on the environmental contamination for the period 1986-2001 compiled by the Working Group B of the MARINA II study from the BNFL and MAFF/CEFAS databases (see report on environmental data in the present study).

8.1.1 Fish, molluscs, crustaceans

The aquatic monitoring programmes carried out by BNFL and MAFF include sampling/measurements of the following components of the marine environment:

- Sea water;

- Sediments;

- Fish (mostly cod *Gadus morhua* and plaice *Pleuronectus platessa*, with some samples of other fish species, e.g. whiting, haddock, bass);

- Molluscs (mostly mussels *Mytilus edulis* and winkles *Littorina littorea*, with some samples of whelks and limpets);

- Crustaceans (crabs and lobsters).

The averaged annual results of monitoring are usually presented for broad categories of biota, e.g. 'fish', 'molluscs', 'crustaceans', and not for individual species; in this context for the purpose of dose calculations the 'fish' data refers directly to cod and plaice as site-specific fish species; 'molluscs' data refers to mussels and winkles, and 'crustaceans' data refers to crabs and lobsters. Calculations of doses to other fish species (herring, haddock, etc.) were made from the general data set on 'fish' contamination.

A number of radionuclides have been measured in the environmental samples in the Sellafield marine area, including ^{137}Cs, ^{90}Sr, ^{99}Tc, ^{241}Am,^{239,240}Pu, ^{238}Pu, ^{60}Co and^{106}Ru. The dose rates to marine biota were calculated, using dose conversion factors, from data on concentrations of radionuclides in organisms and in the biotic environment.

Dose rates to representatives of marine biota in the vicinity of Sellafield are shown in Figure 2 (see also Appendix B, Table B1).

The highest dose rates were estimated for molluscs: annual average dose rates to mussels and winkles varied within the range from $1{\cdot}10^{-4}$ to $4{\cdot}10^{-5}$ Gy day^{-1} (weighted by w_r), see Figure 3. Molluscs feed on suspended matter; these organisms accumulate in their bodies radionuclides which are adsorbed on suspended particles in sea water. Molluscs are also known to bioassimilate some trace elements from seawater, such as cobalt, manganese, zinc, etc. As a general rule, molluscs tend to contain higher levels of radionuclides than crustaceans, which in turn tend to contain more than fish. According to monitoring data, molluscs contain considerably higher concentrations of radionuclides as compared with fish. The major contributors to dose rates to molluscs are incorporated ^{241}Am and ^{239,240}Pu, see Figure 3.

Dose rates to crustaceans (crabs and lobsters) were somewhat lower than those to molluscs, average values vary within the range from $1.4{\cdot}10^{-5}$ to $4{\cdot}10^{-6}$ Gy day^{-1} (weighted by w_r), see Figure 4. Having close contact to bottom sediments, crustaceans are contaminated with radionuclides accumulated in sediment. Also, lobsters are specific accumulators of some particular radionuclides, e.g. ^{99}Tc, probably because of some peculiarities in metabolism. In 1996-2000, ^{99}Tc and ^{241}Am were the major contributors to the dose rate to crustaceans, in the previous period (1986-1993) the most significant contributor was ^{106}Ru, see Figure 4.

Dose rates to fish were lower than those to molluscs and large crustaceans. Typical dose rates to larger fish (cod, plaice) were about $3{\cdot}10^{-6}$-$2.6{\cdot}10^{-7}$ Gy day^{-1} (weighted by w_r) during the assessment period (1986-2001), see Figure 5. Fish can move some tens of kilometers through the concentration gradients in seawater; the resulting level of fish contamination therefore represents an average over a large area. In contrast to molluscs and crustaceans, the main contributor to dose rates to fish was ^{137}Cs, see Figure 5.

Dose rates estimated for smaller planktivorous fish (herring, sardine) were somewhat lower ($8.5 \cdot 10^{-7}$ - $7 \cdot 10^{-8}$ Gy day^{-1} (weighted by w_r)) than those for large fish, reflecting lower exposure from sediments, as well as lower absorption of gamma-energy from incorporated radionuclides within small bodies. Contamination of small fish was not studied within monitoring programmes in the Sellafield coastal area, so the data on radionuclide concentrations in this group of fish were not available. The preliminary dose estimates to small fish were performed using general data on fish contamination.

There are some variations in dose rates to biota between years, resulting from changes in the spectrum of radionuclides discharged to the marine environment, which in turn correlates with changes in technologies at the reprocessing plant. For example, the increase in dose rates to crustaceans in the period 1995-2000 correlates with the increase in the releases of ^{99}Tc. In general, the dose rates to marine biota in the Sellafield coastal waters slowly decreased in the period 1986-2000, the current dose rates amount to about 20-40% of the dose rates to biota in 1986-1987.

During the assessment period, the dose rates to biota at Sellafield exceeded the natural background radiation exposure up to 2–4 times for different organisms. The exposure in this industrial area due to artificial radionuclides was several orders of magnitude higher than such exposure of marine organisms in the remote, relatively ’clean’ areas within the OSPAR region.

Nevertheless, throughout the assessment period 1986-2001, the estimated dose values were all below the levels of deterministic effects of radiation, so it is unlikely any radiation effects will appear in marine organisms.

Some assessments of dose rates to marine biota at Sellafield were made in the earlier period of the operation of the reprocessing plant. The dose rate to hypothetical local plaice resting stationary on the site calculated from conservative assumptions by Woodhead, was estimated to be as high as $1.4 \cdot 10^{-3}$ Gy day^{-1} in late 1960s. Long-term studies with in situ measurements of dose rates to plaice were carried out in 1967-1969 (Woodhead, 1973b). About 3500 plaice were caught in the area 1-2 km south of the Sellafield effluent discharge point. Small dosimeters were attached to fish before releasing them back into the sea. About 1000 fish were recaptured in the subsequent period. The average dose rates to plaice registered with dosimeters were $8.4 \cdot 10^{-5}$ Gy day^{-1} with occasional dosimeters registering dose rates up to $6 \cdot 10^{-4}$ Gy day^{-1}. These dose rates were mainly due to exposure from radionuclides in the contaminated seabed.

8.1.2 Sea birds in the vicinity of the Sellafield

In the early 1980s, concern was expressed about the decline in numbers of waterfowl, waders and gulls in the Ravenglass estuary about 10 km to the south-west from the Sellafield nuclear reprocessing plant. In particular, the colony of black-headed gulls had fallen from over 10 000 pairs before 1976 to about 1500 pairs in 1984, when they bred on the Drigg dunes for the last time. Suggestions have been made that the decline might be due to radioactive contamination of bird's food and their general environment.

Ninety six bird specimen, of 15 different species, were sampled between 1980 and 1984, mainly from Ravenglass; these included black-headed gull (*Larus ridibundus*), greater black-backed gull (*Larus marines*), lesser black-backed gull (*Larus fuscus*), herring gull (*Larus argentatus*), oystercatcher (*Haematopus ostralegus*), bar-tailed godwit (*Limosa lapponica*), shelduck (*Tadorna tadorna*), wigeon (*Anas penelope*), and some others (Lowe, 1991). Most of the birds were shot, but some were natural deaths; all the black-headed gulls samples were from the carcasses of individuals killed on their nests by foxes.

The highest concentrations of radiocaesium were found (in the breast muscles) in oystercatcher (maximum value ^{137}Cs = 636.8 Bq kg^{-1} fresh weight) and bar-tailed godwit (maximum value ^{137}Cs = 478.1 Bq kg^{-1} fresh weight).

Of the other species, only shelduck, wigeon and curlew occasionally reached or came close to 300 Bq kg^{-1}. Among birds, the black-headed gulls had the lowest concentrations of radiocesium, with maximum ^{137}Cs concentration of 45.5 Bq kg^{-1} fresh weight in breast muscles.

The highest concentration of plutonium radionuclides were found in shellduck (max values in liver ^{239,240}Pu = 12.3 ± 1.9(n=2) Bq kg^{-1} and ^{238}Pu = 2.7(n=1) Bq kg^{-1} fresh weight) and wigeon (max values in liver ^{239,240}Pu = 8.08 ± 5.53(n=4) Bq kg^{-1} and ^{238}Pu=2.44± 1.25(n=3) Bq kg^{-1} fresh weight); greater black-backed gull had 5.32 Bq kg^{-1}, whereas the black-headed gull had only 0.54 ± 0.67(n=8) Bq kg^{-1} of ^{239,240}Pu in the liver (Lowe, 1991).

Analysing the radionuclide concentrations in birds from Ravenglass, it should be noted that birds were found to be more contaminated than fish from the Sellafield coastal area (e.g., average radiocesium concentrations in fish in 1986-1988 were about 20-30 Bq kg^{-1} (max 88 Bq kg^{-1}); ^{239,240}Pu concentrations in fish were 0.02-0.03 Bq kg^{-1}). Concentrations of ^{239,240}Pu in bird's liver can be compared with concentrations of these radionuclides in molluscs, which in 1986 were about 15 (max. 50) Bq kg^{-1}. Most probably, the relatively high contamination of birds was the result of consumption of contaminated mud along with invertebrate food items.

In the current study the conservative estimations of internal radiation exposure to seafood-eating birds, based on the maximum observed concentrations provide the following values: whole body dose rate from ^{137}Cs – about $2{\cdot}10^{-6}$ Gy day^{-1}; dose rate to liver – about $2{\cdot}10^{-5}$ Gy day^{-1} (weighted by w_r).

Woodhead (1986) has calculated conservative values of total dose equivalent to the whole body of the black-headed gull, basing his calculations on data in Allen et al. (1983). The total equivalent dose rate to the whole body of black-headed gull was estimated to be equal to $2.4{\cdot}10^{-5}$ Gy day^{-1} (including the contribution from internal organs and external exposure); the total dose equivalent rate to the gut lining was greater, being $3.42{\cdot}10^{-4}$ Gy day^{-1} (weighted by w_r).

From information available on the radiation effects to birds, the dose rates to black-headed gulls (which were not the most contaminated birds in the Sellafield area) were unlikely to produce a direct effect on the mortality of birds. The most likely cause of the desertion of gullery was an increased predation by foxes, which, in turn, was caused by a decrease in rabbit population in the area.

8.1.3 Marine mammals

The marine area in the vicinity of Sellafield (from the Clyde to the Dee Estuary) is poorly populated by seals, so there is no information on radionuclide levels in seals close to Sellafield. Most of the UK seal populations probably feed at some distance from the Sellafield discharges.

In general, information on radionuclides in seals around UK is sparce. Samples of milk and tissues of grey seals were collected in 1987 on the island North Rona (Outer Hebrides) and the Isle of May (Anderson et al., 1990). Measurements of radionuclide concentrations in milk and tissues of grey seals/pups provided the following average results:

Milk ^{137}Cs = 2.9 Bq kg^{-1}; ^{239,240}Pu = <0.3 Bq kg^{-1};
^{137}Cs in muscle and liver was ranging between 6.4 and 27.5 Bq kg^{-1}; ^{239,240}Pu = 2.25 ± 0.31 Bq kg^{-1} (muscle); ^{239,240}Pu = 3.52 ± 0.38 Bq kg^{-1} (liver).

In the present study the estimated dose rates to grey seals were $3.3 \cdot 10^{-6}$ Gy day^{-1} (weighted by w_r), with the predominant contribution from ^{239,240}Pu. In general, the dose rates to grey seals and larger fish are very similar reflecting the trophic status of grey seals as top predators feeding on fish.

Pentreath & Woodhead (1988) calculated the hypothetical radiation dose from ^{137}Cs which might be received by an average grey seal, feeding exclusively on fish in the Sellafield area. Making the assumption that seals would receive the same dose per intake as man, they estimated an annual dose of 36 mSv (10^{-4} Gy day^{-1}). This was a conservative upper estimation because in reality seals don’t feed very close to the Sellafield site.

8.1.4 Uncertainties in dose assessment to marine biota

The uncertainties in the estimations of radiation exposure to organisms in natural marine ecosystems are rather large, the reasons being:

- There is a natural variability in the contamination of individual organisms within one and the same population depending on age, season, variations in metabolism, local habitat, mobility, gradients in contamination, etc.;
- Environmental monitoring programmes provide limited data on the radionuclide content in biological materials, which in some cases are not sufficient for statistical analysis of information;

- Some systematic uncertainties in the results are associated with the methods of dose calculations. Dosimetric models, used in the dose assessment, provide body-averaged dose rates to organisms. However, the actual dose distribution is likely to be non-uniform, resulting in higher exposure of some organs/tissues of organisms. The more precise results can be obtained using more complicated computer codes supplied with detailed experimental information on the radionuclide distribution within an organism. In the assessment of external dose rates from sediments the source of uncertainty is the geometric approximation of the radionuclide distribution within sediments. For example, in the northeast Irish Sea the concentration of radionuclides in sediments declined rapidly with depth, and the gamma-dose rate at the sediment surface was found to be closer to $0.25\,D_{\gamma}(\infty)$ than to $0.5\,D\gamma(\infty)$, which was estimated from a conservative formula (IAEA, 1976).

Only one type of uncertainty is estimated in this report – the uncertainty in dose rates associated with the scattering in radionuclide concentrations registered in the environmental samples.

Three sets of dose calculations can be made for each representative species of organisms:

- Average dose rates based on arithmetic annual average concentrations of each radionuclide in a given organism and its environment;

- Maximum dose rates based on maximum concentrations of each radionuclide registered during each year of observations in a given organism;

- Minimum dose rates based on lowest concentrations of each radionuclide registered during each year in a given organism.

The difference between the highest and lowest dose rate values is considered as the range of uncertainty in dose assessment for a representative organism. The typical ranges of uncertainty are shown in Figure 6 for cod at the Sellafield area.

During periods of continual quasi-equilibrium discharges of radionuclides into the marine environment, the typical range of uncertainty in dose rates to biota is about one order of magnitude. The uncertainties in doses to biota become much larger in cases of sharp changes in radionuclide discharges to the environment when the radioecological situation is strongly non-equilibrium. In this report, the uncertainty in dose assessment to marine biota is considered to be one order of magnitude.
The majority of figures in this report demonstrate the dynamics of average dose rates to biota for a number of years, the associated uncertainties are assumed to be one order of magnitude throughout these graphs.

Some uncertainties in dose estimates are associated with non-uniform radionuclide distribution within an organism. It is well known, that different radionuclides are accumulated specifically in particular organs and tissues of organisms. For instance, ^{90}Sr is deposited in the bones, plutonium isotopes are deposited in the liver and the content of guts can be contaminated with insoluble radionuclides from bottom sediments. As a result of non-uniform radionuclide distribution within a body, the dose rate to different organs can differ from the average value by one order of magnitude and more.

A radiation weighting factor of 20 has been employed as a conservative value to evaluate the biologically equivalent dose rate from the alpha component of the radiation exposure. An improved estimate of the weighting factor for alpha-particle radiation needs further investigation. To estimate the uncertainties associated with using of RBE factors, total dose rates to biota were calculated as absorbed dose rates (w_r=1) and RBE-weighted dose rates (w_r=20 for alpha-emitters), results are presented in the Appendix B. For the Sellafield area the weighted dose rates are, on average, higher than the absorbed dose rates by a factor of 1.1 for fish, 7.7 for molluscs, and 1.5 for crustaceans.

In general, uncertainties in doses to biota should be considered when the possible effects of radiation are estimated.

8.2 Cap de la Hague: dose rates to marine biota

Calculations of dose rates to marine biota in the area of the Cap de la Hague nuclear reprocessing plant were performed, using the radiological monitoring data from the Nord-Cotentin database for the period 1982-1997 (Nord-Cotentin, 1999). A general information on data, which were used for dose assessment to biota in the Cap de la Hague coastal area (France) is given in Table 10, including the monitoring sites, type of samples, and radionuclides measured by different organizations. The scheme of the Cap de la Hague area (Nord-Cotentin Peninsula) with the location of monitoring sites is presented in Figure 7.

To provide conservative estimates of dose rates to biota, the whole set of radionuclides measured at neighbouring monitoring sites was considered in dose calculations.

Due to local hydrobiological conditions, mussels do not inhabit the local area in the vicinity of the Cap de la Hague between Carteret and Barfleur. Instead of mussels, a Gastropoda mollusc Patella (limpet) is used as a bio indicator in the monitoring programmes. So, the dose assessment was made for this mollusc. Dose rates for mussels were calculated for the site Barfleur (the nearest monitoring site, where natural mussel populations exist).

Concentrations of alpha-emitters (^{239,240}Pu, ^{238}Pu, and ^{241}Am) in biological samples were reported only for molluscs Patella, but not for fish, crustaceans and mussels. Thus dose rates to fish, crabs and mussels were calculated without contribution of alpha-emitters; dose rates to limpets (Patella molluscs) were calculated including the input from ^{239,240}Pu, ^{238}Pu and ^{241}Am.

Dose rates to marine biota in the vicinity of the Cap de la Hague site for the period 1982 to 1997 are shown in Figure 8 (see also Appendix B table B2).

Molluscs and crabs were the most exposed organisms among marine biota, see Figures 9 and 10. Dose rates varied within the range $1.6{\cdot}10^{-5} – 6{\cdot}10^{-7}$ Gy day^{-1} (weighted by w_r) to molluscs Patella, and within the range $8{\cdot}10^{-6} – 1.5{\cdot}10^{-7}$ Gy day^{-1} to crabs (excluding contribution by alpha-emitters).

In general, doses to molluscs and crabs in the Cap de la Hague area were lower than those at Sellafield, also the decrease of dose rates in the period 1982-1997 was more pronounced.

The dose rates to fish at Cap de la Hague slowly decreased from $4.3{\cdot}10^{-7}$ Gy day^{-1} in 1982 to $2.1{\cdot}10^{-8}$ Gy day^{-1} in 1997, see Figure 11 (no alpha-emitters considered).

The major contributors to dose to marine biota in the Cap de la Hague area were the following radionuclides (1996 to 1997), see also see Figure 9 to 11:

- Mollusc Patella ^{241}Am – 56%; ^{106}Ru – 16%; ^{239,240}Pu – 13%; ^{248}Pu – 9%;
- Crabs ^{106}Ru – 62%; ^{110m}Ag – 17%; ^{60}Co – 11% (excluding alpha-emitters);
- Fish ^{134,137}Cs – 24%; ^{106}Ru – 23%; ^{110m}Ag – 21%; ^{60}Co – 21% (excluding alpha-emitters).

Additional calculations were made to estimate the potential contribution of alpha-emitters (Pu isotopes) to dose rates to marine biota at Cap de la Hague. For this purpose a reconstruction of ^{238}Pu, ^{239,240}Pu concentrations in marine biota was performed based on available data on Pu-isotopes in seawater and recommended values of concentration factors in marine organisms.

The reconstructed input from Pu-isotopes to dose rate was estimated to be $(1.5 - 4){\cdot}10^{-5}$ Gy day^{-1} (weighted by w_r) for mussels, and $(2\text{-}5){\cdot}10^{-7}$ Gy day^{-1} (weighted by w_r) for fish during the assessment period. Thus, the potential input to dose from Pu-isotopes can be comparable with the input from gamma/beta emitters.

8.3 Impact on marine biota from nuclear power plant (Ringhals NPP, Sweden)

An example of the impact of nuclear power plants on coastal marine biota was assessed using monitoring data from Ringhals NPP in Sweden (SSI Report 2000:04; SSI report 2000:19; Wijk & Luning, 2001).

Ringhals nuclear power plant is situated at the Swedish West Coast, approximately 50 km to the south of Gothenburg and 15 km to the north of Varberg, on the Värö peninsula. The site encompasses 4 reactors, one BWR and 3 PWRs. The installed electrical capacity is 0.75 GW for the BWR and 2.63 GW for the three PWRs.

The plants discharge into the Kattegat. There are two adjacent discharge points immediately at the coastline, one for Units 1-2, and one for Units 3-4. Air-borne releases predominantly are through the main stack of each reactor unit, i.e. from four emission points.

The environmental samples consist of local fauna and flora (algae, fish, shellfish, mosses, game), sediment, as well as local food produce (grain, milk etc.). In dose assessment the following region-specific organisms were considered: cod (*Gadus morhua*), mussel (*Mytilus edulis*), winkle (*Littorina littorea*), lobster (*Homarus gammarus*), and crab (*Cancer pagurus*).

The assessment was performed for the recent period of Ringhals NPP operation (1997 to 2000), available monitoring information on the radionuclide content in biota include the following radionuclides: ^{54}Mn, ^{58}Co, ^{60}Co, ^{137}Cs. The number of samples varied between years from one to 6 of different species; only data from the monitoring sites close to Ringhals were considered.

Since the impact from the NPP to marine biota is known to be small compared with that from other industries, maximum dose rates were estimated, based on the highest concentrations of radionuclides in assessed species found for each year.

Dose rates to cod caught in the vicinity of the Ringhals NPP varied very little from year to year amounting on average to $(1.4\pm0.25)\cdot10^{-8}$ Gy day^{-1} ; these were small values, slightly higher than the man-made background in the OSPAR region.

Dose rates to molluscs were also small with the average value amounting to $(2.9\pm2.6)\cdot10^{-8}$ Gy day^{-1} with larger variability in the contamination of individual specimen.

Dose rates to crustaceans (lobsters and crabs) varied within one order of magnitude from $7\cdot10^{-9}$ to $7\cdot10^{-8}$ Gy day^{-1}. Isotopes of cobalt (^{58}Co, ^{60}Co) were the major contributors to exposure of molluscs and large crustaceans; ^{137}Cs was responsible for the man-made exposure of fish. It should be noted that the estimated values of dose rates include contributions from the regional artificial contamination of the marine environment.

From the point of view of the radiological impact to marine biota dose rates to marine organisms in the vicinity of Ringhals NPP were very low during the assessed period, contributing only a minor addition to natural background.

9 Dose rates to marine biota from non-nuclear industry

9.1 Phosphate plant at Whitehaven, UK

Surveys of concentrations of naturally occurring radioactive materials (NORM) in the coastal waters of the UK revealed (Rollo et al., 1992) that the Albright & Wilson chemical plant at Whitehaven in Cumbria, UK which manufactured phosphoric acid from imported phosphate ore was an important source of NORM radionuclides to the marine environment from 1954.

Phosphogypsum, a waste product of chemical technology, has been discharged as liquid slurry by pipeline to Saltom Bay. The discharges contain low levels of natural radioactivity (NORM) consisting mainly of thorium, uranium and their daughter products, such as ^{238}U, ^{234}U, ^{232}Th, ^{230}Th, ^{228}Th, ^{210}Pb, ^{210}Po.

Since the introduction of changes in waste treatment techniques and cessation of the use of phosphate ore in 1992, the discharges declined substantially, in particular, discharges of uranium decreased by 80%, of ^{230}Th and ^{210}Pb by 95%, and of ^{210}Po by 99% (Poole et al., 1995).

The assessment of dose rates to marine biota from NORM was performed for the site at Parton (Figure 12) situated 5 km north from the phosphate plant, where greater enhancements of NORM were observed due to the local sedimentary transport system. Dose assessment was based on data from monitoring programmes and surveys for the period 1991-1999. At Parton, concentrations of NORM were measured in mussels, winkles, crabs, lobsters, and cod. Local background levels of NORM in seawater and marine biota were measured at Ravenglass, 10 km to the south from the phosphate plant, these data were used in estimation of local background exposure of marine organisms (McCartney et al., 2000; Rollo et al.,1992). The estimated values of local background dose rates to biota are the following (Gy day^{-1}, weighted by w_r): molluscs and crabs – $(2.5 – 3)\cdot10^{-5}$, fish – $1\cdot10^{-6}$.

The dynamics of dose rates to marine biota from NORM (at Parton) are shown in Figure 13, see also Appendix B (table B3). During the period 1991-1999 dose rates to molluscs decreased from $3\cdot10^{-4}$ to $4.8\cdot10^{-5}$ Gy day^{-1} (weighted by w_r), including the natural background. These dose rates are comparable with radiation exposure of biota in the Sellafield coastal area.

The dominant contributor to molluscs' dose is ^{210}Po, which is accumulated with high concentration factors, see Figure 14. The contribution to dose of uranium and thorium isotopes is considerably lower, than that of polonium. However, there is a possibility of chemical toxicity of uranium/thorium in bottom sediments for bottom-dwelling species. The aspects of chemical toxicity of NORM are outside the scope of this assessment.

Dose rates to crustaceans (crab) varied within the range from $7\cdot10^{-5}$ to $2.8\cdot10^{-5}$ Gy day^{-1} (weighted by w_r) including the natural background; with ^{210}Po again being the major dose contributor.

Dose rates to highly mobile organisms, such as fish (cod) from NORM (including the natural background) were estimated to be $(2\text{-}4.8)\cdot10^{-6}$ Gy day^{-1} (weighted by w_r) during 1991-1999. The major contributors to the exposure of cod were ^{40}K (natural background) and ^{210}Po, see Figure 14.

Summarizing the results of dose assessment, the conclusion can be made that at the beginning of the assessment period, the estimated radiological impact to marine biota from a big phosphate plant at Whitehaven was comparable with that from a large nuclear reprocessing plant at Sellafield; in recent years the additional dose rates to marine biota at Whitehaven (from NORM) were of the same order of magnitude as the natural background.

9.2 Offshore oil installations in the North Sea

The offshore oil industry in the North Sea has been faced with the problem of NORM since the early 1980s, when enhanced levels of naturally occurring radionuclides were found in the production systems of several oil fields of the North Sea.

The produced waters from oil reservoirs contain elevated levels of radioactivity, mainly ^{226}Ra, ^{228}Ra and their daughter products. The concentrations of the natural radionuclides ^{226}Ra and ^{228}Ra in produced water from individual platforms oil and gas production wells vary between less than 0.1 Bq L^{-1} to about 200 Bq L^{-1} Lysebo & Strand, 1997, 1998). The average concentration of the radionuclides ^{226}Ra and ^{228}Ra in produced water discharged from all oil and gas producing platforms and over all years is estimated at 10 Bq L^{-1} each.

These concentrations are approximately three orders of magnitude higher than the natural background concentrations of radium in seawater (IAEA, 1990).

Most of radioactivity from oil reservoirs is disposed with produced water into the sea. The amount of produced waters released per platform is estimated to be approximately $(3\text{-}4)\cdot 10^6$ m^3 $year^{-1}$. Solid sludge from offshore oil production also contains enhanced levels of NORM (^{226}Ra, ^{228}Ra, ^{210}Pb).

At present the experimental information on the radioactive contamination of seawater and marine biota in the vicinity of offshore oil platforms in the North Sea is not available for assessment. Calculations, using a model scenario of chronic releases, were made to predict the radium concentrations in seawater around oil platforms and estimate the potential dose loads to local marine biota.

The concentrations of Ra-isotopes in seawater in the vicinity of an oil platform were estimated using a simple hydrological model, representing the marine local zone around a platform as a single compartment of 1000x1000 m^2 size with a depth of the water mixing layer of 20 m, having a natural water exchange with the open sea of about 0.5-1 times per day. The man-made input of radioactivity into this local zone was calculated from the reference concentrations of Ra-isotopes in the produced waters and the annual amount of releases.

From model calculations, the additional radium concentrations in seawater of the local zone around an oil platform are expected to be within the range of 5-10 Bq m^{-3} for each of the radionuclides ^{226}Ra and ^{228}Ra (above local background). The uncertainties in model results depend on the discharges of radionuclides, and the local intensity of water exchange.

Average concentrations of Ra-isotopes in local marine biota living within the marine local zone around the oil platform, were calculated from these predicted concentrations in seawater using typical values of radium bioaccumulation factors in molluscs, crustaceans, and fish (IAEA, 1985). Based on these assumptions the internal dose rates from radium isotopes were estimated to be about $(3\text{-}7)\cdot 10^{-5}$ Gy day^{-1} (weighted by w_r) to molluscs, $(1.7\text{-}3.4)\cdot 10^{-5}$ Gy day^{-1} to fish, and $(3.4\text{-}6.8)\cdot 10^{-6}$ to shrimps.

The main source of external exposure to local marine biota is solid sludge with enhanced levels of NORM, which is accumulated on the seabed in the vicinity of an oil platform; however, there is no sufficient information for estimation of doses to biota from depositions on the seabed.

Model estimations of the radiation impact on marine biota in the vicinity of offshore oil installations in the North Sea demonstrate that the radiation exposure of marine biota in immediate proximity to oil platforms may be enhanced, especially in the local zones with slow water currents. More correct evaluation of this impact is a task for further investigation.

10 Comparison of the radiation exposure of marine biota in different locations of the OSPAR region

Figure 15 presents a scheme of the estimated dose rates to marine biota from activity at the selected locations within the OSPAR region, placed along the scale of radiation effects (chronic exposure) to organisms and populations. The scheme demonstrates the large differences in the exposure of marine biota in the selected sites within the OSPAR region, as well as a general improvement of the radioecological situation in the most impacted sites for the recent period (1991 to 1999).

None of estimated dose rates exceeded the lower boundary of the zone of radiation effects (see section 2 of this report) throughout the assessment period (1980s-1990s), see Figure 15 and Table 11; therefore no impact from radiation is expected for populations of marine biota.

11 Conclusions

1. An appropriate methodology has been identified for estimation of doses and radiation impact on marine biota in the OSPAR region.

2. Dose assessment has been performed for representative organisms, inhabiting selected industry-impacted locations within the OSPAR region, including: a) areas impacted by nuclear industry (Sellafield, Cap de la Hague, NPP in Sweden); b) areas impacted by non-nuclear industries (phosphate plant in UK; offshore oil installations in the North Sea); c) relatively ‘clean’ marine areas remote from industrial activity (Barents Sea). Dose assessment to marine biota was based on monitoring data of measurements of radionuclide concentrations in representative organisms, seawater and sediments for the periods from the early 1980s until the late 1990s.

4. It was found that during the assessment period, dose rates to representative marine organisms within the OSPAR region varied within a very broad range from about 10^{-9} Gy day^{-1} in the remote areas up to 10^{-4} Gy day^{-1} in the industry - impacted zones.

5. Among the marine zones affected by the nuclear industry the highest dose rates to marine biota were estimated for the coastal area impacted by BNFL Sellafield nuclear reprocessing plant.

   During the assessment period (1986-2001), the dose rates to marine biota in the vicinity of Sellafield were below the levels, where any deterministic effects of radiation could be expected in marine organisms from natural populations. A gradual decrease in dose rates to marine biota was observed in the Sellafield area during the assessment period.

6. Dose rates to marine biota in the Cap de la Hague coastal area of France were somewhat lower than those at Sellafield, with a gradual decrease throughout the assessment period 1982-1997.

7. Among the non-nuclear industry-impacted zones, the radiation exposure of marine biota during the assessment period 1991-1999, was estimated in the vicinity of the phosphate plant at Whitehaven (UK). At the beginning of the assessment period, the estimated radiological impact to marine biota from a big phosphate plant was found to be comparable with that from a large nuclear reprocessing plant at Sellafield. In the recent years the additional dose rates to marine biota at Whitehaven (from NORM) were of the same order of magnitude as the natural background due to changes in the production process.

8. Model estimations of the radiation impact on marine biota in the vicinity of offshore oil installations in the North Sea demonstrate, that the additional radiation exposure of marine biota in the immediate proximity to oil platforms may be enhanced, due to releases of produced waters with elevated levels of radium isotopes. More correct evaluation of this impact is a task for further investigation.

9. Estimated dose rates to marine biota in the vicinity of a nuclear power plant (Ringhals NPP in Sweden) were very low during the recent years (1997 to 2000), amounting to a minor addition to natural background.

10. Dose rates from artificial radionuclides in the remote marine areas of the OSPAR region (Barents Sea) are negligible compared with the natural background.

11. According to the available information**,** there is no identifiable impact on populations of marine biota from radioactive discharges.

The methodology for determining the impact of radioactivity on marine biota is still under development. In the future, the methodology of dose assessment to natural biota will be improved following the development of scientific knowledge on the dose-effect relationships in wildlife, and collection of more detailed information on content and radionuclide distribution within organisms.

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Table 1 Region-specific fish in the OSPAR marine region

Type of fish	Habitat	Representative species of fish in the OSPAR region	Recommended organism for dose assessment	Typical geometric size of adult organism, cm (ellipsoid)	Weight, g
Large fish	Predatory/ mixed feeding	Cod, blue whiting, hake, salmon, saithe	‘Cod’	50x10x6	1500
	Benthos-feeding	Haddock	‘Haddock’	50x10x6	1500
Medium-size fish	Pelagic, planktivorous	Herring, mackerel	‘Herring’	25x6x4	300
	Benthos-feeding	Plaice	‘Plaice’	25x20x3	800
Small fish	Pelagic, planktivorous	sardine/ pilchard or capelin (only for the northern part of the OSPAR region),	‘sardine’	15x3x1.5	30
Very small fish	Pelagic, planktivorous	Sprat or anchovy (only for the southern part of the OSPAR region)	‘Sprat’	7x1.5x0.9	5
Latin names of fish species: Anchovy – *Engraulis encrasicholus*; blue whiting – *Gadus poutassou*; capelin – *Mallotus villosus*; cod – *Gadus morhua*; hake – *Merluccius merluccius*; herring – *Clupea harengus*; mackerel – *Scomber scombrus;* pilchard/sardine - *Sardina pilchardus*; plaice - *Pleuronectes platessa*; saithe – *Pollachius virens;* salmon – *Salmo salar;* sprat – *Sprattus sprattus*					

Table 2 Information on environmental behaviour of the region-specific fish

Reference organism	Percentage of time, which fish spend close to bottom	Percentage of time, which fish spend in the water column
‘Cod’	30%	70%
‘Haddock’	70%	30%
‘Herring’	0%	100%
‘Plaice’	80%	20%
‘Sardine’	0%	100%
‘Sprat’	0%	100%

Table 3 Region-specific molluscs in the OSPAR marine region

Type of mollusc	Representative species of molluscs in the OSPAR region	Recommended organism for dose assessment	Typical geometric size of adult organism, cm (ellipsoid)	Weight, g
Bivalve mollusc	Mussels, cockles, scallops	'Mussel'	6x3x2.5 (total size)	5 (without shells)
Gastropoda mollusc	Winkles, limpets, whelks	'Winkle'	4x3x2	3 (without shells)
Latin names of mollusc species: Whelk - *Buccinum undatum;* mussel – *Mytilus edulis;* winkle – *Littorina littorea*; cockles - *Cerostoderma edule;* scallop – *Pecten maximus*				

Table 4 Region-specific large crustaceans in the OSPAR marine region

Representative species of crustaceans in the OSPAR region	Recommended reference organism	Typical geometric size of adult organism, cm (ellipsoid)	Weight, g
Crab, lobster	‘Crab’	10x10x5 (total size)	40 (without shell)
Shrimps	‘shrimp’	7x1.5x1.5	5 (without shell)
Latin names: Crab – *Cancer pagurus*; shrimp – *Pandalus borealis*; lobster -*Homarus gammarus*			

Table 5 Details of the reference organisms used in the previous dose assessments for marine biota

(Pentreath & Woodhead, 1988; IAEA, 1988)

Reference organism	Mass, g	Lengths of the axes of the representational ellipsoid, cm.	Environmental niche
Small crustacean	1.6×10^{-3}	0.6 x 0.3 x 0.2	Pelagic and benthic
Mollusc	1.0	2.5 x 1.2 x 0.6	Benthic
Large crustacean	2.0	3.1 x 1.6 x 0.8	Pelagic and benthic
Fish	1.0×10^{3}	45.0 x 9.0 x 5.0	Pelagic and benthic

Table 6 Typical concentrations of natural radionuclides in surface sea water, and marine organisms

(Woodhead, 1973a)

Radionuclide	Sea water, Bq m^{-3}	Crustaceans Bq kg^{-1}	Molluscs Bq kg^{-1}	Fish Bq kg^{-1}
^{3}H	22-110	0.02-0.1	0.02-0.1	0.02-0.1
^{14}C	7.4	22	18.5	15
^{40}K	12000	93	107	93
^{87}Rb	107	1.5	1.9	1
^{210}Po	0.2-1.6	15-60	15-41	0.02-5 (muscles); 7.4-33 (liver); 0.7-8 (bone)
^{210}Pb	0.4-2.5	1.5-2.6	0.2-0.4	0.007-0.09 (muscles); 0.4-0.9 (liver); 0.3-4.8 (bone)
^{226}Ra	1.5-1.7			0.007-0.2 (flesh)
^{234}U	48			0.003-1.3
^{238}U	44			0.0025-1.1

Table 7 **Summary of dose rates (Gy day^{-1}, weighted by w_r) to marine organisms from natural environmental radioactivity**

(compiled from IAEA, 1976; Woodhead, 1984, 1998)

Source	Molluscs (5 m depth, on the sea bed)	Crustaceans (10 m depth, on the sea bed)	Fish	
			(20 m depth, remote from sea bed)	(20 m depth, on the sea bed)
NATURAL BACKGROUND				
Cosmic radiation (low LET radiation only)	$3.8 \cdot 10^{-7}$	$2.6 \cdot 10^{-7}$	$1.2 \cdot 10^{-7}$	$1.2 \cdot 10^{-7}$
External radionuclides	$(3.6\text{-}38.4) \cdot 10^{-7}$	$(3.6\text{-}38.4) \cdot 10^{-7}$	$2.4 \cdot 10^{-8}$	$(3.6\text{-}38.4) \cdot 10^{-7}$
Internal radionuclides	$(1.9\text{-}7.8) \cdot 10^{-5}$	$(1.2\text{-}34) \cdot 10^{-5}$	$(1.1\text{-}13) \cdot 10^{-6}$	$(1.1\text{-}13) \cdot 10^{-6}$
TOTAL	$(1.9\text{-}7.8) \cdot 10^{-5}$	$(1.2\text{-}34) \cdot 10^{-5}$	$(1.2\text{-}13) \cdot 10^{-6}$	$(1.6\text{-}16.8) \cdot 10^{-6}$

Table 8 Current levels of artificial radionuclides in sea water and commercial species of marine biota in the Barents Sea (1995 to 1999)

Radionuclide	Sea water, Bq m^{-3}	Fish(cod, saithe, haddock, redfish), Bq kg^{-1} fresh weight	Crustaceans (shrimps, crabs, lobsters), Bq kg^{-1}	Molluscs (sea scallops, mussels), Bq kg^{-1}
^{137}Cs	3-6	0.3 (0.2-0.5)	0.2 (0.1-0.4)	0.4(0.2-0.7)
^{90}Sr	3-4	0.02(0.004-0.03) (muscles); 0.1-0.5 (bones)	0.03 (shrimp meat); 0.05(0.03-0.06) (shell)	
$^{239,240}Pu$	$(4\text{-}10)\cdot 10^{-3}$	$(0.6\text{-}2)\ 10^{-3}$	0.0003 (flesh); <0.3 (shell)	0.0008 (flesh); <0.05 (shell)
^{99}Tc	0.1-1.5	-	0.25-0.7 (crabs, shrimps); 0.2-26 (lobsters)	0.5-0.7

Table 9 Dose rates to marine biota due to artificial radionuclides in the remote zone of the OSPAR region: Barents Sea (1997 to 1999)

Organism	Dose rate from artificial radionuclides, Gy day^{-1} (weighted by w_r)
Fish (cod)	$(2\text{-}3)\cdot10^{-9}$
Mollusc (mussel)	$(3\text{-}4)\cdot10^{-9}$
Crustacean (crab)	$(8\text{-}9)\cdot10^{-9}$

Table 10 General information on data from the Nord-Contentin database, which were used for dose assessments to biota in the Cap de la Hague coastal area (France): monitoring sites, type of samples, and radionuclides measured by different organizations

Type of sampling materials	Monitoring site in the vicinity of Cap de la Hague area	Radionuclides measured	Organization in France conducted radionuclide analyses
Water	Cap de la Hague	^{137}Cs, ^{134}Cs, ^{125}Sb, ^{106}Ru	GEA
Water	Flamanville	^{60}Co	GEA
Water	Goury	^{90}Sr, ^{99}Tc	GEA
Water	Moulinets	$^{239,240}Pu$, ^{238}Pu	OFRI
Sediments	Moulinets	^{137}Cs, ^{90}Sr	COGEMA
Sediments	Moulinets	$^{239,240}Pu$, ^{238}Pu	OPRI
Fish (*Gadus luscus*)	Les Huquets	^{137}Cs, ^{65}Zn, ^{110m}Ag	GEA
Fish (*Gadus luscus*)	Moulinets	^{106}Ru, ^{60}Co	OPRI
Mollusc (*Mytilus edulis)*	Barfleur	^{137}Cs, ^{106}Ru, ^{60}Co, ^{125}Sb	LEFRA
Mollusc Patella (limpet, Gastropoda)	Moulinets	^{137}Cs, ^{106}Ru, ^{60}Co, ^{125}Sb, $^{239,240}Pu$, ^{238}Pu, ^{241}Am	COGEMA
Crustacean (*Cancer pagurus*), entire	Huquets	^{137}Cs, ^{106}Ru, ^{60}Co, ^{125}Sb, ^{110m}Ag, ^{65}Zn, ^{54}Mn	GEA

Table 11 Summary of recent dose rates to marine biota at different locations within the OSPAR region, Gy day^{-1} (weighted by w_r)

Local area	Type of organism		
	Molluscs	Crustaceans	Fish
Sellafield	$4 \cdot 10^{-5}$	$4 \cdot 10^{-6}$	$3 \cdot 10^{-7}$
Cap de la Hague*	10^{-7} (mussel); $6 \cdot 10^{-7}$(mollusc Patella)	$2 \cdot 10^{-7}$	$2 \cdot 10^{-8}$
Whitehaven (phosphate plant)**	$2 \cdot 10^{-5}$	$1 \cdot 10^{-5}$	$1 \cdot 10^{-6}$
Ringhals NPP*** (Sweden)	$3 \cdot 10^{-8}$	$7 \cdot 10^{-8}$	$1.4 \cdot 10^{-8}$
Barents Sea (remote area)	$(3\text{-}4) \cdot 10^{-9}$	$(8\text{-}9) \cdot 10^{-9}$	$(2\text{-}3) \cdot 10^{-9}$
Natural radiation background (world data)	$(1.9\text{-}7.8) \cdot 10^{-5}$	$(1.2\text{-}34) \cdot 10^{-5}$	$(1.2\text{-}13) \cdot 10^{-6}$
Local radiation background (Cumbrian waters, UK)	$(2.5\text{-}3) \cdot 10^{-5}$	$(2.5\text{-}3) \cdot 10^{-5}$	10^{-6}

* Dose rates to mussels, crustaceans and fish are given without input from alpha-emitters; dose rate to Patella mollusc includes the contribution from alpha-emitters.

** Dose rates to biota at Whitehaven represent the additional exposure above the local background radiation

*** Dose rates to biota in the vicinity of the Ringhals NPP represent upper estimates based on the highest concentrations of radionuclides in assessed species found for each year.

Figure 1 **Scheme of the Sellafield coastal area in the vicinity of nuclear reprocessing plant operated by BNFL**

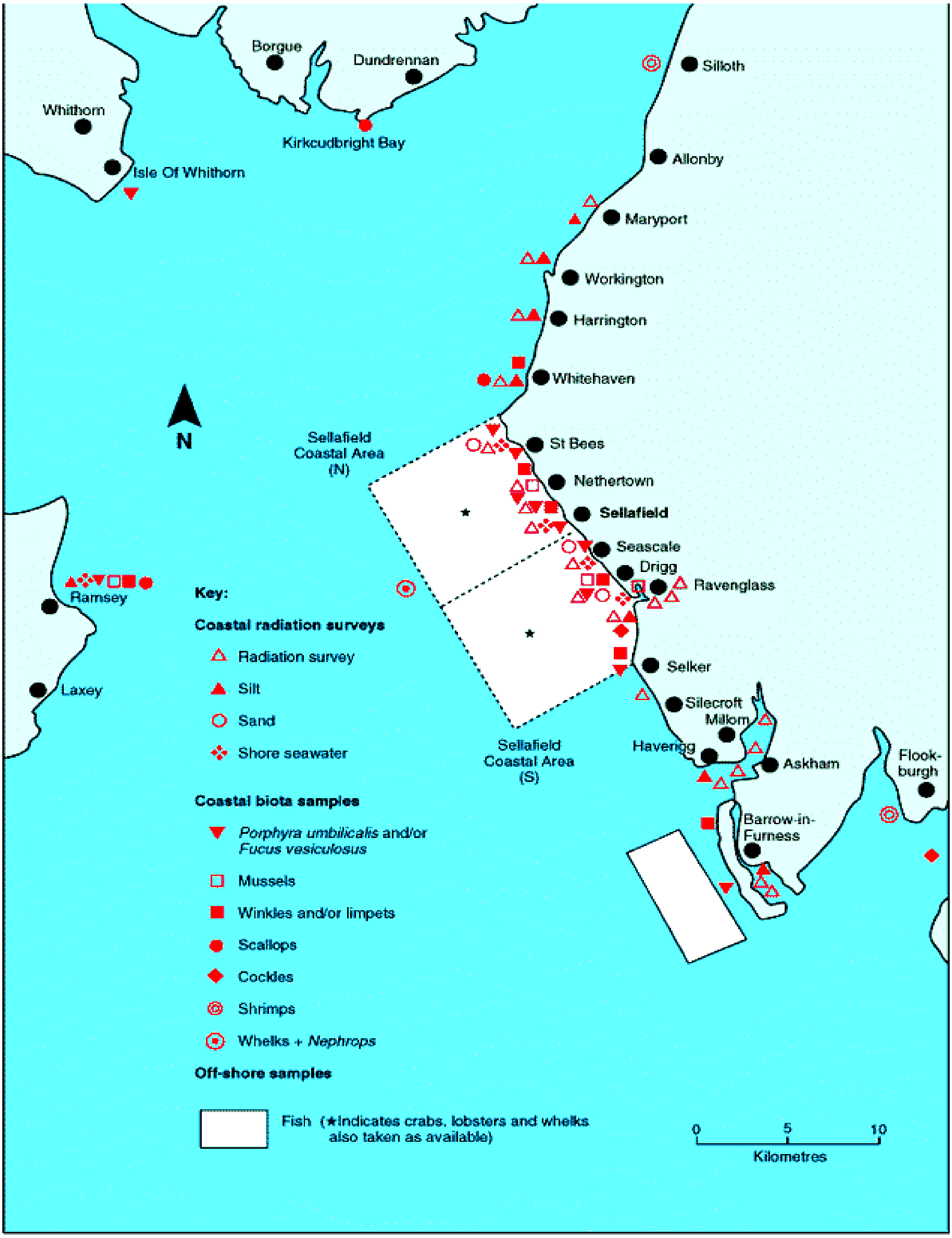


Figure 2 **Dose rates (Gy day^{-1}, weighted by w_r) to marine biota in the Sellafield coastal area (Cumbrian waters, UK) – Artificial radionuclides**

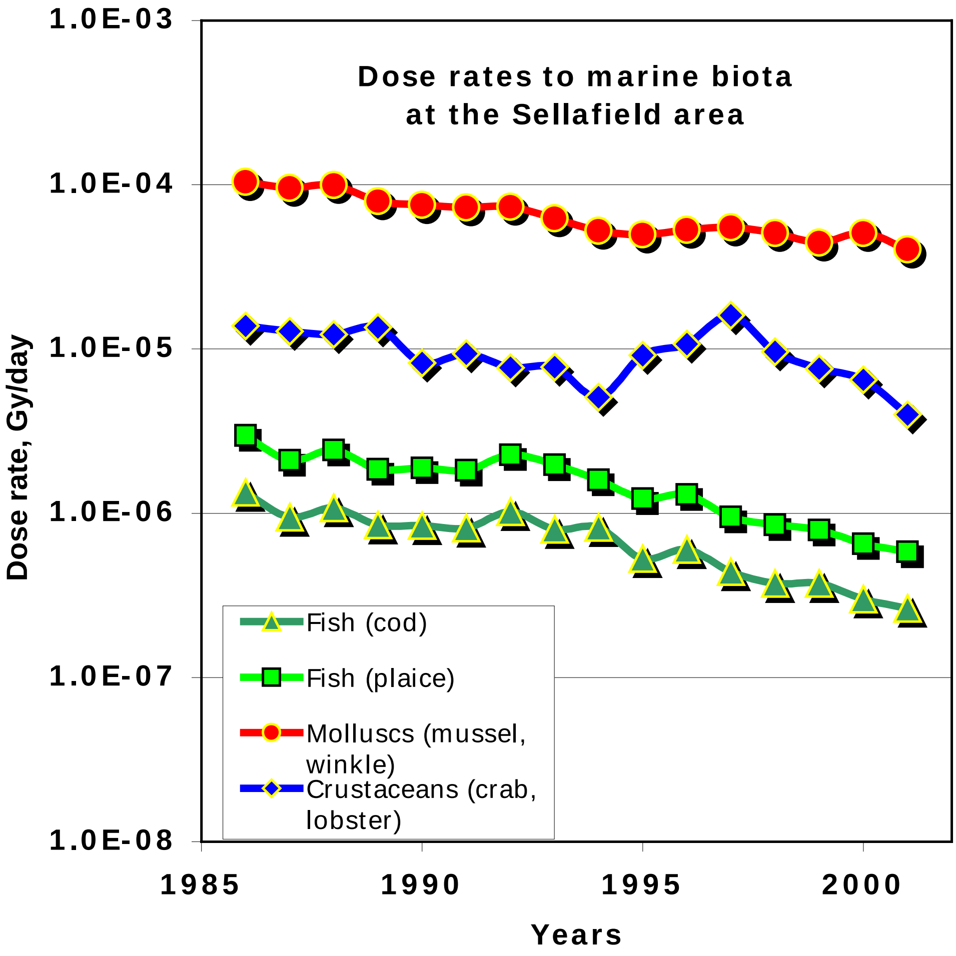
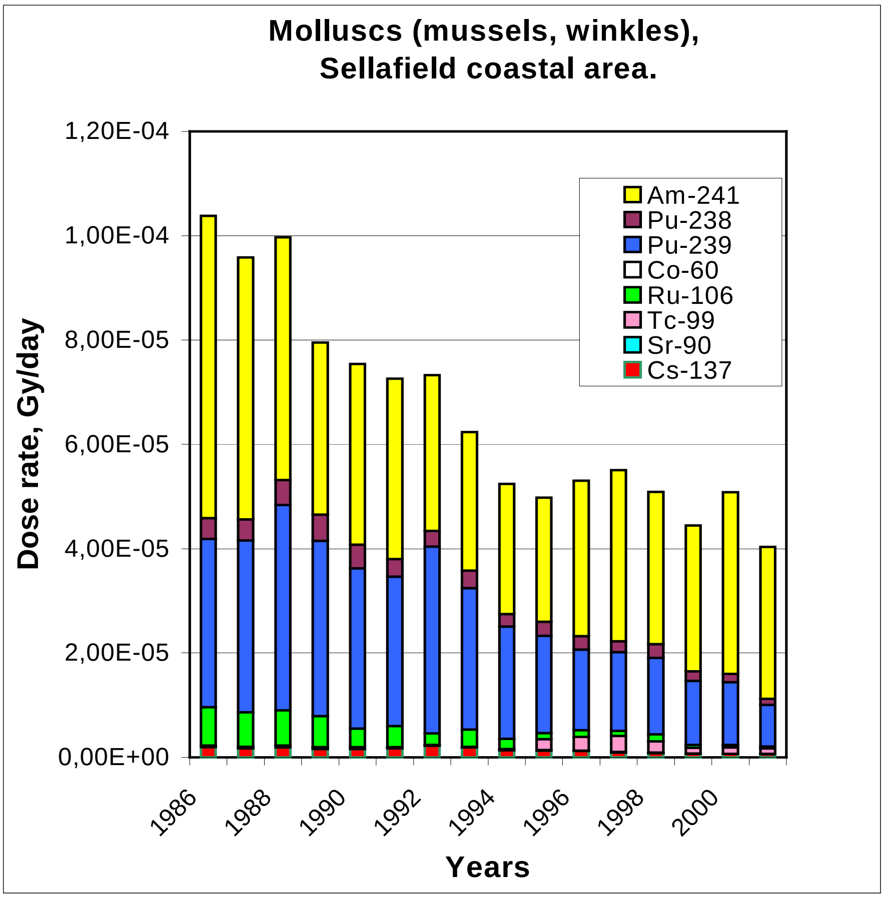


Figure 3 Dose rates (Gy day^{-1}, weighted by w_r) to molluscs, Sellafield coastal area, UK. Dynamics of the input of different radionuclides for the period 1985 to 2001, detailed figure for the year 1999



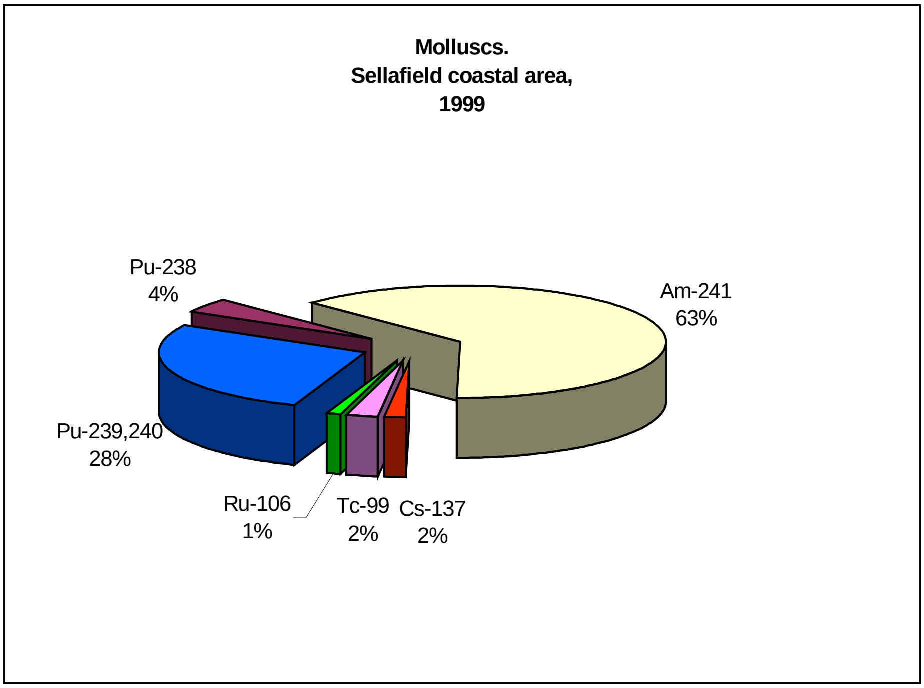
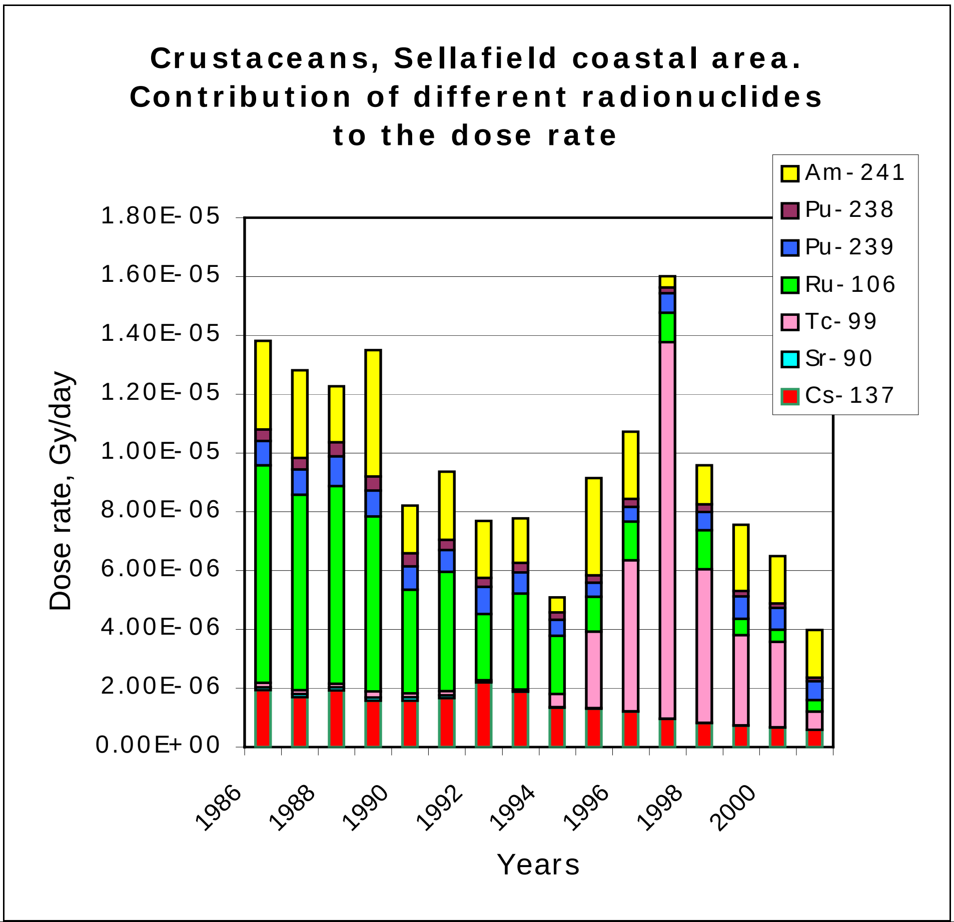


Figure 4 **Dose rates (Gy day^{-1}, weighted by w_r) to large crustaceans (crabs, lobsters), Sellafield coastal area, UK. Dynamics of the input of different radionuclides for the period 1985 to 2001, detailed figure for the year 1999**



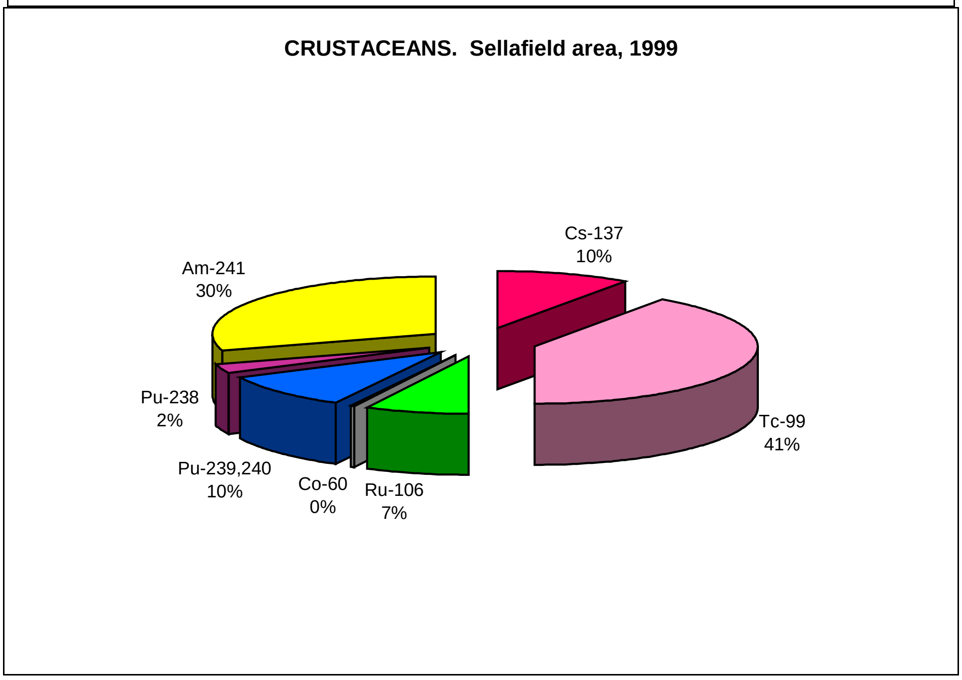
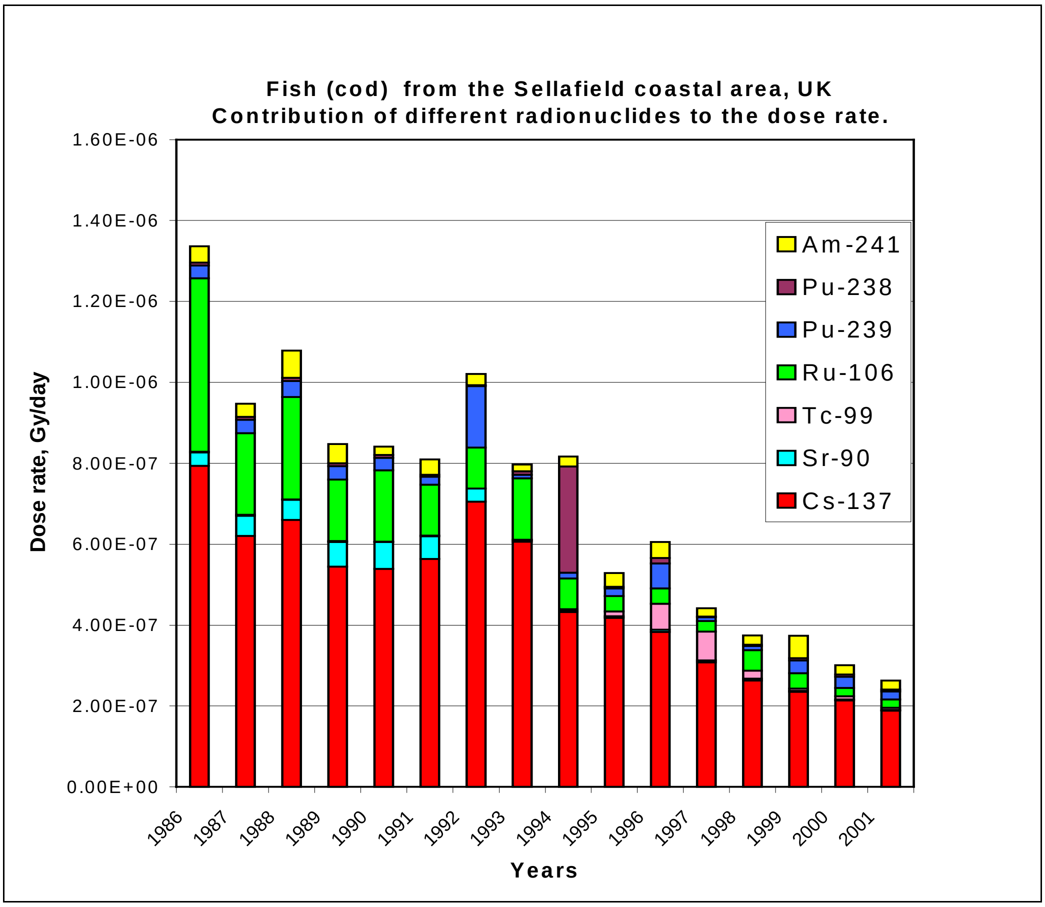


Figure 5 **Dose rates (Gy day^{-1}, weighted by w_r) to fish (cod). Sellafield coastal area, UK. Dynamics of radionuclides contribution in dose rates for the period 1985 to 2001, detailed figure for the year 1999**



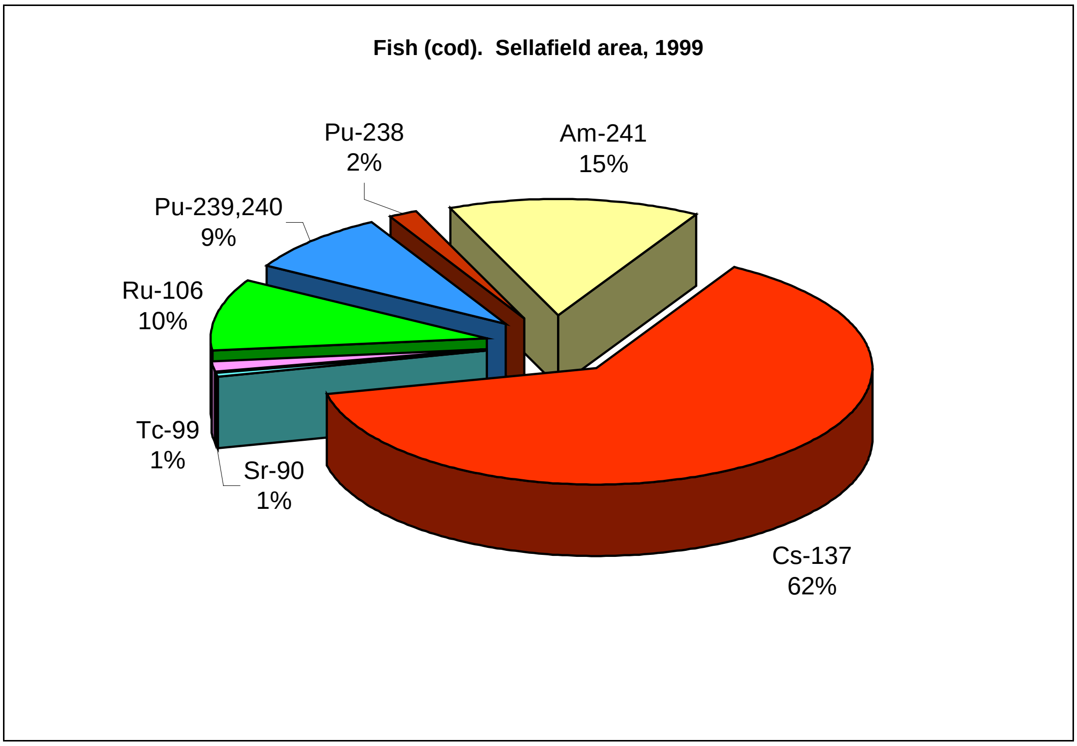


Figure 6 **Lower and upper boundaries of uncertainty in dose assessment for fish (cod). Sellafield coastal area**

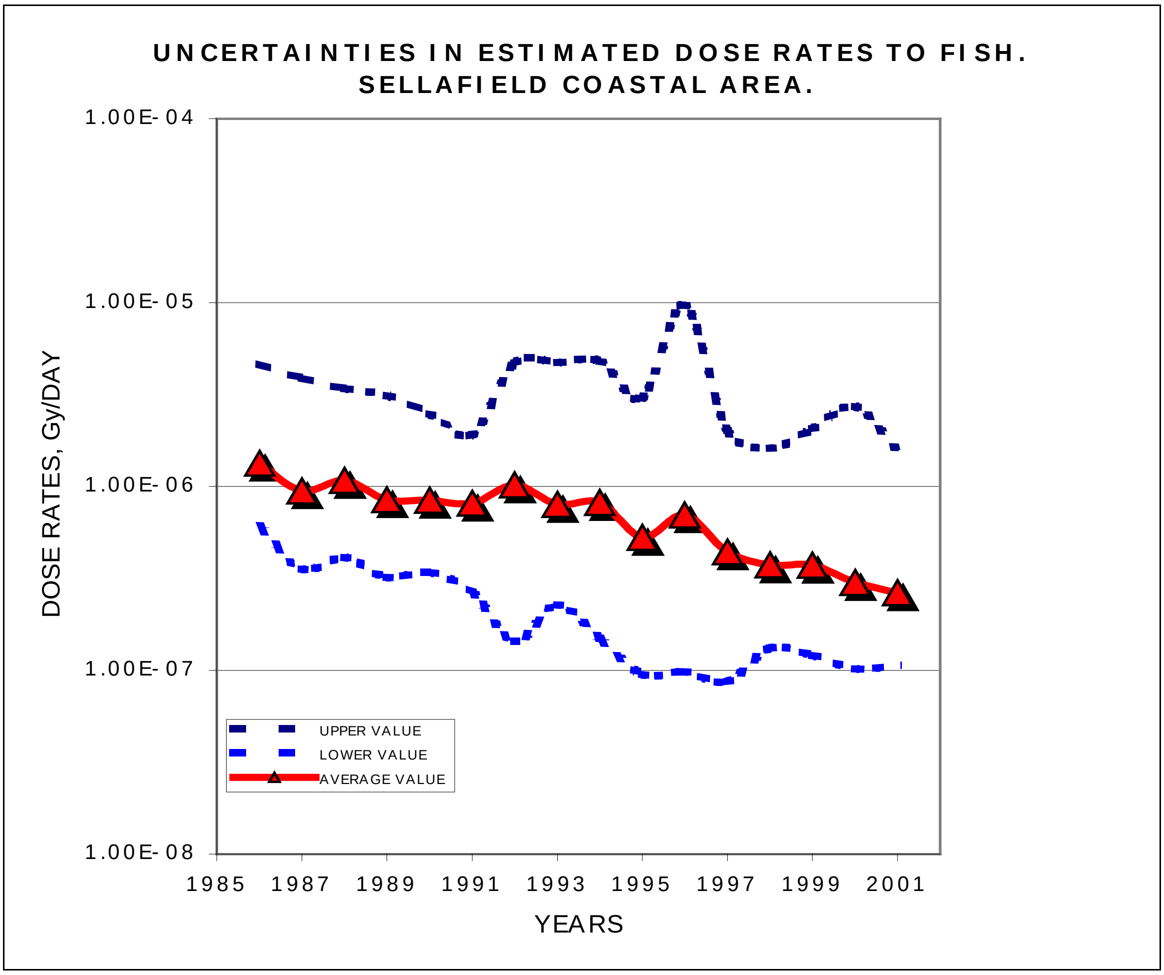


Figure 7 **Scheme of the Cap de la Hague area (France) with indication of the monitoring sites (from Nord-Cotentin database)**

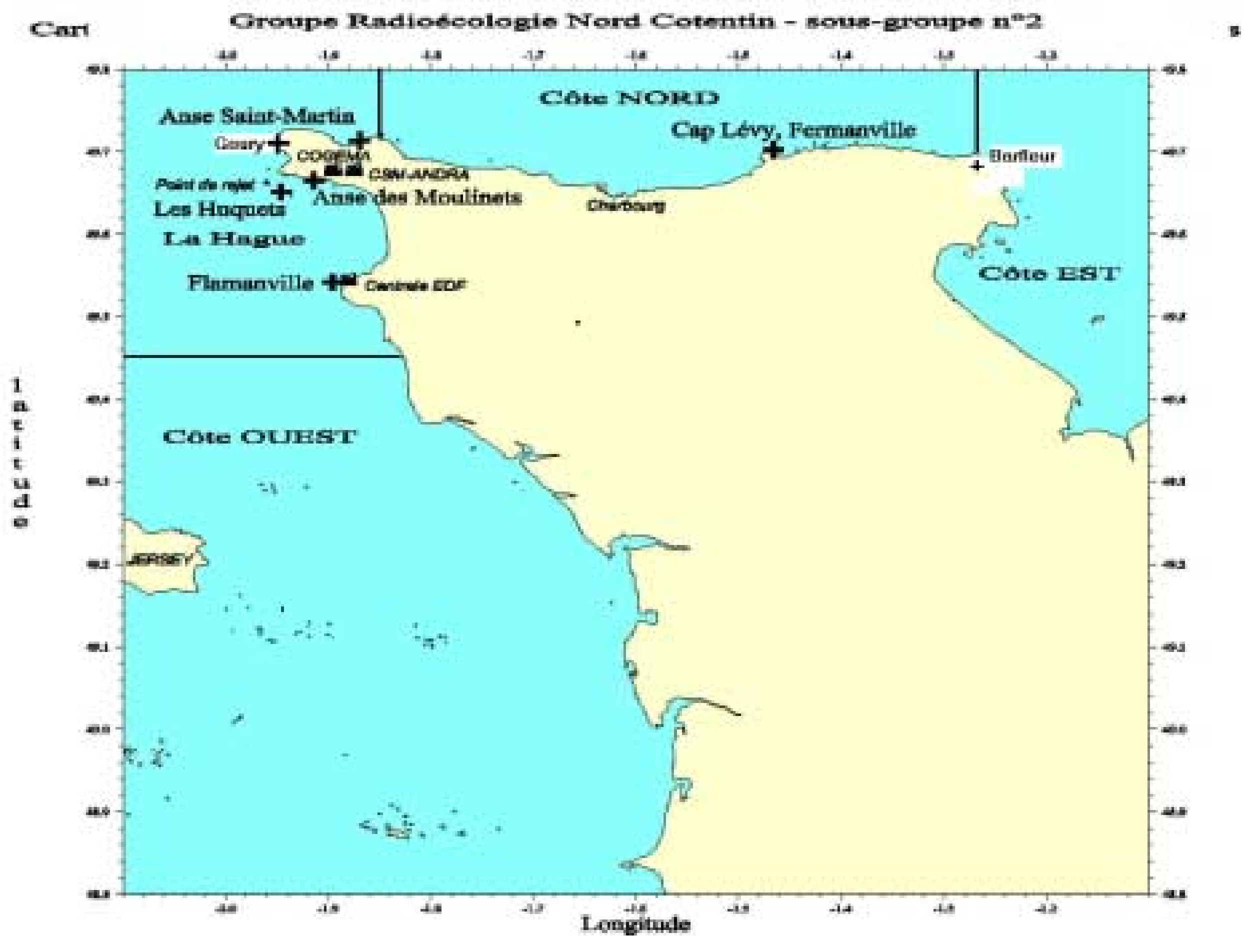


Figure 8 Dose rates (Gy day^{-1}) to marine biota at the Cap de la Hague coastal area (France). Artificial radionuclides. *Data on alpha-emitters were available only for Patella molluscs (limpets)

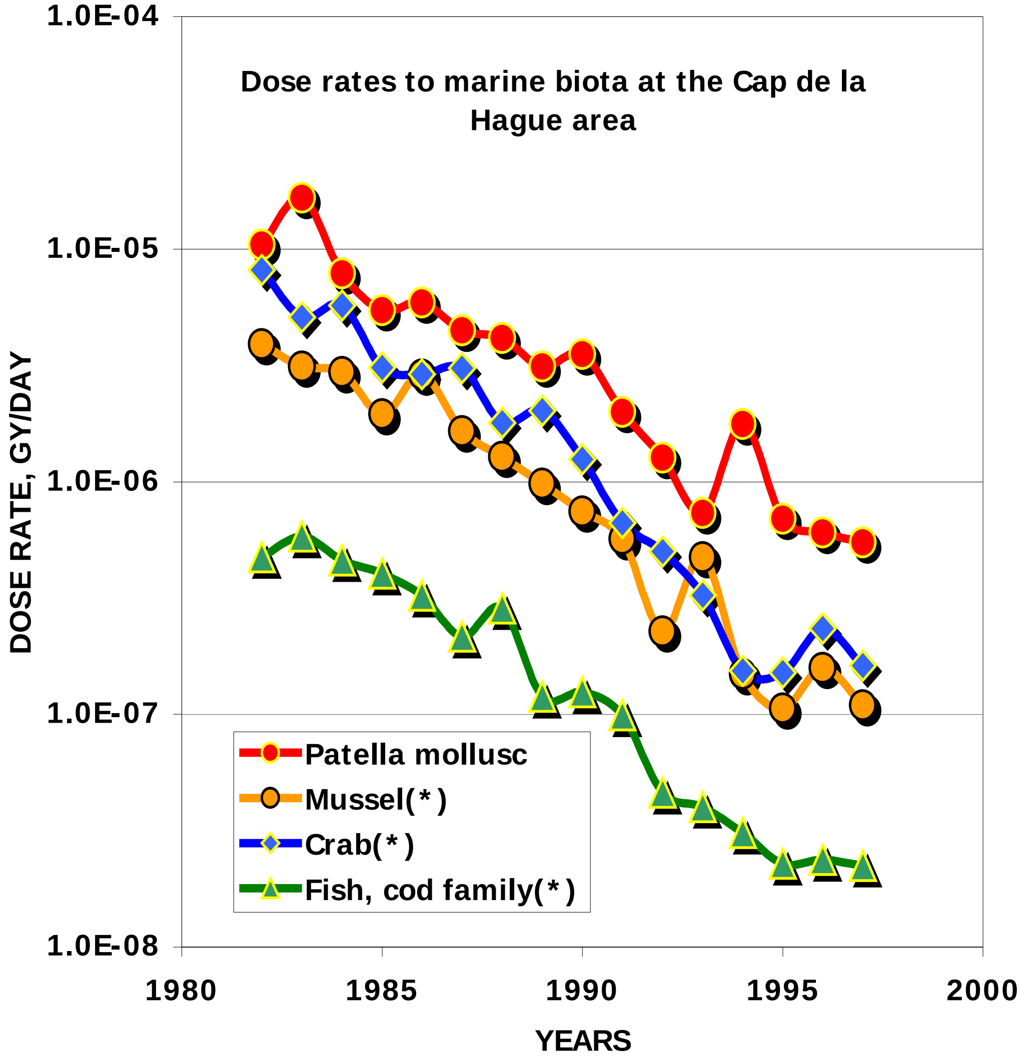
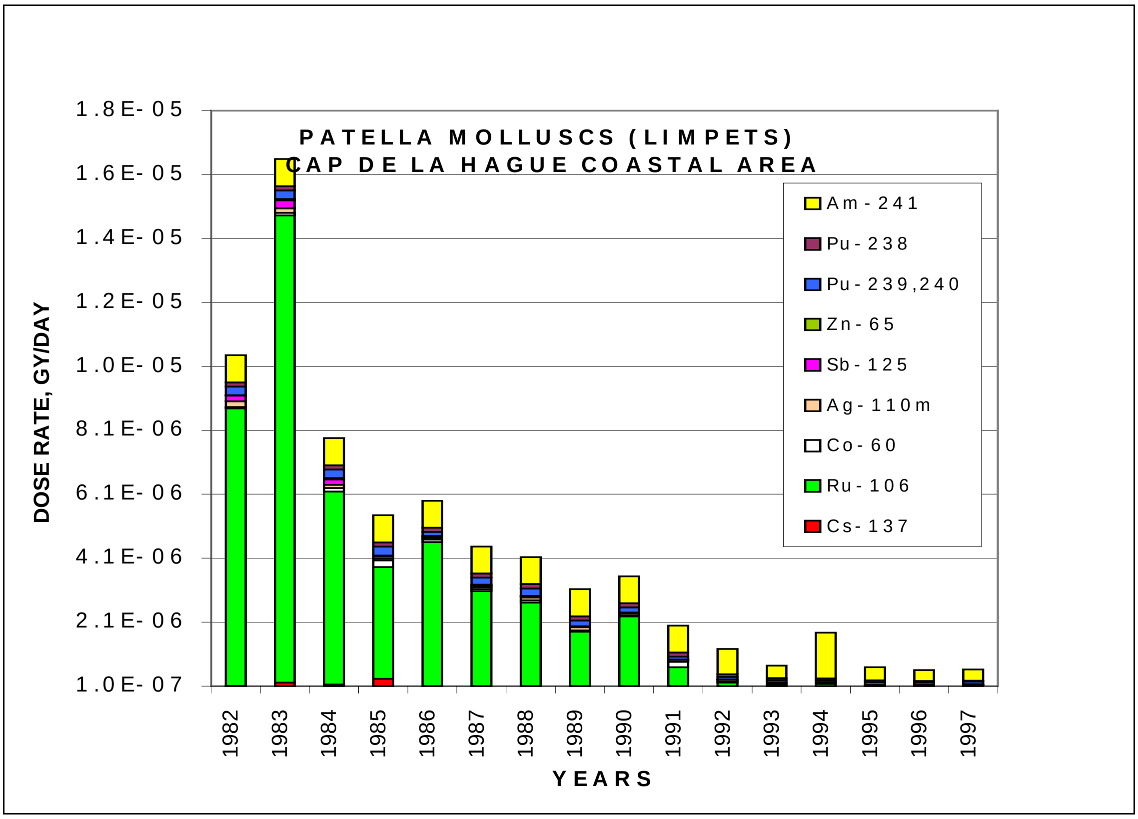


Figure 9 **Dose rates (Gy day^{-1}, weighted by w_r) to Patella molluscs (limpets), Cap de la Hague coastal area (France). Dynamics of the input of different radionuclides for the period 1982 to 1997, detailed figure for the year 1996**



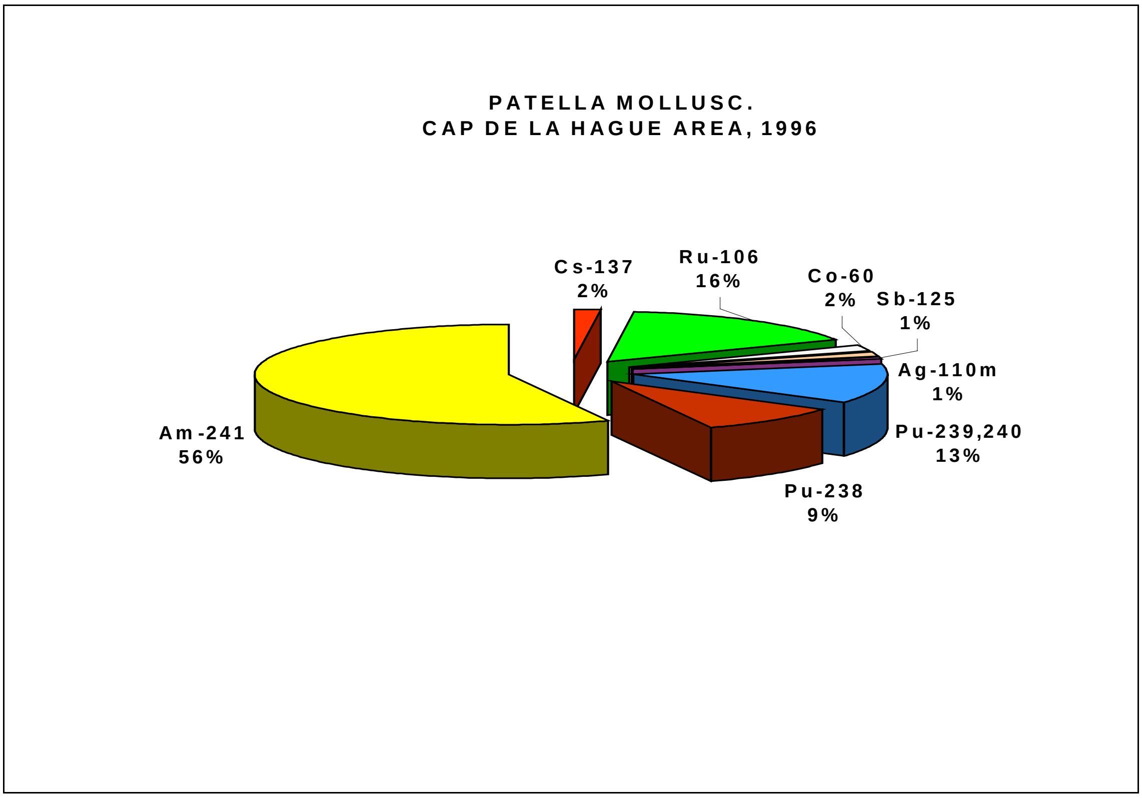
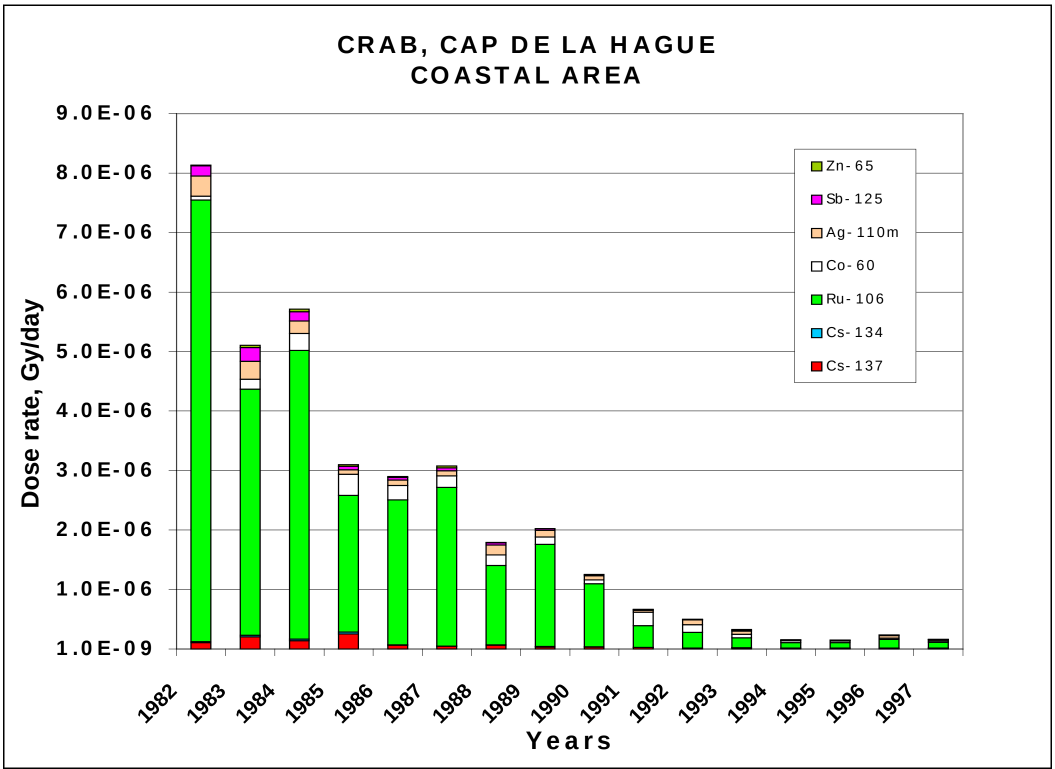


Figure 10 **Dose rates (Gy day^{-1}) to crab, Cap de la Hague coastal area (France). Dynamics of the input of different radionuclides for the period from 1982 to 1997, detailed figure for the year 1996; data on alpha emitters were not available**



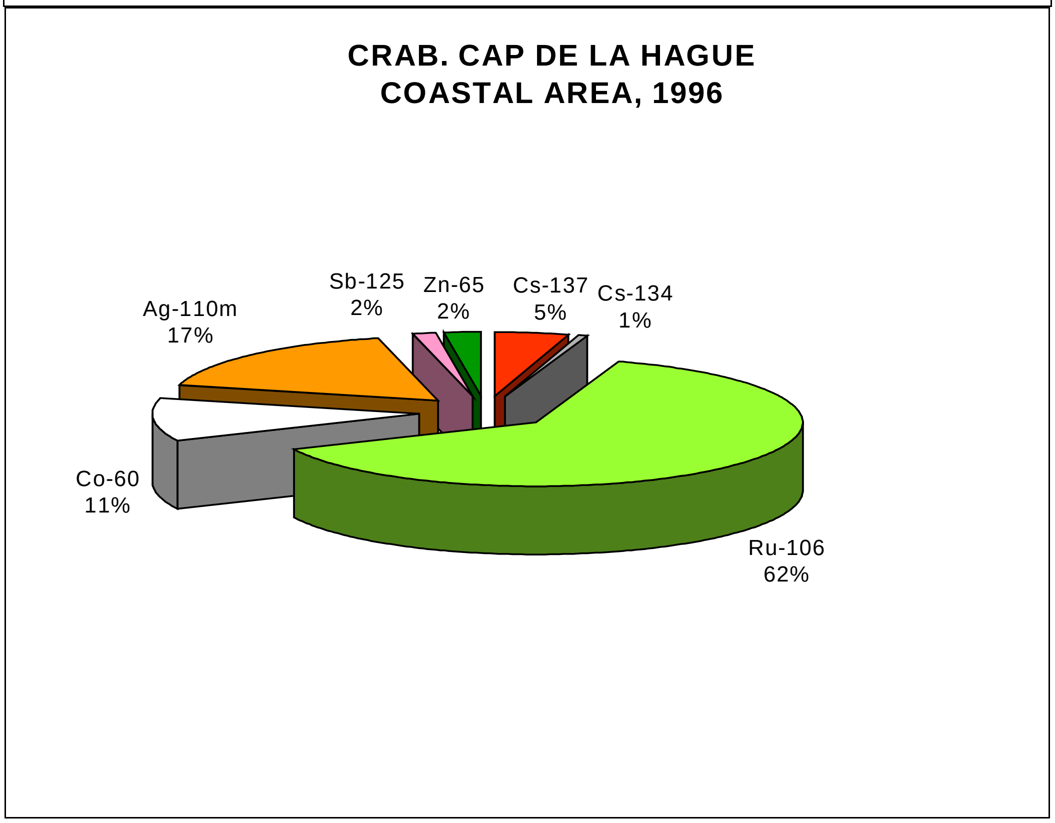
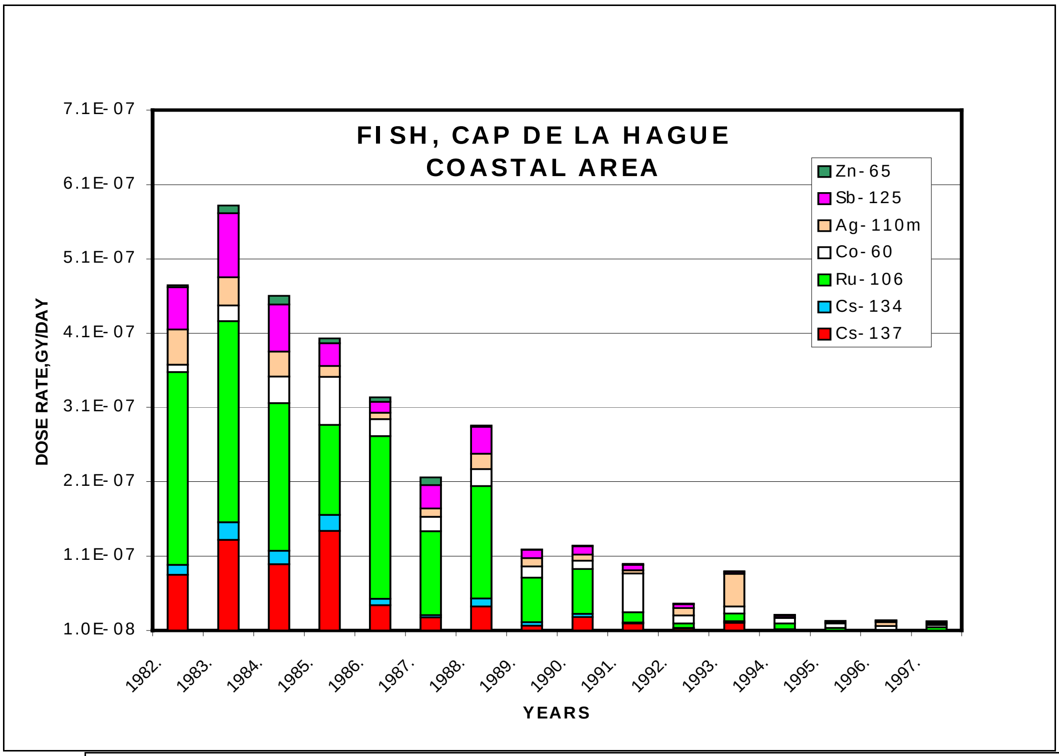


Figure 11 **Dose rate (Gy day^{-1}) to fish (*Gadus luscus*), Cap de la Hague coastal area (France). Dynamics of the input of different radionuclides for the period 1982 to 1997; detailed figure for the year 1996; data on alpha emitters in fish were not available**



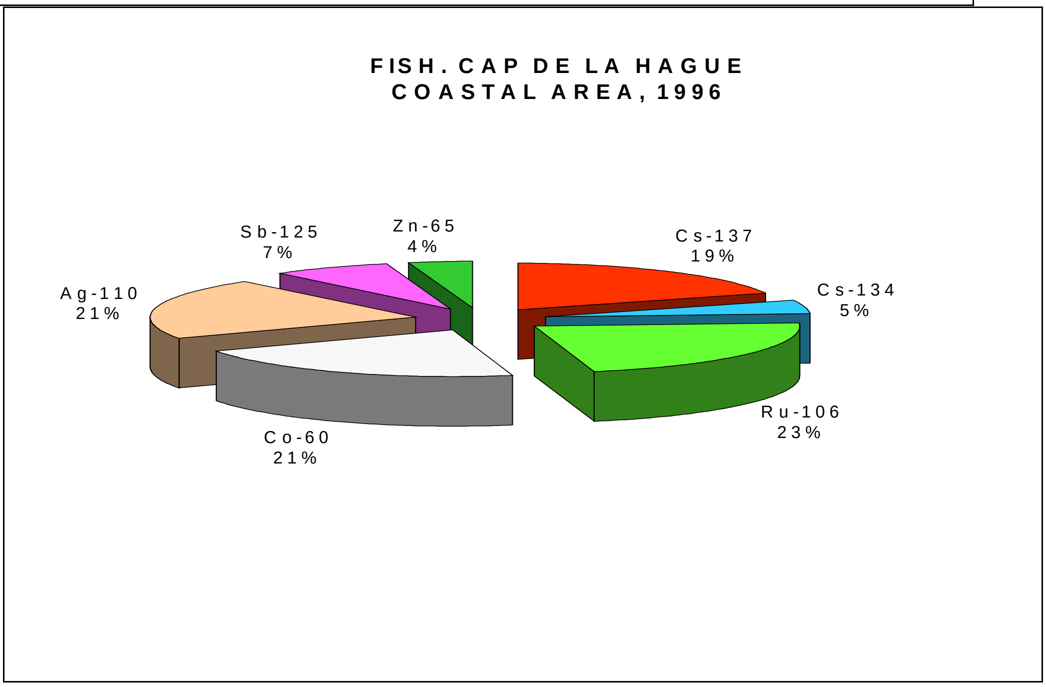


Figure 12　　Scheme of the coastal area in the vicinity of phosphate plant at Whitehaven, UK

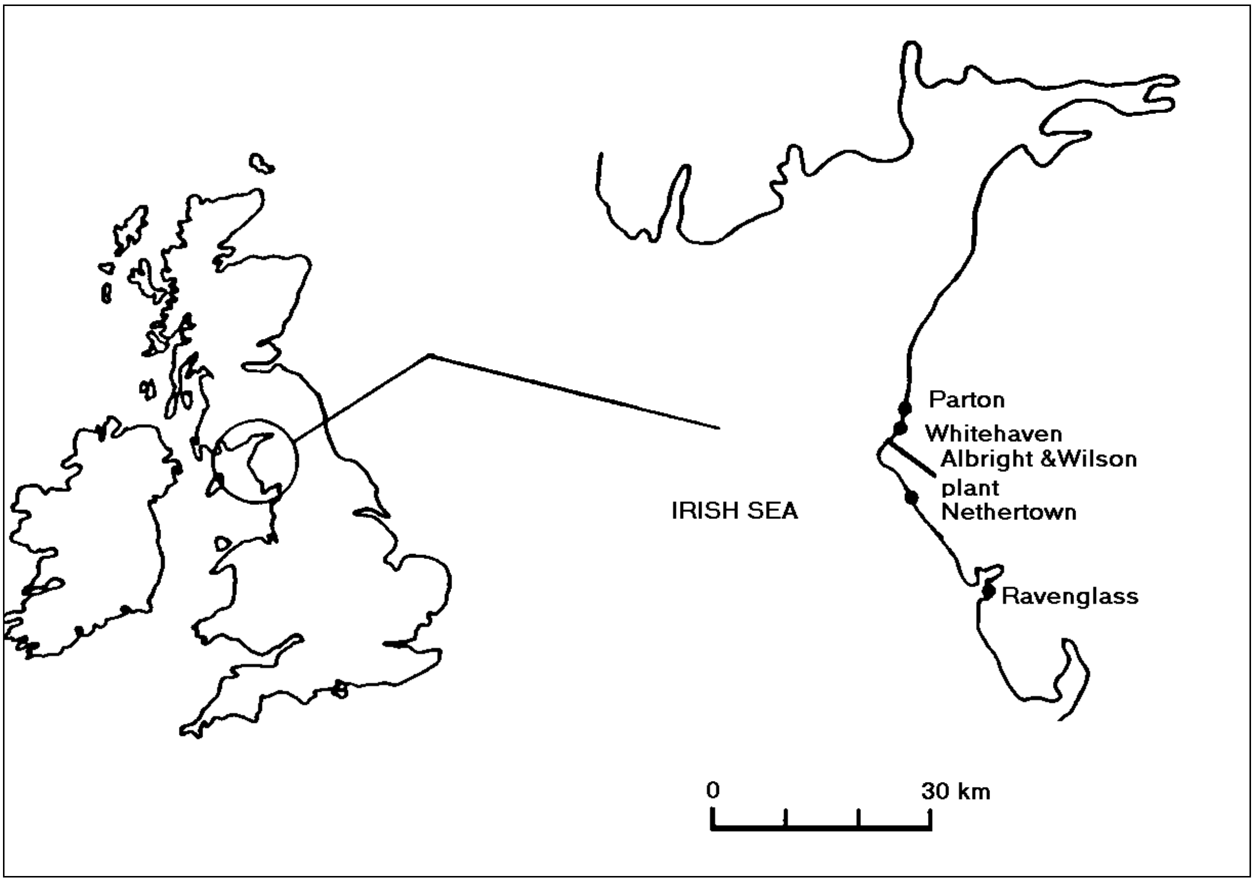


Figure 13 **Dose rates (Gy day^{-1}, weighted by w_r) to marine biota from NORM in the vicinity of phosphate plant at Whitehaven; including natural background exposure from NORM. Monitoring site Parton (5 km to the north from the plant). Cumbria waters, UK**

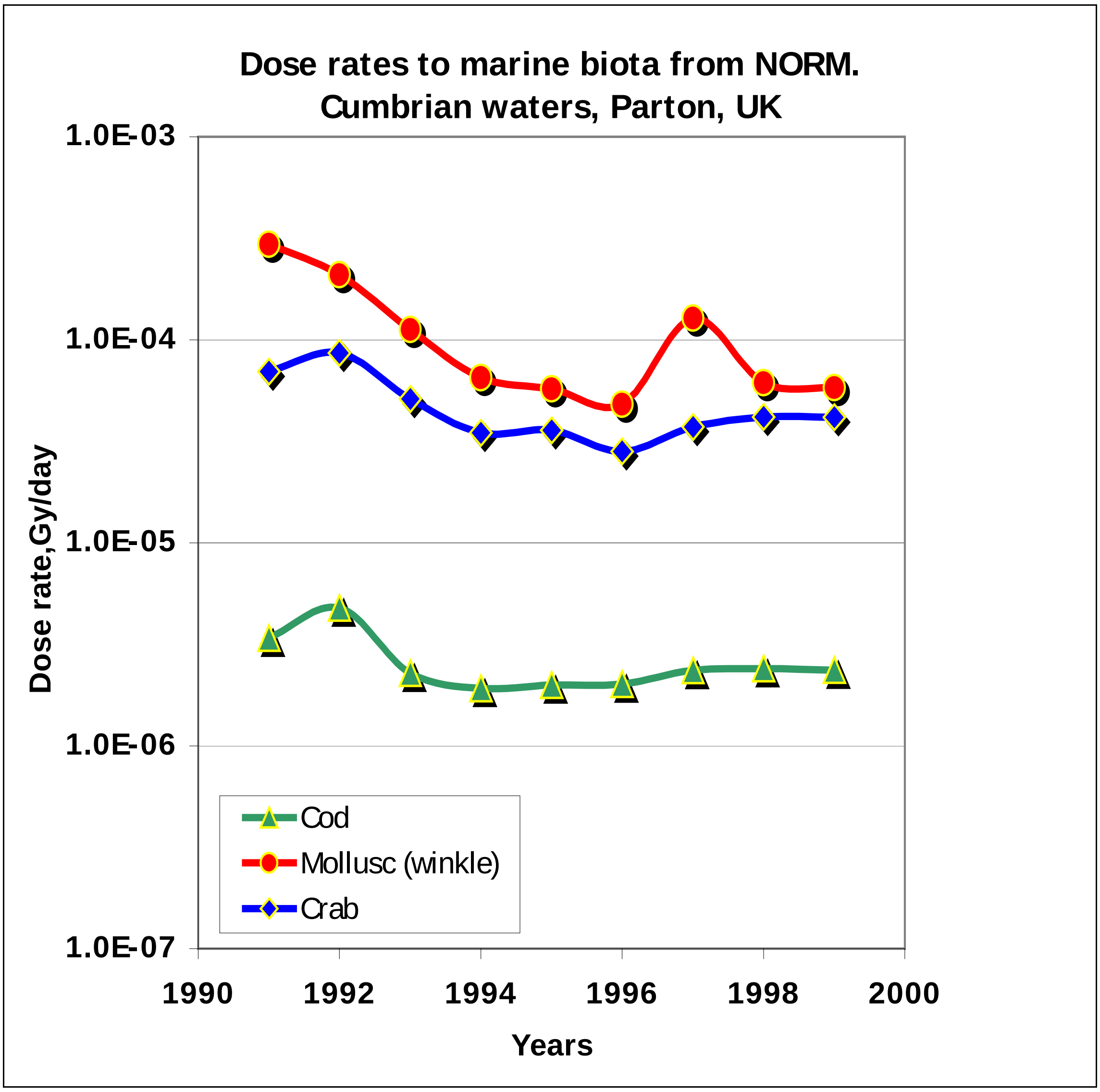
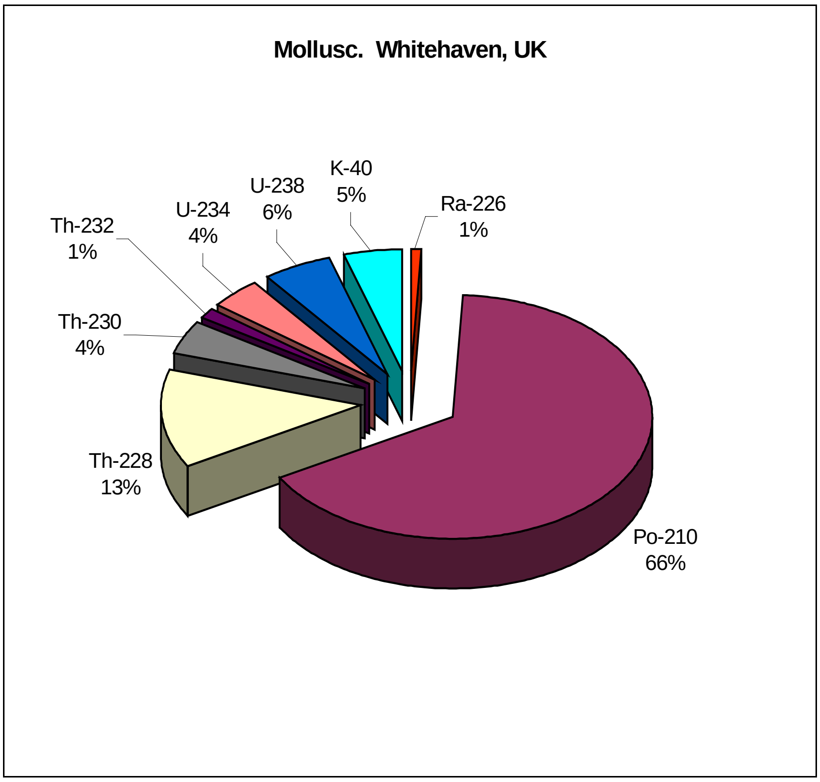
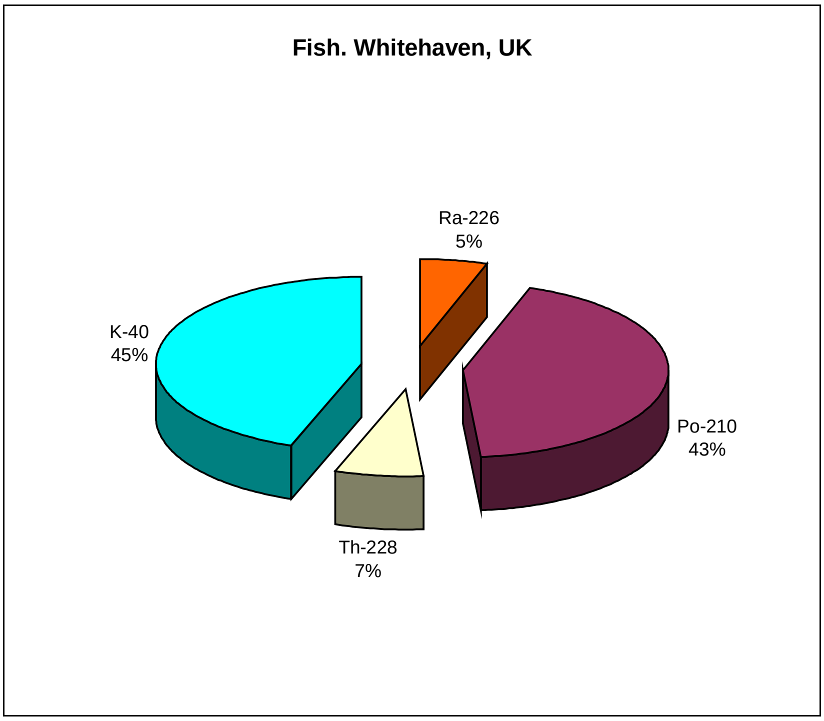


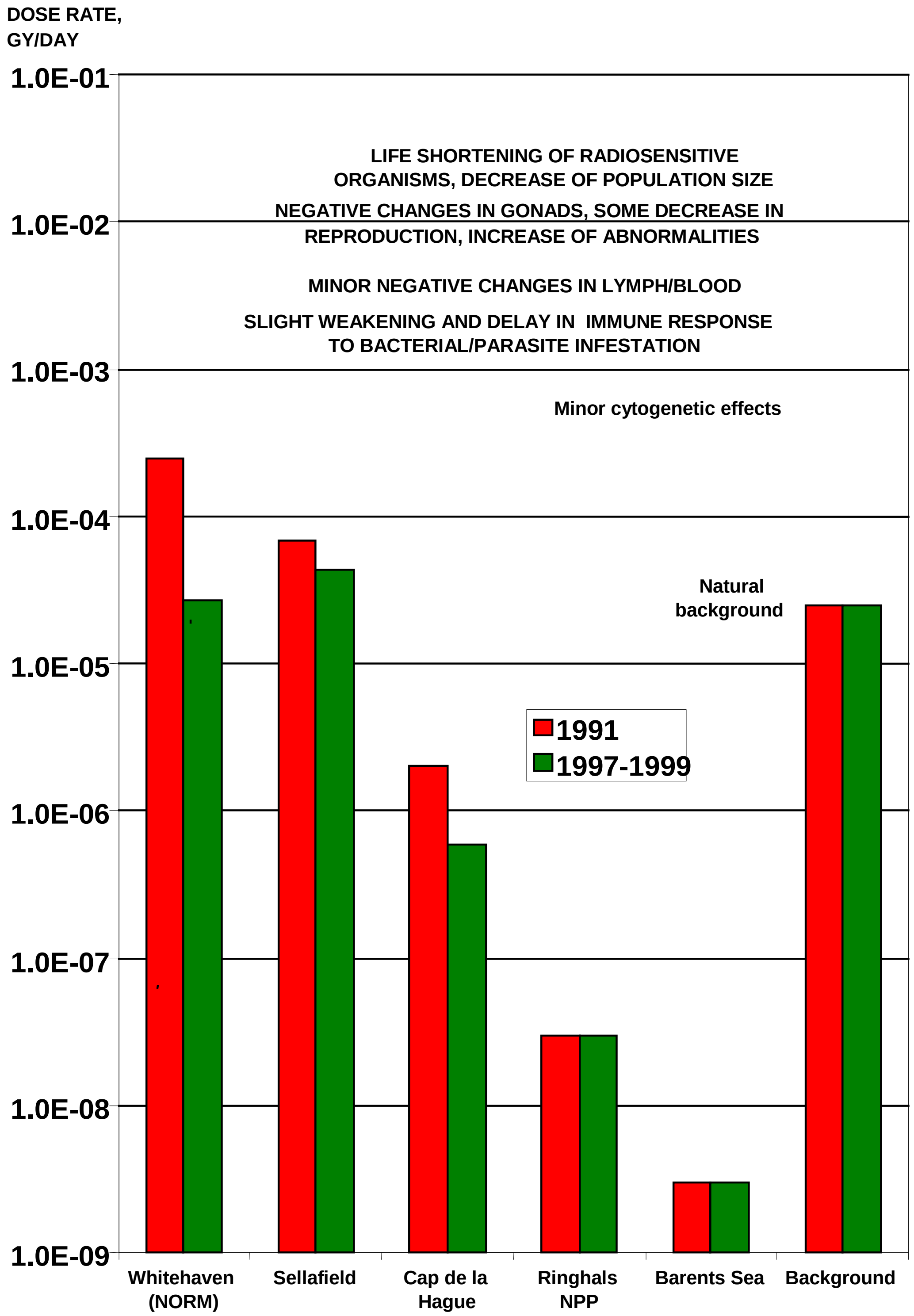
Figure 14 **Contribution of radionuclides (NORM) to the dose rate to mollusc (winkle) and fish in the vicinity of phosphate plant at Whitehaven (1998). Monitoring site Parton (5 km to the north of the plant). Cumbrian waters, UK.**





Note: Dose from K-40 is attributable to presence of this radionuclide in ‘natural’ sea water.

Figure 15 Dose rates (above natural background) to molluscs in the OSPAR region along the scale of radiation effects to aquatic biota.



Note: presented are annual average values of dose rates to molluscs at different locations of the OSPAR region; values for molluscs near Ringhals NPP are upper estimates of dose rates.

Appendix A - Dose conversion factors for marine biota in the North-East Atlantic

Organism	Radionuclide	Internal dose rate, (Gy day^{-1}) per Bq kg^{-1} wet weight	External dose rate from water, (Gy day^{-1}) per Bq L^{-1}	External dose rate from sediments, (Gy day^{-1}) per Bq kg^{-1} sediments, w.w.
cod	K-40	6.34E-09	1.97E-09	3.24E-10
haddock	K-40	6.34E-09	1.97E-09	7.55E-10
herring	K-40	6.27E-09	2.04E-09	0.00E+00
plaice	K-40	6.33E-09	1.99E-09	8.63E-10
sardine	K-40	6.21E-09	2.09E-09	0.00E+00
sprat	K-40	6.18E-09	2.12E-09	0.00E+00
mussel	K-40	6.16E-09	2.14E-09	1.08E-09
crab	K-40	6.29E-09	2.02E-09	1.08E-09
shrimp	K-40	6.18E-09	2.13E-09	0.00E+00
seal	K-40	6.97E-09	1.40E-09	0.00E+00
gull	K-40	6.32E-09	0.00E+00	0.00E+00
winkle	K-40	6.17E-09	2.13E-09	1.08E-09
cod	Co-60	4.64E-09	3.15E-08	5.18E-09
haddock	Co-60	4.64E-09	3.15E-08	1.21E-08
herring	Co-60	3.39E-09	3.27E-08	0.00E+00
plaice	Co-60	4.41E-09	3.17E-08	1.38E-08
sardine	Co-60	2.52E-09	3.35E-08	0.00E+00
sprat	Co-60	1.93E-09	3.40E-08	0.00E+00
mussel	Co-60	1.65E-09	3.43E-08	1.73E-08
crab	Co-60	3.84E-09	3.23E-08	1.73E-08
shrimp	Co-60	1.89E-09	3.40E-08	0.00E+00
seal	Co-60	1.51E-08	2.19E-08	0.00E+00
gull	Co-60	4.37E-09	0.00E+00	0.00E+00
winkle	Co-60	1.85E-09	3.41E-08	1.73E-08
cod	Zn-65	8.82E-10	7.27E-09	1.20E-09
haddock	Zn-65	8.82E-10	7.27E-09	2.80E-09
herring	Zn-65	5.84E-10	7.54E-09	0.00E+00
plaice	Zn-65	8.29E-10	7.32E-09	3.20E-09
sardine	Zn-65	3.79E-10	7.73E-09	0.00E+00
sprat	Zn-65	2.37E-10	7.86E-09	0.00E+00
mussel	Zn-65	1.71E-10	7.92E-09	3.99E-09
crab	Zn-65	6.92E-10	7.44E-09	3.99E-09
shrimp	Zn-65	2.28E-10	7.87E-09	0.00E+00
seal	Zn-65	3.37E-09	4.98E-09	0.00E+00
gull	Zn-65	8.17E-10	0.00E+00	0.00E+00
winkle	Zn-65	2.18E-10	7.87E-09	3.99E-09

Organism	Radionuclide	Internal dose rate, (Gy day^{-1}) per Bq kg^{-1} wet weight	External dose rate from water, (Gy day^{-1}) per Bq L^{-1}	External dose rate from sediments, (Gy day^{-1}) per Bq kg^{-1} sediments, w.w.
cod	Sr-90	1.55E-08	0.00E+00	0.00E+00
haddock	Sr-90	1.55E-08	0.00E+00	0.00E+00
herring	Sr-90	1.55E-08	0.00E+00	0.00E+00
plaice	Sr-90	1.55E-08	0.00E+00	0.00E+00
sardine	Sr-90	1.55E-08	0.00E+00	0.00E+00
sprat	Sr-90	1.55E-08	0.00E+00	0.00E+00
mussel	Sr-90	1.55E-08	0.00E+00	0.00E+00
crab	Sr-90	1.55E-08	0.00E+00	0.00E+00
shrimp	Sr-90	1.55E-08	0.00E+00	0.00E+00
seal	Sr-90	1.55E-08	0.00E+00	0.00E+00
gull	Sr-90	1.55E-08	0.00E+00	0.00E+00
winkle	Sr-90	1.55E-08	0.00E+00	0.00E+00
cod	Tc-99	1.40E-09	0.00E+00	0.00E+00
haddock	Tc-99	1.40E-09	0.00E+00	0.00E+00
herring	Tc-99	1.40E-09	0.00E+00	0.00E+00
plaice	Tc-99	1.40E-09	0.00E+00	0.00E+00
sardine	Tc-99	1.40E-09	0.00E+00	0.00E+00
sprat	Tc-99	1.40E-09	0.00E+00	0.00E+00
mussel	Tc-99	1.40E-09	0.00E+00	0.00E+00
crab	Tc-99	1.40E-09	0.00E+00	0.00E+00
shrimp	Tc-99	1.40E-09	0.00E+00	0.00E+00
seal	Tc-99	1.40E-09	0.00E+00	0.00E+00
gull	Tc-99	1.40E-09	0.00E+00	0.00E+00
winkle	Tc-99	1.40E-09	0.00E+00	0.00E+00
cod	Ru-103	1.73E-09	6.11E-09	1.02E-09
haddock	Ru-103	1.73E-09	6.11E-09	2.37E-09
herring	Ru-103	1.45E-09	6.36E-09	0.00E+00
plaice	Ru-103	1.68E-09	6.15E-09	2.71E-09
sardine	Ru-103	1.26E-09	6.53E-09	0.00E+00
sprat	Ru-103	1.13E-09	6.65E-09	0.00E+00
mussel	Ru-103	1.07E-09	6.71E-09	3.39E-09
crab	Ru-103	1.55E-09	6.27E-09	3.39E-09
shrimp	Ru-103	1.12E-09	6.66E-09	0.00E+00
seal	Ru-103	4.03E-09	3.99E-09	0.00E+00
gull	Ru-103	1.67E-09	0.00E+00	0.00E+00
winkle	Ru-103	1.11E-09	6.67E-09	3.39E-09

Organism	Radionuclide	Internal dose rate, (Gy day^{-1}) per Bq kg^{-1} wet weight	External dose rate from water, (Gy day^{-1}) per Bq L^{-1}	External dose rate from sediments, (Gy day^{-1}) per Bq kg^{-1} sediments, w.w.
cod	Ru-106	2.00E-08	2.54E-09	4.21E-10
haddock	Ru-106	2.00E-08	2.54E-09	9.82E-10
herring	Ru-106	1.99E-08	2.64E-09	0.00E+00
plaice	Ru-106	2.00E-08	2.55E-09	1.12E-09
sardine	Ru-106	1.98E-08	2.71E-09	0.00E+00
sprat	Ru-106	1.98E-08	2.76E-09	0.00E+00
mussel	Ru-106	1.97E-08	2.78E-09	1.40E-09
crab	Ru-106	1.99E-08	2.60E-09	1.40E-09
shrimp	Ru-106	1.97E-08	2.76E-09	0.00E+00
seal	Ru-106	2.09E-08	1.68E-09	0.00E+00
gull	Ru-106	2.00E-08	0.00E+00	0.00E+00
winkle	Ru-106	1.97E-08	2.76E-09	1.40E-09
cod	Ag-110m	2.11E-08	3.56E-08	5.88E-09
haddock	Ag-110m	2.11E-08	3.56E-08	1.37E-08
herring	Ag-110m	1.96E-08	3.69E-08	0.00E+00
plaice	Ag-110m	2.09E-08	3.58E-08	1.57E-08
sardine	Ag-110m	1.86E-08	3.79E-08	0.00E+00
sprat	Ag-110m	1.79E-08	3.85E-08	0.00E+00
mussel	Ag-110m	1.76E-08	3.88E-08	1.96E-08
crab	Ag-110m	2.02E-08	3.64E-08	1.96E-08
shrimp	Ag-110m	1.79E-08	3.86E-08	0.00E+00
seal	Ag-110m	3.37E-08	2.40E-08	0.00E+00
gull	Ag-110m	2.08E-08	0.00E+00	0.00E+00
winkle	Ag-110m	1.78E-08	3.86E-08	1.96E-08
cod	Sb-125	2.36E-09	5.45E-09	8.17E-10
haddock	Sb-125	2.36E-09	5.45E-09	1.91E-09
herring	Sb-125	2.12E-09	5.68E-09	0.00E+00
plaice	Sb-125	2.32E-09	5.49E-09	2.20E-09
sardine	Sb-125	1.95E-09	5.83E-09	0.00E+00
sprat	Sb-125	1.83E-09	5.94E-09	0.00E+00
mussel	Sb-125	1.78E-09	5.99E-09	2.99E-09
crab	Sb-125	2.21E-09	5.59E-09	2.80E-09
shrimp	Sb-125	1.82E-09	5.95E-09	0.00E+00
seal	Sb-125	4.42E-09	3.56E-09	0.00E+00
gull	Sb-125	2.31E-09	0.00E+00	0.00E+00
winkle	Sb-125	1.82E-09	5.95E-09	2.98E-09

Organism	Radionuclide	Internal dose rate, (Gy day^{-1}) per Bq kg^{-1} wet weight	External dose rate from water, (Gy day^{-1}) per Bq L^{-1}	External dose rate from sediments, (Gy day^{-1}) per Bq kg^{-1} sediments, w.w.
cod	Cs-134	4.41E-09	1.94E-08	3.22E-09
haddock	Cs-134	4.41E-09	1.94E-08	7.51E-09
herring	Cs-134	3.56E-09	2.02E-08	0.00E+00
plaice	Cs-134	4.26E-09	1.95E-08	8.58E-09
sardine	Cs-134	2.97E-09	2.07E-08	0.00E+00
sprat	Cs-134	2.57E-09	2.11E-08	0.00E+00
mussel	Cs-134	2.38E-09	2.13E-08	1.07E-08
crab	Cs-134	3.87E-09	1.99E-08	1.07E-08
shrimp	Cs-134	2.54E-09	2.11E-08	0.00E+00
seal	Cs-134	1.15E-08	1.29E-08	0.00E+00
gull	Cs-134	4.22E-09	0.00E+00	0.00E+00
winkle	Cs-134	2.51E-09	2.11E-08	1.07E-08
cod	Cs-137	4.26E-09	7.04E-09	1.06E-09
haddock	Cs-137	4.26E-09	7.04E-09	2.46E-09
herring	Cs-137	3.95E-09	7.33E-09	0.00E+00
plaice	Cs-137	4.21E-09	7.09E-09	2.84E-09
sardine	Cs-137	3.73E-09	7.53E-09	0.00E+00
sprat	Cs-137	3.58E-09	7.66E-09	0.00E+00
mussel	Cs-137	3.51E-09	7.73E-09	3.86E-09
crab	Cs-137	4.06E-09	7.22E-09	3.61E-09
shrimp	Cs-137	3.57E-09	7.67E-09	0.00E+00
seal	Cs-137	6.91E-09	4.61E-09	0.00E+00
gull	Cs-137	4.20E-09	0.00E+00	0.00E+00
winkle	Cs-137	3.56E-09	7.68E-09	3.84E-09

Organism	Radionuclide	Internal dose rate, (Gy day^{-1}) per Bq kg^{-1} wet weight	External dose rate from water, (Gy day^{-1}) per Bq L^{-1}	External dose rate from sediments, (Gy day^{-1}) per Bq kg^{-1} sediments, w.w.
cod	Pb-210	5.89E-09	0.00E+00	0.00E+00
haddock	Pb-210	5.89E-09	0.00E+00	0.00E+00
herring	Pb-210	5.89E-09	0.00E+00	0.00E+00
plaice	Pb-210	5.89E-09	0.00E+00	0.00E+00
sardine	Pb-210	5.89E-09	0.00E+00	0.00E+00
sprat	Pb-210	5.89E-09	0.00E+00	0.00E+00
mussel	Pb-210	5.89E-09	0.00E+00	0.00E+00
winkle	Pb-210	5.89E-09	0.00E+00	0.00E+00
crab	Pb-210	5.89E-09	0.00E+00	0.00E+00
shrimp	Pb-210	5.89E-09	0.00E+00	0.00E+00
seal	Pb-210	5.89E-09	0.00E+00	0.00E+00
gull	Pb-210	5.89E-09	0.00E+00	0.00E+00
cod	Po-210	7.45E-08	0.00E+00	0.00E+00
haddock	Po-210	7.45E-08	0.00E+00	0.00E+00
herring	Po-210	7.45E-08	0.00E+00	0.00E+00
plaice	Po-210	7.45E-08	0.00E+00	0.00E+00
sardine	Po-210	7.45E-08	0.00E+00	0.00E+00
sprat	Po-210	7.45E-08	0.00E+00	0.00E+00
mussel	Po-210	7.45E-08	0.00E+00	0.00E+00
crab	Po-210	7.45E-08	0.00E+00	0.00E+00
shrimp	Po-210	7.45E-08	0.00E+00	0.00E+00
seal	Po-210	7.45E-08	0.00E+00	0.00E+00
gull	Po-210	7.45E-08	0.00E+00	0.00E+00
winkle	Po-210	7.45E-08	0.00E+00	0.00E+00
cod	Ra-228	7.88E-09	1.16E-08	1.93E-09
haddock	Ra-228	7.88E-09	1.16E-08	4.49E-09
herring	Ra-228	7.39E-09	1.21E-08	0.00E+00
plaice	Ra-228	7.79E-09	1.17E-08	5.13E-09
sardine	Ra-228	7.05E-09	1.24E-08	0.00E+00
sprat	Ra-228	6.82E-09	1.26E-08	0.00E+00
mussel	Ra-228	6.71E-09	1.27E-08	6.42E-09
crab	Ra-228	7.57E-09	1.19E-08	6.42E-09
shrimp	Ra-228	6.80E-09	1.26E-08	0.00E+00
seal	Ra-228	1.20E-08	7.87E-09	0.00E+00
gull	Ra-228	7.77E-09	0.00E+00	0.00E+00
winkle	Ra-228	6.79E-09	1.27E-08	6.42E-09

Organism	Radionuclide	Internal dose rate, (Gy day^{-1}) per Bq kg^{-1} wet weight	External dose rate from water, (Gy day^{-1}) per Bq L^{-1}	External dose rate from sediments, (Gy day^{-1}) per Bq kg^{-1} sediments, w.w.
cod	Ra-226* low LET high LET	3.52E-07 1.49E-08 3.37E-07	2.22E-08 2.22E-08 0.00E+00	3.33E-09 3.33E-09 0.00E+00
haddock	Ra-226* low LET high LET	3.52E-07 1.49E-08 3.37E-07	2.22E-08 2.22E-08 0.00E+00	7.76E-09 7.76E-09 0.00E+00
herring	Ra-226* low LET high LET	3.51E-07 1.40E-08 3.37E-07	2.30E-08 2.30E-08 0.00E+00	0.00E+00 0.00E+00 0.00E+00
plaice	Ra-226* low LET high LET	3.52E-07 1.48E-08 3.37E-07	2.23E-08 2.23E-08 0.00E+00	8.93E-09 8.93E-08 0.00E+00
sardine	Ra-226* low LET high LET	3.50E-07 1.34E-08 3.37E-07	2.36E-08 2.36E-08 0.00E+00	0.00E+00 0.00E+00 0.00E+00
sprat	Ra-226* low LET high LET	3.50E-07 1.30E-08 3.37E-07	2.39E-08 2.39E-08 0.00E+00	0.00E+00 0.00E+00 0.00E+00
mussel	Ra-226* low LET high LET	3.50E-07 1.28E-08 3.37E-07	2.41E-08 2.41E-08 0.00E+00	1.21E-08 1.21E-08 0.00E+00
crab	Ra-226* low LET high LET	3.51E-07 1.44E-08 3.37E-07	2.27E-08 2.27E-08 0.00E+00	1.14E-08 1.14E-08 0.00E+00
shrimp	Ra-226* low LET high LET	3.50E-07 1.30E-08 3.37E-07	2.40E-08 2.40E-08 0.00E+00	0.00E+00 0.00E+00 0.00E+00
seal	Ra-226* low LET high LET	3.59E-07 2.23E-08 3.37E-07	1.54E-08 1.54E-08 0.00E+00	0.00E+00 0.00E+00 0.00E+00
gull	Ra-226* low LET high LET	3.52E-07 1.47E-08 3.37E-07	0.00E+00 0.00E+00 0.00E+00	0.00E+00 0.00E+00 0.00E+00
winkle	Ra-226* low LET high LET	3.50E-07 1.30E-07 3.37E-07	2.40E-08 2.40E-08 0.00E+00	1.20E-08 1.20E-08 0.00E+00

Organism	Radionuclide	Internal dose rate, (Gy day^{-1}) per Bq kg^{-1} wet weight	External dose rate from water, (Gy day^{-1}) per Bq L^{-1}	External dose rate from sediments, (Gy day^{-1}) per Bq kg^{-1} sediments, w.w.
cod	Th-228*	4.28E-07	1.94E-08	2.91E-09
	low LET	1.03E-08	1.94E-08	2.91E-09
	high LET	4.18E-07	0.00E+00	0.00E+00
haddock	Th-228*	4.28E-07	1.94E-08	6.80E-09
	low LET	1.03E-08	1.94E-08	6.80E-09
	high LET	4.18E-07	0.00E+00	0.00E+00
herring	Th-228*	4.28E-07	2.01E-08	0.00E+00
	low LET	9.50E-09	2.01E-08	0.00E+00
	high LET	4.18E-07	0.00E+00	0.00E+00
plaice	Th-228*	4.28E-07	1.96E-08	7.82E-09
	low LET	1.02E-08	1.96E-08	7.82E-09
	high LET	4.18E-07	0.00E+00	0.00E+00
sardine	Th-228*	4.27E-07	2.06E-08	0.00E+00
	low LET	9.00E-09	2.06E-08	0.00E+00
	high LET	4.18E-07	0.00E+00	0.00E+00
sprat	Th-228*	4.27E-07	2.10E-08	0.00E+00
	low LET	8.60E-09	2.10E-08	0.00E+00
	high LET	4.18E-07	0.00E+00	0.00E+00
mussel	Th-228*	4.27E-07	2.11E-08	1.06E-08
	low LET	8.50E-09	2.11E-08	1.06E-08
	high LET	4.18E-07	0.00E+00	0.00E+00
crab	Th-228*	4.28E-07	1.99E-08	9.94E-09
	low LET	9.80E-09	1.99E-08	9.94E-09
	high LET	4.18E-07	0.00E+00	0.00E+00
shrimp	Th-228*	4.27E-07	2.10E-08	0.00E+00
	low LET	8.60E-09	2.10E-08	0.00E+00
	high LET	4.18E-07	0.00E+00	0.00E+00
seal	Th-228*	4.35E-07	1.35E-08	0.00E+00
	low LET	1.68E-08	1.35E-08	0.00E+00
	high LET	4.18E-07	0.00E+00	0.00E+00
gull	Th-228*	4.28E-07	0.00E+00	0.00E+00
	low LET	1.01E-08	0.00E+00	0.00E+00
	high LET	4.18E-07	0.00E+00	0.00E+00
winkle	Th-228*	4.27E-07	2.10E-08	1.05E-08
	low LET	8.60E-09	2.10E-08	1.05E-08
	high LET	4.18E-07	0.00E+00	0.00E+00

Organism	Radionuclide	Internal dose rate, (Gy day^{-1}) per Bq kg^{-1} wet weight	External dose rate from water, (Gy day^{-1}) per Bq L^{-1}	External dose rate from sediments, (Gy day^{-1}) per Bq kg^{-1} sediments, w.w.
cod	Th-230	6.54E-08	0.00E+00	0.00E+00
haddock	Th-230	6.54E-08	0.00E+00	0.00E+00
herring	Th-230	6.54E-08	0.00E+00	0.00E+00
plaice	Th-230	6.54E-08	0.00E+00	0.00E+00
sardine	Th-230	6.54E-08	0.00E+00	0.00E+00
sprat	Th-230	6.54E-08	0.00E+00	0.00E+00
mussel	Th-230	6.54E-08	0.00E+00	0.00E+00
crab	Th-230	6.54E-08	0.00E+00	0.00E+00
shrimp	Th-230	6.54E-08	0.00E+00	0.00E+00
seal	Th-230	6.54E-08	0.00E+00	0.00E+00
gull	Th-230	6.54E-08	0.00E+00	0.00E+00
winkle	Th-230	6.54E-08	0.00E+00	0.00E+00
cod	U-234	6.73E-08	0.00E+00	0.00E+00
haddock	U-234	6.73E-08	0.00E+00	0.00E+00
herring	U-234	6.73E-08	0.00E+00	0.00E+00
plaice	U-234	6.73E-08	0.00E+00	0.00E+00
sardine	U-234	6.73E-08	0.00E+00	0.00E+00
sprat	U-234	6.73E-08	0.00E+00	0.00E+00
mussel	U-234	6.73E-08	0.00E+00	0.00E+00
winkle	U-234	6.73E-08	0.00E+00	0.00E+00
crab	U-234	6.73E-08	0.00E+00	0.00E+00
shrimp	U-234	6.73E-08	0.00E+00	0.00E+00
seal	U-234	6.73E-08	0.00E+00	0.00E+00
gull	U-234	6.73E-08	0.00E+00	0.00E+00
cod	U-238	7.11E-08	0.00E+00	0.00E+00
haddock	U-238	7.11E-08	0.00E+00	0.00E+00
herring	U-238	7.11E-08	0.00E+00	0.00E+00
plaice	U-238	7.11E-08	0.00E+00	0.00E+00
sardine	U-238	7.11E-08	0.00E+00	0.00E+00
sprat	U-238	7.11E-08	0.00E+00	0.00E+00
mussel	U-238	7.11E-08	0.00E+00	0.00E+00
crab	U-238	7.11E-08	0.00E+00	0.00E+00
shrimp	U-238	7.11E-08	0.00E+00	0.00E+00
seal	U-238	7.12E-08	0.00E+00	0.00E+00
gull	U-238	7.11E-08	0.00E+00	0.00E+00
winkle	U-238	7.11E-08	0.00E+00	0.00E+00

Organism	Radionuclide	Internal dose rate, (Gy day^{-1}) per Bq kg^{-1} wet weight	External dose rate from water, (Gy day^{-1}) per Bq L^{-1}	External dose rate from sediments, (Gy day^{-1}) per Bq kg^{-1} sediments, w.w.
cod	Pu-238	7.73E-08	0.00E+00	0.00E+00
haddock	Pu-238	7.73E-08	0.00E+00	0.00E+00
herring	Pu-238	7.73E-08	0.00E+00	0.00E+00
plaice	Pu-238	7.73E-08	0.00E+00	0.00E+00
sardine	Pu-238	7.73E-08	0.00E+00	0.00E+00
sprat	Pu-238	7.73E-08	0.00E+00	0.00E+00
mussel	Pu-238	7.73E-08	0.00E+00	0.00E+00
winkle	Pu-238	7.73E-08	0.00E+00	0.00E+00
crab	Pu-238	7.73E-08	0.00E+00	0.00E+00
shrimp	Pu-238	7.73E-08	0.00E+00	0.00E+00
seal	Pu-238	7.73E-08	0.00E+00	0.00E+00
gull	Pu-238	7.73E-08	0.00E+00	0.00E+00
cod	Pu-239	7.22E-08	0.00E+00	0.00E+00
haddock	Pu-239	7.22E-08	0.00E+00	0.00E+00
herring	Pu-239	7.22E-08	0.00E+00	0.00E+00
plaice	Pu-239	7.22E-08	0.00E+00	0.00E+00
sardine	Pu-239	7.22E-08	0.00E+00	0.00E+00
sprat	Pu-239	7.22E-08	0.00E+00	0.00E+00
mussel	Pu-239	7.22E-08	0.00E+00	0.00E+00
crab	Pu-239	7.22E-08	0.00E+00	0.00E+00
shrimp	Pu-239	7.22E-08	0.00E+00	0.00E+00
seal	Pu-239	7.22E-08	0.00E+00	0.00E+00
gull	Pu-239	7.22E-08	0.00E+00	0.00E+00
winkle	Pu-239	7.22E-08	0.00E+00	0.00E+00
cod	Pu-240	7.23E-08	0.00E+00	0.00E+00
haddock	Pu-240	7.23E-08	0.00E+00	0.00E+00
herring	Pu-240	7.23E-08	0.00E+00	0.00E+00
plaice	Pu-240	7.23E-08	0.00E+00	0.00E+00
sardine	Pu-240	7.23E-08	0.00E+00	0.00E+00
sprat	Pu-240	7.23E-08	0.00E+00	0.00E+00
mussel	Pu-240	7.23E-08	0.00E+00	0.00E+00
crab	Pu-240	7.23E-08	0.00E+00	0.00E+00
shrimp	Pu-240	7.23E-08	0.00E+00	0.00E+00
seal	Pu-240	7.23E-08	0.00E+00	0.00E+00
gull	Pu-240	7.23E-08	0.00E+00	0.00E+00
winkle	Pu-240	7.23E-08	0.00E+00	0.00E+00

Organism	Radionuclide	Internal dose rate, (Gy day^{-1}) per Bq kg^{-1} wet weight	External dose rate from water, (Gy day^{-1}) per Bq L^{-1}	External dose rate from sediments, (Gy day^{-1}) per Bq kg^{-1} sediments, w.w.
cod	Am-241	7.69E-08	0.00E+00	0.00E+00
haddock	Am-241	7.69E-08	0.00E+00	0.00E+00
herring	Am-241	7.69E-08	0.00E+00	0.00E+00
plaice	Am-241	7.69E-08	0.00E+00	0.00E+00
sardine	Am-241	7.69E-08	0.00E+00	0.00E+00
sprat	Am-241	7.69E-08	0.00E+00	0.00E+00
mussel	Am-241	7.69E-08	0.00E+00	0.00E+00
crab	Am-241	7.69E-08	0.00E+00	0.00E+00
shrimp	Am-241	7.69E-08	0.00E+00	0.00E+00
seal	Am-241	7.69E-08	0.00E+00	0.00E+00
gull	Am-241	7.69E-08	0.00E+00	0.00E+00
winkle	Am-241	7.69E-08	0.00E+00	0.00E+00
* The dose conversion factors for Ra-226 and Th-228 include contribution of short-lived daughter nuclides assumed in equilibrium with the parent.				

Appendix B - Dose rates to marine biota in the OSPAR region

Table B1. Dose rates to marine biota in the Sellafield coastal area

Fish (cod)				
Years	Low-LET	High-LET	Absorbed dose rate, (Gy day^{-1})	Weighted dose rate (radiation weighting factor for high-LET w_r=20), Gy day^{-1}
1986	1.26E-06	3.95E-09	1.26E-06	1.34E-06
1987	8.74E-07	3.64E-09	8.78E-07	9.47E-07
1988	9.64E-07	5.69E-09	9.70E-07	1.08E-06
1989	7.59E-07	4.41E-09	7.63E-07	8.47E-07
1990	7.83E-07	2.88E-09	7.86E-07	8.41E-07
1991	7.47E-07	3.15E-09	7.50E-07	8.10E-07
1992	8.38E-07	9.11E-09	8.47E-07	1.02E-06
1993	7.63E-07	1.71E-09	7.65E-07	7.97E-07
1994	5.15E-07	1.51E-08	5.30E-07	8.17E-07
1995	4.71E-07	2.85E-09	4.74E-07	5.28E-07
1996	4.90E-07	3.00E-09	4.93E-07	6.00E-07
1997	4.09E-07	1.58E-09	4.11E-07	4.41E-07
1998	3.38E-07	1.80E-09	3.40E-07	3.74E-07
1999	2.80E-07	4.65E-09	2.85E-07	3.73E-07
2000	2.44E-07	2.81E-09	2.47E-07	3.00E-07
2001	2.16E-07	2.38E-09	2.18E-07	2.64E-07
Fish (plaice)				
Years	Low-LET	High-LET	Absorbed dose rate, (Gy day^{-1})	Weighted dose rate (radiation weighting factor for high-LET w_r=20), Gy day^{-1}
1986	2.89E-06	3.95E-09	2.89E-06	2.97E-06
1987	2.02E-06	3.64E-09	2.02E-06	2.10E-06
1988	2.31E-06	5.69E-09	2.32E-06	2.42E-06
1989	1.76E-06	4.41E-09	1.76E-06	1.85E-06
1990	1.83E-06	2.88E-09	1.83E-06	1.89E-06
1991	1.76E-06	3.15E-09	1.76E-06	1.83E-06
1992	2.08E-06	9.11E-09	2.09E-06	2.27E-06
1993	1.94E-06	1.71E-09	1.94E-06	1.97E-06
1994	1.29E-06	1.51E-08	1.31E-06	1.60E-06
1995	1.17E-06	2.85E-09	1.17E-06	1.23E-06
1996	1.14E-06	3.74E-08	1.18E-06	1.30E-06
1997	9.17E-07	1.58E-09	9.19E-07	9.48E-07
1998	8.16E-07	1.80E-09	8.18E-07	8.52E-07
1999	6.96E-07	4.65E-09	7.01E-07	7.89E-07
2000	5.97E-07	2.81E-09	6.00E-07	6.53E-07
2001	5.34E-07	2.38E-09	5.36E-07	5.81E-07

Dose rates to marine biota in the Sellafield coastal area (Continued)

Molluscs (mussel, winkle)				
Years	Low-LET	High-LET	Absorbed dose rate, (Gy day^{-1})	Weighted dose rate (radiation weighting factor for high-LET w_r=20), Gy day^{-1}
1986	9.65E-06	4.71E-06	1.44E-05	1.04E-04
1987	8.65E-06	4.36E-06	1.30E-05	9.58E-05
1988	8.98E-06	4.54E-06	1.35E-05	9.97E-05
1989	7.88E-06	3.58E-06	1.15E-05	7.95E-05
1990	5.49E-06	3.50E-06	8.99E-06	7.54E-05
1991	5.99E-06	3.33E-06	9.32E-06	7.26E-05
1992	4.60E-06	3.43E-06	8.03E-06	7.33E-05
1993	5.30E-06	2.85E-06	8.15E-06	6.23E-05
1994	3.55E-06	2.44E-06	5.99E-06	5.24E-05
1995	4.66E-06	2.26E-06	6.92E-06	4.98E-05
1996	5.21E-06	2.39E-06	7.60E-06	5.30E-05
1997	5.08E-06	2.50E-06	7.58E-06	5.50E-05
1998	4.43E-06	2.32E-06	6.75E-06	5.09E-05
1999	2.38E-06	2.10E-06	4.48E-06	4.45E-05
2000	2.38E-06	2.42E-06	4.80E-06	5.08E-05
2001	2.12E-06	1.91E-06	4.03E-06	4.03E-05
Crustaceans (crab, lobster)				
Years	Low-LET	High-LET	Absorbed dose rate. (Gy day^{-1})	Weighted dose rate (radiation weighting factor for high-LET w_r=20). Gy day^{-1}
1986	9.59E-06	2.12E-07	9.80E-06	1.38E-05
1987	8.59E-06	2.12E-07	8.80E-06	1.28E-05
1988	8.88E-06	1.70E-07	9.05E-06	1.23E-05
1989	7.87E-06	2.82E-07	8.15E-06	1.35E-05
1990	5.37E-06	1.43E-07	5.51E-06	8.23E-06
1991	5.98E-06	1.70E-07	6.15E-06	9.38E-06
1992	4.52E-06	1.58E-07	4.68E-06	7.69E-06
1993	5.23E-06	1.27E-07	5.36E-06	7.78E-06
1994	3.79E-06	6.50E-08	3.86E-06	5.09E-06
1995	5.12E-06	2.02E-07	5.32E-06	9.16E-06
1996	7.68E-06	1.53E-07	7.83E-06	1.07E-05
1997	1.48E-05	6.14E-08	1.49E-05	1.60E-05
1998	7.39E-06	1.10E-07	7.50E-06	9.60E-06
1999	4.38E-06	1.60E-07	4.54E-06	7.59E-06
2000	4.01E-06	1.24E-07	4.13E-06	6.49E-06
2001	1.61E-06	1.19E-07	1.73E-06	3.98E-06

Table B2. Dose rates to marine biota in the Cap de la Hague coastal area

Fish (*Gadus luscus*)				
Years	Low-LET	High-LET	Absorbed dose rate, (Gy day^{-1})	Total weighted dose rate (radiation weighting factor for high-LET w_r=20), Gy day^{-1}
1982	4.30E-07	nd	4.30E-07	
1983	5.16E-07	nd	5.16E-07	
1984	4.12E-07	nd	4.12E-07	
1985	3.80E-07	nd	3.80E-07	
1986	3.12E-07	nd	3.12E-07	
1987	1.93E-07	nd	1.93E-07	
1988	2.60E-07	nd	2.60E-07	
1989	1.11E-07	nd	1.11E-07	
1990	1.16E-07	nd	1.16E-07	
1991	9.38E-08	nd	9.38E-08	
1992	4.24E-08	nd	4.24E-08	
1993	2.18E-07	nd	2.18E-07	
1994	2.92E-08	nd	2.92E-08	
1995	2.16E-08	nd	2.16E-08	
1996	2.24E-08	nd	2.24E-08	
1997	2.10E-08	nd	2.10E-08	
Note: nd – data were not available				
Mollusk (Patella)				
Years	Low-LET	High-LET	Absorbed dose rate, (Gy day^{-1})	Total weighted dose rate (radiation weighting factor for high-LET w_r=20), Gy day^{-1}
1982	9.08E-06	6.25E-08	9.14E-06	1.03E-05
1983	1.52E-05	6.25E-08	1.52E-05	1.64E-05
1984	6.50E-06	6.25E-08	6.56E-06	7.75E-06
1985	4.15E-06	6.31E-08	4.22E-06	5.41E-06
1986	4.77E-06	5.50E-08	4.83E-06	5.87E-06
1987	3.24E-06	5.98E-08	3.30E-06	4.44E-06
1988	2.90E-06	6.07E-08	2.96E-06	4.11E-06
1989	1.96E-06	5.78E-08	2.02E-06	3.12E-06
1990	2.40E-06	5.65E-08	2.45E-06	3.53E-06
1991	9.23E-07	5.31E-08	9.76E-07	1.98E-06
1992	3.03E-07	4.79E-08	3.51E-07	1.26E-06
1993	2.11E-07	2.60E-08	2.36E-07	7.30E-07
1994	2.15E-07	7.75E-08	2.92E-07	1.76E-06
1995	1.36E-07	2.77E-08	1.64E-07	6.89E-07
1996	1.32E-07	2.35E-08	1.55E-07	6.01E-07
1997	1.54E-07	2.34E-08	1.78E-07	6.22E-07

Table B3. Dose rates to marine biota in the area impacted by Whitehaven phosphate plant

Whitehaven phosphate plant, monitoring site at Parton				
Fish (cod)				
Year	Low-LET	High-LET	Absorbed dose rate, (Gy day^{-1})	Total weighted dose rate (radiation weighting factor for high-LET w_r=20), Gy day^{-1}
1991	6.88E-07	1.36E-07	8.23E-07	3.40E-06
1992	6.88E-07	2.04E-07	8.92E-07	4.77E-06
1993	6.88E-07	7.97E-08	7.67E-07	2.28E-06
1994	6.88E-07	6.16E-08	7.49E-07	1.92E-06
1995	6.87E-07	2.32E-08	7.11E-07	1.15E-06
1996	6.87E-07	6.64E-08	7.54E-07	2.02E-06
1997	6.87E-07	8.32E-08	7.71E-07	2.35E-06
1998	6.88E-07	8.56E-08	7.73E-07	2.40E-06
1999	6.87E-07	8.35E-08	7.71E-07	2.36E-06
Mollusc (winkle)				
Year	Low-LET	High-LET	Absorbed dose rate, (Gy day^{-1})	Total weighted dose rate (radiation weighting factor for high-LET w_r=20), Gy day^{-1}
1991	1.24E-06	1.47E-05	1.59E-05	2.95E-04
1992	8.82E-07	1.04E-05	1.13E-05	2.09E-04
1993	8.38E-07	5.58E-06	6.42E-06	1.12E-04
1994	8.47E-07	3.21E-06	4.05E-06	6.50E-05
1995	1.01E-06	2.82E-06	3.82E-06	5.73E-05
1996	9.07E-07	2.36E-06	3.27E-06	4.81E-05
1997	2.02E-06	6.28E-06	8.30E-06	1.28E-04
1998	7.86E-07	3.03E-06	3.81E-06	6.14E-05
1999	7.78E-07	2.86E-06	3.64E-06	5.80E-05
Crustacean (crab)				
Year	Low-LET	High-LET	Absorbed dose rate, (Gy day^{-1})	Total weighted dose rate (radiation weighting factor for high-LET w_r=20), Gy day^{-1}
1991	7.73E-07	3.44E-06	4.21E-06	6.96E-05
1992	7.71E-07	4.27E-06	5.04E-06	8.61E-05
1993	7.92E-07	2.52E-06	3.31E-06	5.11E-05
1994	7.63E-07	1.71E-06	2.47E-06	3.49E-05
1995	7.55E-07	1.75E-06	2.51E-06	3.58E-05
1996	7.54E-07	1.37E-06	2.13E-06	2.82E-05
1997	7.54E-07	1.82E-06	2.58E-06	3.72E-05
1998	7.54E-07	2.04E-06	2.80E-06	4.16E-05
1999	7.54E-07	2.04E-06	2.80E-06	4.16E-05

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