

RADIOACTIVITY IN THE MARINE ENVIRONMENT: UNDERSTANDING THE BASICS OF RADIOECOLOGY

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ABSTRACT

Natural and anthropogenic radionuclides are ubiquitous in the marine biosphere. They are used to study a suite of environmental processes, including those related to marine food webs, yet they also potentially negatively impact marine biota and humans. The goal of this lecture is to provide upper level undergraduate and graduate students with a basic understanding of marine radioecology and how marine organisms bioaccumulate and influence the cycling of radionuclides in the environment. The lecture begins with a brief introduction to the methods and models used to understand biological radionuclide uptake and loss, followed by how organisms biogeochemically and physically transfer radioactive substances throughout the ocean. The remaining lecture focuses on current methods for assessing potential radiological impacts on marine biota and risks associated with contaminated seafood consumption. This is the last lecture of a four-part lecture series on radionuclides in the marine environment.

SLIDES

- 1) Title Page
- 2) What is Marine Radioecology
- 3) Lecture Goals
- 4) There are three main sources of radionuclides to the environment. They are loosely classified as the naturally occurring or primordial U-Th series, cosmogenically produced radionuclides, and radionuclides produced by anthropogenic processes. Note that other primordial radionuclides exist as well, such as ^{40}K , but are less commonly used in marine applications. Radioactive elements enter the ocean via both point and non-point sources and their distributions are controlled by their biological and chemical reactivity and their half-lives. See Lectures 2 (Radioactivity in the Marine Environment: Uranium-Thorium Decay Series) and 3 (Radioactivity in the Marine Environment: Cosmogenic and Anthropogenic Radionuclides) for more information.
- 5) Once radionuclides enter the marine environment, they undergo a variety of processes that include transport and dilution by currents, scavenging by particles, and uptake by marine biota. Marine organisms acquire radioactive elements during ingestion (through absorption across the gut wall and into tissue); via contaminated seawater, or consuming contaminated food or sediment. Fish may also be contaminated by radionuclide adsorption to external surfaces or absorption through external surfaces (e.g., gills (respiratory exchange), skin, etc.). Generally speaking, accumulation of radionuclides through external passive adsorption varies in proportion to the surface to volume ratio (non allometric). For absorbed radionuclides involved in metabolic pathways, variations are allometric, i.e., proportional to body weight. Contaminated marine organisms eliminate radionuclides through excretion processes, including feces production. There are many factors that influence the magnitude of this bioaccumulation. Environmental factors include: Temperature, salinity, seawater composition (trace metal competition, oxidation state (chemical form), organic complexation), and exposure time. Biological factors include: Organism age, size, sex, reproductive state, physiology and metabolism, food type, feeding mode, ingestion and filtering rate, and even external tissue composition.
- 6) Relative contributions (%) of the three ingestion/uptake pathways (sediment, seawater, and food) to the total bioaccumulation of ^{134}Cs in marine organisms. Note how they differ across

species, for instance, clam (*G. pectinatum*) and shrimp (*P. stylirostris*) consumption of food is the main uptake route of Cs, whereas the oysters (*I. isognomum* and *M. regula*) ingest a variety of sources. In practice seawater includes sorption processes.

- 7) Terminology. In marine radioecology, both the Concentration Factor (CF) and the Transfer Factor (TF) are commonly used to quantify radionuclide uptake and to assess the relative bioavailability of radioactive elements to a given organism. As mentioned earlier, these factors are dependent on both environmental and biological influences and are usually determined under steady-state conditions. Knowledge of TF and CF ultimately enable the development of models that can be used to predict radionuclide bioaccumulation under specific conditions. They are thus useful for predicting human exposure through marine food consumption. For a detailed overview of the CF, including strengths and weaknesses, please see Carvalho (2018).
- 8) Both CF and TF assume a homogenous distribution in organism tissues. However, not all organism tissue accumulates and retains radioactive elements and compounds in the same manner. For example, two years after the Fukushima Daiichi Nuclear Power Plant Accident in 2011, 73% of the accumulated Cs was found in fish muscle. In contrast, ⁹⁰Sr was preferentially found in the fish skeleton. These distributions correspond to our general knowledge of the behavior of these radionuclides in biota.
- 9) Lab radiotracer experiments have been conducted to better understand how marine organisms accumulate and eliminate radionuclides from their bodies. In essence, when an organism is placed in contaminated seawater (or fed with contaminated food or placed in an aquarium with contaminated sediment), the concentration of the radionuclide within the organism increases until reaching a plateau. This corresponds to the CF (or TF) of **this element** for **this organism** under **specific conditions** (e.g., equilibrium). When the same organism is placed into clean seawater, its radionuclide concentration progressively decreases allowing scientists to determine specific loss rates as well as retention.
- 10) The uptake phase depends on time (kinetic factors). The steady state CF is a function of the uptake rate constant (k_u) and the loss or depuration rate constant (k_e). By definition, the concentration factor at steady state (CF_{ss}) is equal to the uptake rate constant (k_u) divided by the depuration rate constant (k_e). Therefore, equilibrium (steady state or plateau) is reached when k_u is equal to k_e . It is important to note that the k_e defined during the uptake phase integrates across all components under the given experimental conditions (closed system, and relatively constant concentration/activity levels). As such, the depuration rate constant is often determined during the depuration phase. In this example, a one component uptake model is used, which may not be appropriate depending on the radionuclide or organism of interest (See Slides 8 and 14).
- 11) This figure depicts laboratory derived uptake kinetics of ¹³⁴Cs for several species in seawater. Note the difference in CF between bivalves and algae, and the difference in time needed to approach steady state. The curve fit assumes a one component uptake model.
- 12) This figure depicts the uptake kinetics of plutonium for a number of trophic levels. Note the orders of magnitude difference in plutonium uptake relative to Cs as well as the time needed to reach steady state. Very high CFs occur with plankton versus bottom fish. Intermediate CFs are found for various invertebrates (starfish, clam, urchins).
- 13) As noted earlier, the physical environment, e.g., temperature, can also impact the CF and differs between radionuclides. This figure describes the accumulation of various radionuclides at 2°C

versus 12°C in a series of laboratory radiotracer experiments with the brown macroalgae, *Fucus vesiculosus*. Concentration factors in the thallus were temperature-dependent and significantly decreased at 2°C for ⁶⁰Co, but not for ²⁴¹Am and ¹³⁴Cs. This is of particular importance as most of the data used in radioecology and radiological impact assessment are from temperate climates.

- 14) The loss (depuration) phase also depends on time (kinetics). In this formulation, loss rates are determined by placing contaminated organisms in seawater and monitoring the radioactive element loss rate (k_e) to the surrounding environment (see Slide 10). This formulation is often used with $A_0 = 1$ (100%). However, it could also be used with concentrations or activity (e.g., Bq g⁻¹ or Bq). This loss rate is then used to determine a biological half-life ($t_{b1/2}$), the time it takes for an organism/tissue to lose half of its activity.
- 15) This figure depicts an experiment examining the loss rate of ¹³⁴Cs from two species, *L. varigeta* (algae) and *P. stylirostris* (shrimp) expressed in terms of the percentage of remaining activity (i.e., activity at time t divided by initial activity measured in the organism at the beginning of the decontamination period). Loss rates were fit with a one component model.
- 16) In certain cases, loss kinetics are not well described by a one component model. This often occurs when radionuclide uptake and loss rates differ across various tissues (e.g., muscle versus scales versus the skeleton, see Slide 8). Here, a 2 component model is shown as it is rare to be able to fit more than 2 components during this depuration phase. The general equation is:

$$A_t = A_0 \times \sum_{i=1}^n (N_i \times e^{-k_{ei} \times t})$$

With: $\sum_{i=1}^n (N_i) = 1$

n = number of compartments, i

A_t = remaining activities at time t (%)

A_0 = remaining activities at time t_0 (%)

This formulation is often used with A_0 equal to 100% (or 1), but also works using concentration or specific activity (Bq g⁻¹ or Bq). The biological half-life for a specific compartment, i , is then = $T_{bi} = \text{Ln}(2)/k_{ei}$.

- 17) This figure is similar to that shown on Slide 15 and depicts an experiment examining the loss rate of ¹³⁴Cs from the bivalve *G. pectinum* expressed in terms of the percentage of remaining activity. Here, the loss rate of ¹³⁴Cs is fit with a **two component model**.
- 18) This table provides the steady state Concentration Factor (CF) of selected radionuclides within different taxonomic groups. Note the differences between trophic levels and radionuclide.
- 19) This table provides a summary of selected Transfer Factors (TFs) of radionuclides accumulated by marine biota from contaminated sediments. Note that TFs from contaminated sediment for several key radionuclides are quite low (< 1).
- 20) The Assimilation Efficiency (AE) is the fraction of ingested radionuclide via food that is absorbed and retained for metabolism. AE data was determined from a series of laboratory radiotracer experiments (Data from Fowler and Fisher (2004) and Fowler (unpublished)). Numbers highlighted in red indicate the food fed to the organisms in order to determine the AE.

- 21) Bulk TF in the field (combined ingestion and excretion pathways) are reflective of the organism's feeding habits, which can change with size. For example, the ^{137}Cs activity in European Hake increases with fish size mainly due to shift in the trophic regime. At a given size, males contain higher activities than females due to differences in growth rate (i.e., at a given size, females are younger than males).
- 22) Once radionuclides enter the marine environment they undergo a variety of processes that include transport and dilution by currents (horizontal advection) and uptake/loss by marine biota. For example, some radionuclides are particle reactive. As particles sink, they transport particle reactive radionuclides to deeper waters and the seafloor where they can enter the benthic food web. In this figure blue arrows represent seawater uptake, green arrows represent food uptake, and brown arrows represent biological uptake from sediment.
- 23) One example of the role of biota in horizontal transport is in fish. In 2008, the Pacific Bluefin tuna (PBFT) caught near California contained ^{137}Cs activities that were relatively low (derived from atmospheric nuclear bomb testing) and ^{134}Cs activities below detection. Following the Fukushima Dai-ichi Nuclear Power Plant accident (March 2011), significant ^{134}Cs activities were detected in the muscle of PBFT sampled in California in August 2011. The presence of this isotope is clearly related to the accident. The time lag between the accident and when the fish were caught was too short to be due to transport of ^{134}Cs by currents alone. Thus, higher ^{134}Cs activities in the PBFT near California are due to feeding in contaminated waters close to Japan followed by migration. In contrast, Yellowfin tuna, which only inhabit the waters off the California coast, had no detectable ^{134}Cs activities in their tissue in August 2011. Note that active horizontal transport by PBFT is relatively small compared to both water and atmospheric transport.
- 24) Vertical migration of various species (plankton, fish) as well as the production of fecal pellets, aggregation into marine snow, etc. also leads to downward transport of contaminants with various efficiency through the water column.
- 25) Radionuclides appear to be significantly enriched in zooplankton fecal pellets compared to the whole organism. This is particularly evident for ^{210}Po and Cs isotopes.
- 26) Due to the transfer of particle reactive radioactive elements to depth, bottom sediments may act as repositories for further contamination. In this example, fish that lived in the water column were continuously sampled close to the Fukushima Dai-ichi Nuclear Power Plant after the 2011 accident and compared to fish living close to the bottom. Benthic fish living close to the seafloor contained significantly higher ^{137}Cs activities. Because sediments act as constrained reservoirs, bottom feeding fish may continue to feed upon and retain higher activities of ^{137}Cs than they might otherwise obtain if they fed in the water column, where ^{137}Cs activities were more efficiently diluted due to larger scale ocean mixing.
- 27) Biomagnification reflects the increase in concentration of a substance in the tissues of organisms at successively higher levels in a food chain. Here, Dichlorodiphenyltrichloroethane (DDT) is compared to ^{137}Cs to depict how biomagnification takes place in nature. For DDT, there is an increase of a 1000 between water and phytoplankton followed by successive increases of an order of magnitude at each higher trophic level (the biomagnification factor is 10). This results in DDT concentrations higher by a factor of 10^7 in top predators relative to water. For ^{137}Cs , biomagnification is much more limited (the biomagnification factor is ~ 2), but still significant. In top predators, the Cs concentration is ~ 300 times higher than that in seawater. For more information, regarding bioaccumulation/biomagnification of ^{137}Cs , see Kasamatsu and

Ishikawa (1997), Zhou et al. (2001), Heldel et al. (2003), Harmelin-Vivien et al. (2012), and Pouil et al. (2018). Another isotope which may show biomagnification is naturally occurring ^{210}Po (produced from ^{210}Pb decay), particularly at the lower trophic levels, i.e., in zooplankton, marine invertebrates, and fish (Cherry et al., 1983, Stewart et al. 2005, Mathews and Fisher, 2008). This is especially important as Po is highly radiotoxic (See Slide 42).

- 28) Once radionuclides are released into the environment and incorporated into marine organisms, how do we assess potential impacts on the environment, the organism itself, and the risks associated with seafood consumption by humans?
- 29) In order to understand potential deleterious impacts on marine biota and humans, we must first review radiation. For more detailed information, see Lecture 1 (Radioactivity in the Marine Environment: Understanding the Basics of Marine Radioactivity). When discussing radionuclides and radioprotection, we focus on ionizing radiation. Ionizing radiation has enough energy to change normal cellular functioning and may cause cells to die or transform into a cancerous cell.
- 30) The radiation types we focus on most often are alpha, beta, and gamma as they are the major radioactive decay mechanisms. Alpha particles are the least penetrating and can be stopped by clothing. Yet these particles cause the most damage if inhaled due to their high energy. For more detailed information, see Lecture 1 (Radioactivity in the Marine Environment: Understanding the Basics of Marine Radioactivity).
- 31) Beta particles are generally more penetrating.
- 32) Gamma particles are the most penetrating type of radiation. Gamma emission is the most common form of energy release and nearly always occur with alpha and beta decays.
- 33) The main international organizations involved in radiation protection, safety standards, and implementation are: the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the International Commission on Radiation Protection (ICRP), and the International Atomic Energy Agency (IAEA).
- 34) Health effects due to ionizing radiation depend on the radiation dose. When discussing dose, we use two different types of units: Grays and Sieverts. The Gray (Gy) is the absorbed dose per unit of mass, while the Sievert (Sv) takes into account biological damage associated with the amount and type of radiation (i.e., alpha, beta, gamma), the organ or tissue being irradiated, and the length of exposure. The effective dose sums all of the biologically adjusted radiation exposure. Absorbed dose is a measurable quantity, while equivalent and effective doses are estimated quantities used for management purposes of *human health only*.
- 35) There are different types of radiological impacts. For deterministic effects, the severity increases with the dose. Radiation dose levels or “thresholds,” are determined, below which, effects from radiation exposure are absent. They are generally short term effects. For more information, see: <http://www.imagewisely.org/imaging-modalities/computed-tomography/imaging-physicians/articles/ionizing-radiation-effects-and-their-risk-to-humans>.
- 36) For stochastic effects, the severity is independent of the dose. There is no threshold and the probability of having an effect is proportional to the dose absorbed. In other words, depending on the conditions of exposure, effects may or may not occur. Epidemiological data are mainly from studies on survivors of the atomic bombings of Hiroshima and Nagasaki, Japan that occurred in August 1945. There are no data for low doses and various assumptions are made regarding the response curve. The current international system of radioprotection is based on several assumptions, approximations and simplifications. One of them assumes a linear no threshold (LNT) relationship by extrapolating the data from the Hiroshima Nagasaki survivors.

Although the incidence of hereditary defects in patients exposed to radiation in Japan and Chernobyl are not significant, animal experiments suggest that risk does exist. For more information: <http://www.imagewisely.org/imaging-modalities/computed-tomography/imaging-physicians/articles/ionizing-radiation-effects-and-their-risk-to-humans>. This figure describes three risk response curves based on dose:

- (a) The observed response in the moderate-dose range is extrapolated linearly down to a zero incremental dose above that from normal natural background radiation (e.g., this would be a linear non-threshold (LNT) relationship).
 - (b) The risk response at low and very low doses is substantially higher than expected from a LNT relationship (e.g., this would be a supralinear relationship);
 - (c) The risk response at low and very low doses is substantially lower than expected from a LNT relationship (e.g., this would be a threshold or hormetic relationship).
- 37) How do we determine the Effective Dose to humans? The function describing uptake and retention of a radionuclide in a human body following its ingestion, inhalation, or direct absorption through skin is complex. Therefore it is convenient to describe the transfer of radionuclides by simple models that facilitate calculation and yield estimates of dose sufficiently accurate for the purpose of radioprotection. This is an example of a generic biokinetic model used by ICRP for radioactive element transfer into and within a human. Note the relative simplicity of this model relative to what we now understand about the human body.
- 38) Effective dose rates to humans. Absorbed dose is measurable, whereas effective dose is not. Furthermore, effective dose models are only valid for low doses and stochastic effects as the model assumes a LNT relationship (see Slide 36). The absorbed dose is averaged over an entire organ, which means that radionuclides are assumed to be homogeneously deposited in the tissue. Parameters are assessed for a reference man and woman and the behavior of radionuclides in the human body is described by generic models (see previous slides). Nonetheless, this model is what is currently used for radiation protection and it can only address “typical” situations.
- 39) Tissue weighting factors (W_T) are approximated and need to take into account the differential sensitivity of tissues by gender and age. Results are then generalized to all populations. Radiation weighting factors (W_R) depend on the type of radiation (e.g., α , β , γ , etc.).
- 40) Humans are exposed to radiation both externally and internally. External exposure (irradiation) is from radiation emitted from radionuclides in the surrounding environmental media (e.g., air, water and soils). Internal exposure occurs after radionuclides are incorporated into the human body. This occurs mainly by inhalation of contaminated air, or ingestion of contaminated water and food, although contamination via cuts, wounds, etc., may also occur.
- 41) One common source of exposure to radiation when dealing with the marine environment is via ingestion of contaminated seafood. In order to determine effective doses from radionuclide concentrations in food, water, or air ($D_{\text{eff-ing}}$), one must first determine a dose coefficient (DC) for a given radionuclide. More information on specific numbers can be found from international agencies such as the ICRP.
- 42) This figure provides DCs for several radionuclides for the ingestion pathway. Dose coefficients are determined for reference humans assuming a homogeneous distribution of the radionuclide in organs. Ingestion of 1 Bq of polonium or plutonium is orders of magnitude more radiotoxic than the ingestion of 1 Bq of tritium (^3H) or cobalt-60 (^{60}Co). Regarding seafood ingestion, ^{210}Po

is by far the major contributor to radiation exposure, while ^{137}Cs , mainly arising from nuclear bomb tests, is negligible (Aarkrog et al., 1997).

- 43) When a radionuclide enters the human body, it is eliminated through a combination of radioactive decay (physical) and biological excretion. The effective half life (λ_e) of a radionuclide represents the sum of the biological and physical decay constants $\lambda_e = \lambda_p + \lambda_b$. For example ^{137}Cs will last 70 days after incorporation into the human body compared to its radioactive half life of 30.17 years.
- 44) Now that we know the various ways in which radiation exposure can occur, what are the major sources of radiation exposure to the average person? Radiation exposure includes annual background radiation from naturally occurring radionuclides in the environment as well as cosmic rays (plane rides). Note that significant radiation exposure is through medical treatments, e.g., x-rays, and is about $3 - 6 \text{ mSv y}^{-1}$. The ICRP recommends limiting artificial radiation exposure of the general public to $\sim 1 \text{ mSv y}^{-1}$.
- 45) Over the past decade, average human radiation exposure has increased. This is mainly due to the increase in medical treatments. Medical procedures, such as diagnostic X-rays, nuclear medicine, and radiation therapy are by far the most significant source of human-made radiation exposure to the general population. Humans are also exposed to radiation from consumer products, such as tobacco (^{210}Po), combustible fuels (gas, coal, etc.), televisions, luminous watches and dials (^3H), airport X-ray systems, smoke detectors (americium), electron tubes, and gas lantern mantles (thorium). The very small “other” slice includes radiation exposure from nuclear accidents and weapon’s testing.
- 46) Now that we understand how radioactive elements impact marine biota and humans, how do we move forward with regards to environmental protection? How do we measure and assess the ecological risks associated with radiation?
- 47) Until the late 1980’s, the primary objective of international radiological protection agencies has been the protection of humankind, with environmental protection viewed as a subset within this human based conceptual framework; “...if man is adequately protected **then other living things** are also likely to be sufficiently protected” (ICRP, 1977). It was increasingly recognized, however, that radiological impacts on non-humans needed to be assessed, particularly in situations/practices where high amounts of radionuclides could be released in remote geographical regions. While this leads to low potential impacts on humans, marine organisms could bioaccumulate radionuclides and be at risk from elevated doses (see IAEA, 1988, Pentreath, 1998). As a result, the need to specifically assess the effects of ionizing radiation on the environment and to protect non-human biota from adverse effects is now formally recognized (i.e., see ICRP, 2007; IAEA, 2006).
- 48) The current framework for human radioprotection of the general public is well developed after decades of iteration. In contrast, a system to help manage the actual or potential effects of radiation on the environment is still in its infancy. Current environmental radioprotection efforts are based on the human developed framework (Pentreath, 2009). Specific reference, animals and plants (RAP) have been selected to play similar, though much simpler roles than that of a “Representative Person” in order to derive some form of numerical guidance in aiding management decision making with regards to radiation exposure. For human health, the ICRP’s objectives are to manage and control an *individual’s* exposure to ionizing radiation in order to prevent deterministic effects and to reduce the risk of stochastic effects. For protection of the

environment, the objective is to reduce ionizing radiation to levels where only negligible impacts *on populations* occur on the maintenance of biological diversity, the conservation of species, and the health and status of natural habitats, communities and ecosystems (ICRP 2008). Derived consideration reference levels (DCRLs) are essentially a dose band range within which there is likely to be some chance of deleterious effects of ionizing radiation occurring to individuals of a specific RAP. DCRLs, when considered with other information, can thus be used as a reference point for optimizing the level of effort expended on environmental protection as a function of overall management objectives and the specific radiation exposure situation (ICRP, 2008).

- 49) Unfortunately, we have only limited data on the impacts of radiological exposure to animals and plants. Acute exposure or dose is a high dose received in a short time period. Responses to acute irradiation are frequently expressed as the median lethal dose or LD 50/30, which is the dose that kills 50% of the population within 30 days. Mammals appear to be the most radiosensitive species, with lethal doses achieved between 10 -100 Gy. Note that for non-human living organisms, only absorbed doses are used (radiation weighting factors are used in some cases, see Slide 39).
- 50) Chronic exposure or dose is continuous or episodic radiation exposure that occurs over a longer period of time. Chronic Exposure Species Sensitivity Distributions (SSDs) reflects the variation in sensitivity between species. In this example, SSDs are illustrated by the relationship between dose rate and the fraction of species affected by chronic gamma exposure, where EDR_{10} is the Chronic Effect Dose-Rate that results in a 10% effect on a specific species survival, growth or morbidity endpoint. The dose rate ranges from $< 10 \mu\text{Gy h}^{-1}$ for the most sensitive vertebrate species, to $>100\ 000 \mu\text{Gy h}^{-1}$ for the most radio-tolerant invertebrate species, respectively.
- 51) So what is the dose to consider for radiological protection of the environment? It depends on the end goal. UNSCEAR (2008) concluded that chronic irradiation of a small proportion of individuals in a population should not exceed dose rates of $400 \mu\text{Gy h}^{-1}$ in order to minimize risks at the population level for non-human organisms. In contrast, ICRP (2008) defined DCRLs for a given RAP that span a much wider range, with certain marine organisms impacted at doses well below $400 \mu\text{Gy h}^{-1}$. Various scientific discussions and experiments have led to the selection of a Predicted No Effect Dose Rate (PNEDR) of $10 \mu\text{Gy h}^{-1}$ for a generic ecosystem, below which no deleterious effects at the population level should be observed (for chronic gamma exposure).
- 52) The ERICA tool. ERICA is a software program available online developed through international cooperation to assess the radiological risk to terrestrial, freshwater and marine biota. This tool is based on the screening benchmark value of $10 \mu\text{Gy h}^{-1}$ and is regularly updated. Due to the limited data available, the initial RAPs considered were limited to those typically found in terrestrial and freshwater environments. In ERICA, the RAPs list has been extended to include more organisms that occur in the marine environment, such as flat fish, seaweed, and crab. It is important to note that a RAP assumes basic biological characteristics of a particular type of animal or plant, at the general taxonomic Family level (with defined anatomical, physiological, and life-history properties). RAPs are mainly representative of temperate regions only, due to insufficient data at other latitudes (Pentreath 2009, ICRP 2008).
- 53) In summary, radionuclide bioaccumulation depends on a variety of environmental and biological factors.
- 54) More information is needed to develop specific criteria and models for environmental protection.
- 55) Acknowledgements

56) References

References

Aarkrog A., Baxter M.S., Bettencourt A., Bojanowski R., Bologna A., Charmasson S., Cunha, P.I., Delfanti R., Duran E., Holm E., Jeffre R., Livingston H.D., Mahapanyawong S., Nies H., Osvath I., Li, P., Povinec P.P., Sanchez A., Smith J. N., Swift P.D. (1997) A Comparison of Doses from ^{137}Cs and ^{210}Po in Marine Food: A Major International Study. *Journal of Environmental Radioactivity*, 34: 69-90.

Blaylock, B.G., Theodorakis, C.W., Shugart, L.R. (1996) Biological effects of ionising radiation. In: Amiro B, Avadhanula R, Johansson G, Larsson CM, Luning M, editors. *Proceedings of the First International Symposium on Ionising Radiation*, Stockholm, May 20–24.

Boisson, F., Hutchins, D.A., Fowler, S.W., Fisher, N.S., Teyssie, J-L (1997) Influence of temperature on the accumulation and retention of 11 radionuclides by the marine alga *Fucus vesiculosus* (L.), *Marine Pollution Bulletin* 35: 313-321.

Buesseler, K.O., Jayne, S.R., Fisher, N.S., Rypina, I.I., Baumann, H., Baumann, Z., Breier, C.F., Douglass, E.M., George, J., Macdonald, A.M., Miyamoto, H., Nishikawa, J., Pike, S.M., Yoshida, S. (2012) Fukushima-derived radionuclides in the ocean and biota off Japan. *Proceedings of the National Academy of Sciences* 109(16): 5984-5988.

Buesseler, K., Dai M., Aoyama, M., Benitez-Nelson, C., Charmasson, S., Higley, K., Maderich, V., Masqué, P., Oughton, D., Smith, J.N. (2017) Fukushima Daiichi–Derived Radionuclides in the Ocean: Transport, Fate, and Impacts. *Annual Review of Marine Science* 9.

Carvalho, F.P. (2011) Polonium (^{210}Po) and lead (^{210}Pb) in marine organisms and their transfer in marine food chains. *Journal of Environmental Radioactivity* 102: 462-472.

Carvalho, F.P. (2018) Radionuclide concentration processes in marine organisms: A comprehensive review. *Journal of Environmental Radioactivity* 186: 124-130.

Cherry, R.D., Heyraud, M., Higgo, J.J.W. (1983) Polonium-210: its relative enrichment in the hepatopancreas of marine invertebrates, *Marine Ecology Progress Series* 13: 229-236.

Fowler, S. W. (1997) Marine biogeochemistry of radionuclides. *Strategies and methodologies for applied marine radioactivity studies*, IAEA-TCS-7, 82.

Fowler, S.W., Heyraud, M., Beasley, T.M. (1975) Experimental studies on plutonium kinetics in marine biota. In: *Impacts of nuclear releases into the aquatic environment proceedings series*. IAEA: p. 157-176.

Fowler, S.W., Buat-Menard, P., Yokoyama, Y., Ballestra, S., Holm, E., Van Nguyen, H. (1987) Rapid removal of Chernobyl fallout from Mediterranean surface waters by biological activity. *Nature* 329: 56 – 58.

Fowler, S.W., Fisher, N.S. (2005) Radionuclides in the biosphere. In: Livingston HD, editor. *Radioactivity in the Environment: Marine Radioactivity*. Amsterdam: Elsevier Science. p. 167-203.

[http://dx.doi.org/10.1016/S1569-4860\(05\)80007-5](http://dx.doi.org/10.1016/S1569-4860(05)80007-5)

Garnier-Laplace, J., Della-Vedova, C., Gilbin, R., Copplestone, D., Hingston, J., Ciffroy, P. (2006) First Derivation of Predicted-No-Effect Values for Freshwater and Terrestrial Ecosystems Exposed to Radioactive Substances. *Environmental Science and Technology* 40: 6498-6505.

Garnier-Laplace, J., Della-Vedova, C., Andersson, P., Copplestone, D., Cailles, C., Beresford, N.A., Howard, B.J., Howe, P., Whitehouse, P. (2010) A multi-criteria weight of evidence approach to derive ecological benchmarks for radioactive substances. *Journal of Radiological Protection* 30: 215-233.

Harmelin-Vivien, M., Bodiguel, X., Charmasson, S., Loizeau, V., Mellon-Duval, C., Tronczyński, J., Cossa, D. (2012) Differential biomagnification of PCB, PBDE, Hg and Radiocesium in the food web of the European hake from the NW Mediterranean. *Marine pollution bulletin* 64(5): 974-983.

Heldal H.E., Føyn L., Varskog P. (2003) Bioaccumulation of ¹³⁷Cs in pelagic food webs in the Norwegian and Barents Seas. *Journal of Environmental Radioactivity* 65: 177-185.

IAEA (1985) Sediment Kds and Concentration Factors for Radionuclides in the Marine Environment. International Atomic Energy Agency Technical Report Ser. No. 247, Vienna, Austria.

IAEA (1988) Assessing the Impact of Deep Sea Disposal of Low Level Radioactive Waste on Living resources. International Atomic Energy Agency Technical Report Ser. No. 288, Vienna, Austria.

IAEA (2004) Sediment distribution coefficients and concentration factors for biota in the marine environment. International Atomic Energy Agency Technical Report Ser. No. 422, Vienna, Austria.

ICRP (1997) Individual Monitoring for Internal Exposure of Workers. ICRP Publication 78. Ann. ICRP 27 (3-4).

ICRP (2007) Recommendations of the International Commission on Radiological Protection. Ann. ICRP publication 103. Ann. ICRP 37(2.4), 2.

ICRP (2008) Environmental Protection - the Concept and Use of Reference Animals and Plants. Ann. ICRP Publication 108. Ann. ICRP 38 (4).

ICRP (2009) Environmental Protection – Transfer Parameters for Reference Animals and Plants. Ann. ICRP Publication 114. Ann. ICRP 39 (6).

Johansen, M.P., Ruedig, E., Tagami, K., Uchida, S., Higley, K., Beresford, N.A., Mathew, P. (2015) Radiological dose rates to marine fish from the Fukushima Daiichi accident: the first three years across the North Pacific. *Environmental Science and Technology* 49(3): 1277-1285.

Kasamatsu, F., Ishikawa, Y. (1997) Radiocesium contamination of cetaceans stranded along the coast of Hokkaido, Japan, and an estimation of their travel routes. *Marine Ecology Progress Series* 160: 109-120.

Lieser, K.H. (2008) Nuclear and radiochemistry: fundamentals and applications. 2nd Edition John Wiley & Sons. 462 p.

Madigan, D.J., Baumann, Z., Fisher, N.S. (2012) Pacific Bluefin Tuna transport Fukushima-derived radionuclides from Japan to California. *Proceedings of the National Academy of Sciences*, 109(24): 9483-9486.

Mathews, T., Fisher, N. (2008) Evaluating the trophic transfer of cadmium, polonium, and methylmercury in an estuarine food chain. *Environmental Toxicology and Chemistry* 27(5): 1093-101. doi: 10.1897/07-318.1.

Metian, M., Pouil, S., Hédouin, L., Oberhänsli, F., Teyssié, J-L, Bustamante, P., Warnau, M. (2016) Differential bioaccumulation of ^{134}Cs in tropical marine organisms and the relative importance of exposure pathways. *Journal of Environmental Radioactivity* 152: 127-135.

Peck, D., Samei, E. (2017) How to understand and communicate radiation risk. Image Wisely, <http://www.imagewisely.org/imaging-modalities/computed-tomography/medical-physicists/articles/how-to-understand-and-communicate-radiation-risk> Accessed May 2017.

Pentreath, R.J. (1998) Radiological Protection Criteria for the Natural Environment. *Radiation Protection Dosimetry*, 75: 175-179.

Pentreath, R.J. (2009) Radioecology, radiobiology, and radiological protection: frameworks and fractures. *Journal of environmental radioactivity* 100(12): 1019-1026.

Pouil, S., Oberhänsli, F., Swarzenski, P.W., Bustamante, P., Metian, M. (2018) The role of salinity in the trophic transfer of ^{137}Cs in euryhaline fish. *Journal of Environmental Radioactivity* 189: 255-260.

Stewart, G.M., Fowler, S.W., Teyssié, J.L., Cotret, O., Cochran, J.K., Fisher, N.S. (2005) Contrasting transfer of polonium-210 and lead-210 across three trophic levels in marine plankton. *Marine Ecology Progress Series*, 290: 27-33.

Tateda, Y. (1998) Concentration Factor of ^{137}Cs for Zooplankton Collected from the Misaki Coastal Water. *Fisheries Science* 64(1): 176-177.

UNSCEAR (2000) Report to the General Assembly with Scientific Annexes, Sources and Effects of Ionizing Radiation, Scientific Annex E. UN publication, ISBN 92-1-142238-8.

UNSCEAR (2008) Report Sources and Effects of Ionizing Radiation. Volume I: SOURCES Report to the General Assembly Scientific Annexes A and B. Scientific Annex E. UN publication, ISBN 978-92-1-142274-0.

UNSCEAR (2012) Sources, Effects, and Risks of Ionizing Radiation, United Nations Scientific Committee on the Effects of Atomic Radiation, Report to the General Assembly with Scientific Annexes ISBN: 978-92-1-142307-5

Whicker, F.W., Schultz, V. (1982) *Radioecology: Nuclear Energy and the Environment*. CRC Press, Boca Raton, 212 p.

Zhao, X., Wang, W-X., Yu, K-N, Lam, P.K.S. (2001) Biomagnification of radiocesium in a marine piscivorous fish, *Marine Ecology Progress Series* 222: 227-237.

Reading Lists

Carvalho, F.P. (2018) Radionuclide concentration processes in marine organisms: A comprehensive review. *Journal of Environmental Radioactivity* 186: 124-130.

Fisher N.S., Fowler, S.W., Boisson, F., Carroll, J., Rissanen, K., Salbu, B., Sazykina, T.G., Sjoebloom, K-L. (1999) Radionuclide Bioconcentration Factors and Sediment Partition Coefficients in Arctic Seas Subject to Contamination from Dumped Nuclear Wastes. *Environmental Science and Technology* 33: 1979-1982.

Fowler, S.W., Fisher, N.S. (2004) Radionuclides in the biosphere. In: Livingston HD, editor. *Radioactivity in the Environment: Marine Radioactivity*. Amsterdam: Elsevier Science. p. 167-203.

[http://dx.doi.org/10.1016/S1569-4860\(05\)80007-5](http://dx.doi.org/10.1016/S1569-4860(05)80007-5)

IAEA (2004) *Sediment Distribution Coefficients and Concentration Factors for Biota in the Marine Environment*. Vienna: International Atomic Energy Agency: IAEA Technical Reports Series No. 422.

http://www-pub.iaea.org/MTCD/publications/PDF/TRS422_web.pdf

Lieser, K.H. (2008) *Nuclear and radiochemistry: fundamentals and applications*. 2nd Edition John Wiley & Sons. 462 p.

Pentreath, R.J. (2009) Radioecology, radiobiology, and radiological protection: frameworks and fractures. *Journal of environmental radioactivity*, 100(12): 1019-1026.

Vives i Batlle J, et al. (2018) Marine radioecology after the Fukushima Dai-ichi nuclear accident: Are we better positioned to understand the impact of radionuclides in marine ecosystems? *Science of The Total Environment* 618: 80-92.

Websites of Interest:

International Atomic Energy Agency (IAEA): <https://www.iaea.org/>

ERICA Assessment Tool: <http://www.ERICA-tool.com/>

International Commission on Radiation Protection (ICRP): <http://www.icrp.org/>

International Union of Radioecology: <http://www.iur-uir.org/en/>

Radioecology Exchange: <http://www.radioecology-exchange.org/>

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR):

<http://www.unscear.org/>

RiO5 Cookbook. For more information on how to measure specific radionuclides in seawater:

<https://cmer.whoi.edu/cookbook>

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