# ENVIRONMENTAL PATHWAYS AND RADIOLOGICAL DOSIMETRY FOR BIOTA

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# VOIES ENVIRONNEMENTALES CRITIQUES ET DOSIMÉTRIE RADIOLOGIQUE POUR LE BIOTE

**RÉSUMÉ**

Les radionucléides qui se retrouvent dans l'environnement à la suite d'activités humaines peuvent être transportés, dilués, ou concentrés dans les milieux biotiques et abiotiques de l'écosystème. Les organismes vivant dans un environnement contaminé par des déchets radioactifs reçoivent une irradiation externe provenant des radionucléides dans l'eau, l'air, la végétation, le sol ou les sédiments, et une irradiation interne par les radionucléides incorporés dans leur tissus, soit par inhalation, soit par absorption directe à travers la peau. Cet exposé examine les voies par lesquelles le biote (flore et faune) est exposé aux produits radioactifs répandus dans l'environnement et analyse les méthodes de calcul des doses de radiation auxquelles est soumis le biote. En général, la méthode de calcul des doses de radiation auxquelles est soumis le biote, dans l'environnement naturel, est mieux développée pour les organismes aquatiques que pour les organismes terrestres. Les diverses méthodes de calcul de doses de radiation auxquelles est soumis le biote aquatique ont été analysées. Si la protection des espèces non humaines doit faire partie des programmes d'étude d'impacts d'installations nucléaires sur l'environnement, force est de constater que d'importants progrès restent à faire pour mettre au point des méthodes de calcul de doses de radiation auxquelles est soumis le biote. Le rapport recommande de simplifier et de normaliser les calculs de dose : il faut mettre au point les facteurs de conversion de dose pour un bon nombre d'organismes génériques, tant aquatiques que terrestres.

**ABSTRACT**

Radionuclides entering the environment as a result man's activities may be transported, cycled, and/or concentrated in the biotic and abiotic compartments of the ecosystem. Organisms in an environment contaminated with radioactive waste may be irradiated externally by radionuclides in air, water, vegetation, soil or sediment and internally by radionuclides accumulated within their bodies by inhalation or by direct absorption through their skin. The purpose of this paper is to examine the pathways in which biota are exposed to radioactive releases to the environment and to review the methods used to calculate radiation doses to the biota. In general, the methodology for estimating radiation doses to biota in their natural environment is better developed for aquatic biota than for terrestrial biota. The different methodologies which have been used for calculating radiation doses to aquatic biota were reviewed. If the protection of non-human biota is an issue in addressing environmental assessments of nuclear facilities, then the methodology for estimating radiation doses to biota should be improved. It is recommended that dose calculations should be simplified and standardized by developing dose conversion factors for a number of generic aquatic and terrestrial organisms.

## 1.0 INTRODUCTION

The effects of radiation on humans has been a primary concern of the nuclear age. In the early years, concerns centered around nuclear explosions or exposure to world-wide fallout from nuclear testing. Later the emphasis was on exposures from the release of radionuclides from various nuclear facilities involved in the nuclear fuel cycle, including nuclear-powered electric generating plants. Recent concerns involve disposal and/or releases of nuclear waste from various nuclear fuel cycle facilities into the environment. This paper focuses on the potential effects of higher-than-background radiations on biota other than humans.

Radionuclides enter aquatic and terrestrial environments where they may be transported, cycled, and/or concentrated in the biotic and abiotic compartments of the ecosystem. The object of this paper is to examine the pathways in which biota are exposed to radioactive releases to the environment and to review the methods used to calculate radiation dose to the biota.

## 2.0 RADIATION PROTECTION STANDARDS

Radiation protection standards have been developed for the protection of human health; however, it has been generally accepted and adopted by those involved with radiation protection standard that by "*protecting humans we are protecting the environment.*" The 1972 BEIR Report (Biological Effects of Ionizing Radiation; National Academy of Sciences, 1972) states that: "*Evidence to-date indicates that probably no other living organisms are very much more radiosensitive than man so that if man as an individual is protected then other organisms as populations would be most unlikely to suffer harm.*" Similar statements can be found in the recommendations of the International Commission on Radiological Protections, (ICRP, 1977). The latest statement on the subject from ICRP (1991) has been modified as follows: "*The commission believes that the standard of environmental control needed to protect man to the degree currently thought desirable will ensure that other species are not put at risk. Occasionally, individual members of non-human species might be harmed, but not to the extent of endangering whole species or creating imbalance between species.*"

Fortunately, for many situations, if one protects humans, then the environment is protected. This statement appears to be true if humans are inhabiting and deriving sustenance from the same environment in which other organisms are exposed. In ICRP 109 (1991) one proposed scenario considered that if humans receive a dose of 1 mSv $a^{-1}$ from drinking water, consumption of fish and exposure to sediments, then the biota in the aquatic environment is protected. The short-coming of this scenario is that the environment may not be used or only receive limited use by man. In many instances the public is protected from radiation exposure by being removed from the site, but the endemic biota is exposed.

The practice of discharging radioactive waste into the terrestrial and aquatic environment entails a potential for the contamination of the environment with higher than background concentrations of radionuclides. Such contamination increases the exposure of populations of organisms and the impact of the increased exposure can only be assessed if the magnitude of the incremental radiation dose can be assessed.

## 3.0 PATHWAYS

Biota in an environment contaminated with radioactive waste may be irradiated externally by radionuclides in air, water, vegetation, soil or sediment, and internally by radionuclides accumulated within the body by inhalation or by direct absorption through the gills or skin of the organisms. Organisms are also exposed to radionuclides accumulated from the ingestion of food and water. A radionuclide, depending on the element, can be differential distributed among the organs and tissues of an organism. In addition, the relative significance of internal and external sources can be markedly altered by the size and behavior of the organisms.

The various pathways resulting in the exposure of aquatic biota from releases of radioactive effluents from the different process in the enriched uranium fuel cycle were investigated by Blaylock and Witherspoon (1975). Releases from the different facilities of the fuel cycle were considered: uranium mining, uranium milling, conversion facilities (uranium hexafluoride production), isotopic (uranium) enrichment, fuel fabrication, light water reactors, and fuel reprocessing. The potential for the greatest radiation exposure to biota appear to be with the nuclear fuel supply facilities (i.e. mining and milling). The major dose contributing radionuclides were $^{226}Ra$, $^{210}Po$ and $^{230}Th$. Good documentation exists showing that radionuclides released into the environment can be expected to produce similar or even substantially higher doses to certain organisms than to people inhabiting and deriving sustenance from the same environment (IAEA, 1976; NCRP 109). Therefore, the risk of radiation effects would appear to be as high or higher for natural biota than for humans in an environment receiving radioactive waste.

## 4.0 DOSIMETRY

Terrestrial and aquatic organisms have always been exposed to radiation from natural sources, both from internal emitters and from external sources in the environment including cosmic rays (Folsom and Harley, 1957). A knowledge of the absorbed dose rate from natural background sources has been used as a base line in assessment of biological significance of the dose-rate increment contributed by the activities of man.

In one of the early studies in which doses were calculated to biota in a natural environment Nelson and Blaylock (1963) determined the radiation dose to the midge, *Chrionomus tentans*. A radiation dose was calculated for larvae that inhabited the radioactive bottom sediment of a lake, which received radioactive effluents from the Oak Ridge National Laboratory. In the same lake, the radiation dose received by the mosquitofish (*Gambusia affinis*), which lived in the upper end of Lake was calculated (Blaylock, 1969; Trabalka and Allen, 1973) and to the snail *Physa heterostropha* inhabiting one of the seeps in the upper end of the lake (Cooley and Nelson, 1970).

However, in most early studies that attempted to access the ecological effects of radioactivity, much of the concern was directed toward exposure to global radioactive fallout from nuclear weapons testing. Such concerns overshadowed localized releases from individual nuclear facilities. Polikarpov (1966) reported the controversial results of a series of experiments that attempted to determine the effects of radionuclide input from fallout sources on marine fisheries in the Black Sea. Although dose calculations were not provided, the results appeared to indicate that exposure of planktoic fish embryos to low-level concentration of $^{90}Sr$-$^{90}Y$, sufficient only to increase the dose rate by a fraction of natural background, introduced significant detrimental effects. These findings influenced several investigators to perform rigorous dosimetric treatments for radiobiological studies on fish embryos in order to resolve the controversy. Adams (1968) provided a comprehensive theoretical treatment using two point-source dose functions: the inverse square law, appropriate for gamma radiation and high energy beta radiation for small sphere (egg) radii; and the Loevinger formula (Loevinger et al., 1956) generally applicable for beta radiation. Adams (1968) provided equations for nearly all the expected activity distributions in fish eggs, and for aggregations of eggs as well.

Woodhead (1970) determined the activity distribution and concentration factors of five fission products ($^{144}Ce$-$^{144}Pr$, $^{137}Cs$, $^{106}Ru$-$^{106}Rh$, $^{90}Sr$-$^{90}Y$, and $^{95}Zr$-$^{95}Nb$) in eggs of the plaice (*Pleuronects platessa*). Trabalka (1971) exposed adults and embryos of the fathead minnow (*Pinephales promelas*) to $^{144}Ce$-$^{144}Pr$ in large micro-ecosystems. He found that the absorbed dose to the adult ovary was over two orders of magnitude greater than that delivered to the embryos during development.

In the early days little attention was paid to alpha emitters. However, as shown by Folsom and Beasley (1968), distributions of naturally occurring $^{210}Po$ are important since polonium accumulates to relatively high levels in marine organisms. They suggested that actual background dose rates could be up to 500% greater than previously thought. Their treatment did not take into account higher relative biological effectiveness (RBE) values for alpha emitters.

Woodhead (1973b) reviewed published data on levels of radioactivity in seawater, the seabed, and marine biota from natural sources, fallout, and waste disposal operations. He provided expected estimates of dose rates to marine organisms by using representative physical dimensions for phytoplankton, zooplankton, mollusks, large crustaceans, and fish in dosimetric calculations. Woodhead concluded that on a global scale level, fallout from weapons testing was the major source of increased radiation exposure to marine biota. Dose rates from fallout sources were comparable to natural background. The significance of the sedimentary contribution to the dose rate depended strongly on the ecological affinity of the organism for the sediment-water interface.

## 5.0 ENVIRONMENTAL DOSIMETERS

Various methods have been used for direct measurements of radiation dose to organisms. Such techniques are appropriate for external gamma radiation and large organisms but do not provide internal dose rates from alpha- or beta-emitting radionuclides or a measure of the exposure of a particular small target, e.g. gonads, developing embryos or plant meristems. Techniques for measuring dose rates to aquatic organisms have been reviewed by IAEA (1972; 1979), Blaylock and Trabalka (1978), NRCC (1979) and Woodhead (1984). Methods for determining the radiation exposure of terrestrial organism were discussed in a review by Whicker and Fraley in 1974.

Thermoluminescent dosimeters were widely used in radioecological studies. They were available in a wide range of phosphors and encapsulate schemes and were suitable for environmental studies under very low dose-rate regimes (French et al., 1974; Styron, 1971). Woodhead (1973a) attached lithium fluoride (encapsulated between PVC sheets) thermoluminescent dosimeters to plaice (*Pleuronectes platessa*), captured and released in the Irish Sea. The mean dose rate to the gonad was estimated to be 207 µrad/hr. This value was three orders of magnitude greater than the calculated dose to embryos reported in earlier work (Woodhead, 1970). The major contributions were from accumulations of beta and gamma radiation in bottom sediments, occurring as a result of releases from Windscale.

The 1976 IAEA Technical Report No. 172 provided concentrations of radionuclides in aquatic environments and the resultant radiation dose rates received by aquatic organisms as well as the methods used to calculate doses to biota.

## 6.0 COMPARISON OF DOSE CALCULATIONS TO AQUATIC AND TERRESTRIAL ORGANISMS

Radiation dose calculations have been more intensely studied for aquatic biota than for terrestrial biota. One reason is that radioactive waste is often released in liquid form into aquatic ecosystems where it is more easily detected. In aquatic systems the concentration in an organism is attained with a very simple model known as the bioconcentration factor. Bioconcentration is the concentration of the element of interest in the water multiplied by a value which represents the relationship between the concentration in the biota at equilibrium condition and the water. In terrestrial studies, in contrast, more complicated food chain models are used to predict the concentration of radionuclides in terrestrial biota. Considerably more information is needed to estimate the various parameter values for inhalation, immersion in air, and external dose from soil and vegetation, etc.

In 1983 the National Research Council of Canada published "Radioactivity in the Canadian Aquatic Environment" which included dose conversion factors for estimating the dose to aquatic biota. These conversion factors were for algae, mollusk/crustaceans, fish, and waterfowl/shore birds. A "Dose Conversion Factor" based on the EXREM III computer code (Trubey and Kaye, 1973) and the exposure to 1 μCi/ml in water was used to obtain an estimated dose to the various types of biota. In 1988 Pentreach and Woodhead (1988) published dose equivalent rate for marine biota for unit water concentration for coastal waters to reduce the effort of calculated doses. More recently Amiro (1992) published radiological dose conversion factors for non-human biota. The dose conversion factors were for fish, plants, mammals and birds, but only for a limited number of radionuclides $^{14}C$, $^{99}Tc$, $^{129}I$ and $^{137}Cs$. These are very conservative dose conversion factors which means that the doses are overestimated. Future plans include expanding the list of radionuclides.

## 7.0 APPROACHES TO CALCULATING DOSES TO BIOTA

Doses to humans are calculated by knowing the intake or exposure and then using the proper dose conversion factor. In contrast, calculating a dose to biota starts with an equation and several assumptions. One of the primary differences is that a "standard man" is available for humans, but for the many types of biota a generic organism that represents many species must be assumed.

Several factors make estimating the radiation dose to biota difficult. Radionuclides are differentially distributed among the organs and tissues of an organism, affecting the radiation dose that sensitive organs and tissue may receive. In addition, the relative significance of internal and external sources of radiation to an organism can be markedly altered by the size and behavior of the organism.

The three most common approaches that have been employed for calculating radiation doses to aquatic biota were reviewed by Woodhead (NCRP, 1991). In the first method, CRITR, a set of models and associated computer codes was developed by Soldat et al. (1974) and recently revised by Baker and Soldat (1992) for application to discharges of effluents into surface waters. A simplified means was provided for calculating the concentrations of radionuclides in water, sediment, and two groups of organisms using a restricted number of parameters relating to the discharge sources and receiving water body.

A second approach involved two models, EXREM III and BIORAD (Trubey and Kaye, 1973), which were developed from the starting point of unit concentration of a radionuclide in water from which the concentration in an organism is determined by the application of a concentration factor. No means are given for estimating the concentration of a radionuclide in sediment or determining the exposure from contaminated sediment, which may be significant.

A third approach, "Point Source Distribution" (IAEA, 1976; 1979) is advantageous because it can be applied to any combination of radiation sources and target geometric. For any extended (nonpoint) source of ionizing radiation, the dose rate at a specified point can be obtained by the integration of an appropriate point source dose function over the source geometry. Although it is possible to derive theoretical expressions from first principles, these calculations are frequently complex due to the multiplicity of absorption and scattering phenomena which must be considered. For ease of computation, simple empirical expressions have been described for calculating doses to aquatic biota (IAEA 1976, 1979).

## 8.0 PROTECTING SPECIES OTHER THAN MAN

The effects of ionizing radiation occurs at all levels of biological organization ranging from the molecular level to the ecosystem level (Whicker and Shultz, 1982). Extremely high doses are required to demonstrate effects at the community and ecosystem level; however, much lower exposure can be detected at the molecular and cellular level. Molecular and cellular level responses do not necessarily lead to observable effects at the population or ecosystem level.

The main concern for non-human species is focused at the population level of organization. Deleterious effects can occur at individual level which do not effect the survival or well being of the population. For organisms whose reproductive rates are very high and on which selective pressures are strong, the value of one individual or even thousands of individuals to the population may be insignificant (IAEA, 1976). In such populations, only a small fraction of the individuals will mature and perpetuate the population, even in the absence of radiation effects. Most genetic changes are selected against because they are highly unlikely to show a selective advantage. Typical, measured attributes at the population level include number of individuals, mortality rate, reproduction rate, mean growth rate, etc.

Among the complicated factors is the possibility of hormesis. Hormesis has been defined as a beneficial effect of a toxic substance at low doses. The wide range of radiosensitivities of organisms comprising most natural communities creates a condition where sensitive species may be effected, but more resistant species may gain a significant competitive advantage and increase in abundance and vigor (IAEA, 1992). This could be interpreted as hormesis (or a stimulatory effect).

## 9.0 IMPROVING DOSIMETRIC METHODS FOR BIOTA

The question is whether the methodology for calculating radiation doses to biota should be improved. If we accept the thesis that by protecting man we are protecting the biota, the present methods used for estimating the dose to biota is probably adequate. If the concern is for determining the radiation dose to predict the effects on biota, the methodology needs to be improved. In addition, if the protection of non-human biota is an important issue in addressing environmental assessments of nuclear facilities, then the methodology for estimating radiation doses to biota should be improved. Dose calculations could be simplified and standardized by developing dose conversion factors for a number of generic aquatic and terrestrial organisms.

For calculating radiation doses to humans "standard man" is used as a representative individual. Organ size and functions are also standard. Calculation of doses to biota must take into account that there are many species with greatly varying sizes occupying a variety of habitats. Different size were considered for calculating doses to generic aquatic organisms in the IAEA report (1976); however, the radionuclide was considered to be uniformly distributed in the organism. For small organisms the point is insignificant, but for large organisms, especially for bone-seeking radionuclides, this could be important for dose calculations. To obtain the distribution of radionuclide in organisms may require some additional work, but a considerable amount of information is available in the literature.

The habitat in which an organisms lives and the ecological niche that it fills in the ecosystem will influence the radiation dose received by the organism. For example an earthworm which spends its time in the soil, or a cottontail rabbit which spends a majority of its time above ground can influence the dosimetry. For terrestrial organisms a model is required to predict the concentration of the radionuclide in the organisms. Using a model requires additional values or estimates of a number of parameter values.

## 10.0 RECOMMENDATIONS

Dose conversions factors should be developed for a number of generic aquatic and terrestrial organisms which would represent the different types of sensitive organisms. Important parameter values for the different generic organisms would be provided in such a manner that they could be modified to change the dose conversion factor for specific organisms. If little is known about an organism, the generic values could be used to obtain a dose estimate. As information becomes available for a specific organism, the important parameter would be modified to provide a more accurate dose conversion factor.

## 11.0 DISCUSSION

***Question No.1:*** ***In IAEA Technical Report No. 332, are the dose calculations based on a contaminated environment? I would prefer to see calculations for the immediate environment, i.e., at point of release.***

Dr. Blaylock responded that they had an environment that is not used [by humans], but they did calculations assuming that humans are exposed.

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