Assessment of doses for Arctic marine biota

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Abstract. The objectives of this paper are the presentation of site-specific radioecological information and development of models, which can be used to calculate doses to Arctic marine biota. The methodology of calculating doses from α, β, and γ-emitters is presented. This methodology is realized in form of computer code DOSBIO, and model parameters are evaluated. The following annual doses to biota are calculated: internal dose from radionuclides incorporated in the organisms; external dose from contaminated water; external dose from contaminated bottom sediments; total dose as a sum of internal and external doses. Dose conversion factors are calculated for 15 species of marine biota, including fish, sea mammals, molluscs. The list of species includes cod, plaice, haddock, herring, redfish, Greenland halibut, char, saithe, Greenland seal, white whale, ringed seal, bearded seal, and others. The calculations are performed for adult representatives of each species. Calculated dose conversion factors are presented for 11 different radionuclides (H-3, C-14, K-40, Sr-90, Tc-99, Sb-124, Cs-137, Eu-152, Po-210, Pu-239, Am-241). The current and potential doses to marine biota from the Barents and Kara Seas are estimated.

1. INTRODUCTION

The subject of this paper is development of a computer model, which can be used to calculate doses to Arctic marine biota, and to estimate current and potential doses to the arctic biota from the Barents and Kara Seas. It is taken into account that doses to biota are summing over external irradiation owing to the presence of radionuclides in the water column and bottom sediments, and internal irradiation owing to the uptake and assimilation of radionuclides by biota.

2. METHODOLOGY FOR DOSE ASSESSMENT TO AQUATIC BIOTA

2.1 Radiation dose from incorporated radionuclides

If the dimensions of aquatic organism are large compared to the path length of alpha and beta particles, the dose rate to an aquatic organism is approximately equal to the specific dose rate created in the infinite volume of an absorbing material, within which the radionuclide is uniformly distributed. The radionuclide activity concentration y (Bq·kg^{-1} of the absorber mass) corresponds to the emitter content in the organism's tissues. The value of dose rate P_α^∞ or P_β^∞ (pGy·s^{-1}) can be found using the following formula [1-5]:

$$P_\alpha^\infty = 0.16 \cdot \overline{E}_\alpha y \quad (1)$$

$$P_\beta^\infty = 0.16 \cdot \overline{E}_\beta y; \quad (2)$$

where $\overline{E}_\alpha$ is the average energy of alpha particle per decay (MeV).

The average dose rate in the tissue from the uniformly incorporated gamma emitters is calculated with the following formula [1-5]:

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$$P_\gamma = 1.1454 \cdot y \cdot \Gamma \cdot g \cdot 10^{-5}; \tag{3}$$

where P_γ is the average dose rate, $pGy \cdot s^{-1}$; y is the activity concentration of a radionuclide in the tissue, $Bq \cdot kg^{-1}$; Γ is the gamma radiation constant of the radionuclide, $aGy \cdot m^2 \cdot (s \cdot Bq)^{-1}$; g is the average geometric factor, cm. The values of the average geometric factors for cylinders of different sizes were calculated in the specialized dosimetric literature [1].

2.2 Radiation dose from external sources

The dose rates to aquatic organisms from alpha and beta emitters scattered in the water depth are calculated with the following formulas:

$$P_{\alpha,W} = P_\alpha^\infty - P_\alpha(F)_V \tag{4}$$

$$P_{\beta,W} = P_\beta^\infty - P_\beta(F)_V; \tag{5}$$

where P_α^∞ and P_β^∞ are calculated with the formulas (2) and (4), whereas $P_\alpha(F)_v$ and $P_\beta(F)_v$ characterize the dose rates in the area occupied by the organism. All these quantities are determined from the radionuclide concentration in water.

Considering the water depth as an infinite source with a uniformly distributed gamma emitter, we can calculate the external gamma-radiation dose rate to aquatic organisms P_γ^∞ (in $pGy \cdot s^{-1}$) with the following formula [4-5]:

$$P_\gamma^\infty = \frac{4\pi \cdot 1.11 \cdot \Gamma \cdot X}{\mu_S}\left(\frac{A_1}{1-\alpha_1} + \frac{1-A_1}{1+\alpha_2}\right); \tag{7}$$

where A_1, α_1 and α_2 are the coefficients in the exponential Taylor representation of the accumulation factor of scattered radiation [4]; X is the concentration of the radionuclide in water, $Bq \cdot L^{-1}$; μ_s is the gamma radiation attenuation factor, cm^{-1}.

When radionuclides are concentrated in thick (>10 cm) surface layer of bottom sediments, the external gamma-radiation dose rate from the sediments to the organisms can be estimated as equal to $0.5 \cdot P_\gamma^\infty$. If the thickness of the contaminated layer is less then 10 cm the external gamma-radiation dose rate from the sediments can be estimated using a well-known relationship for the determination of the gamma-radiation field from a source in the form of a shielded sheet [4].

3. CALCULATION OF DOSE CONVERSION FACTORS FOR THE ARCTIC BIOTA USING THE COMPUTER CODE *DOSBIO*

The computer code DOSBIO was developed for calculating doses to marine biota in the Arctic Seas from natural and technogenic radionuclides. The internal, external and total doses from α, β, and γ-emitters were calculated for 15 species of marine biota, including fish, sea mammals and molluscs. The calculations are performed for adult representatives of each species. Programme DOSBIO was used for calculating the dose conversion factors from the unit concentration of each radionuclide in organisms or in the marine environment. Calculations of dose conversion factors were performed for 35 different radionuclides. The programme starts with the automatic reading of the data base information. The programme runs a dialog with the user, asking to specify the request on calculations. The user types the request, selecting the radionuclide, the aquatic organism, activity in water, sediments, and organism's tissues. If no data on sediment or biota contamination were provided by the user, these information is calculated automatically by the programme, using default values from data base. Programme runs the dose calculations, according to formulas (1) – (7). The detailed description of the programme DOSBIO is given in the publication [6].

The dose conversion factors calculated with the DOSBIO code for the Arctic biota for the most important radionuclides are shown in Table 1.

Table 1. Calculated dose conversion factors for marine biota in the Arctic Seas

Species	H-3	C-14	K-40	Sr-90	Tc-99	Sb-124	Cs-137	Eu-152	Po-210	Pu-239	Am-241
Internal dose conversion factors, $(10^{-6}$ Gy/year$)\cdot($Bq/kg w.w.$)^{-1}$											
Greenland halibut	0.0288	0.2488	2.3436	5.6714	0.4839	3.1334	1.3179	1.4827	27.2471	26.3893	28.1049
Haddock	0.0288	0.2488	2.3074	5.6714	0.4839	2.6851	1.1669	1.1898	27.2471	26.3893	28.1049
Capelin	0.0288	0.2488	2.2682	5.6714	0.4839	2.1980	1.0028	0.8715	27.2471	26.3893	28.1049
Polar cod	0.0288	0.2488	2.2699	5.6714	0.4839	2.2186	1.0097	0.8850	27.2471	26.3893	28.1049
Plaice	0.0288	0.2488	2.3121	5.6714	0.4839	2.7423	1.1861	1.2272	27.2471	26.3893	28.1049
Char	0.0288	0.2488	2.3327	5.6714	0.4839	2.9985	1.2724	1.3945	27.2471	26.3893	28.1049
Saithe	0.0288	0.2488	2.3220	5.6714	0.4839	2.8658	1.2277	1.3079	27.2471	26.3893	28.1049
Herring	0.0288	0.2488	2.2793	5.6714	0.4839	2.3352	1.0490	0.9612	27.2471	26.3893	28.1049
Cod	0.0288	0.2488	2.3513	5.6714	0.4839	3.2295	1.3502	1.5455	27.2471	26.3893	28.1049
Redfish	0.0288	0.2488	2.3054	5.6714	0.4839	2.6600	1.1584	1.1734	27.2471	26.3893	28.1049
Greenland seal	0.0288	0.2488	2.4646	5.6714	0.4839	4.6361	1.8241	2.4645	27.2471	26.3893	28.1049
White whale	0.0288	0.2488	2.5217	5.6714	0.4839	5.3452	2.0629	2.9277	27.2471	26.3893	28.1049
Ringed seal	0.0288	0.2488	2.4268	5.6714	0.4839	4.1673	1.6661	2.1581	27.2471	26.3893	28.1049
Bearded seal	0.0288	0.2488	2.4959	5.6714	0.4839	5.0250	1.9551	2.7185	27.2471	26.3893	28.1049
Mollusc	0.0288	0.2488	2.2800	5.6714	0.4839	2.3444	1.0521	0.9672	27.2471	26.3893	28.1049
External dose conversion factors, $(10^{-6}$ Gy/year$)\cdot($Bq/L$)^{-1}$											
All species	-	-	3.3326	-	-	13.034	4.4591	7.8415	-	-	-

4. DOSE ASSESSMENT TO THE ARCTIC BIOTA

4.1 Dose assessment to the Arctic biota based on the actual radioactivity levels

The estimated doses for the biota of the Barents and Kara Seas obtained on the basis of actual radiooactivity levels in components of the marine ecosystem are presented in Table 2 [7]. One can see from this table that for Arctic marine biota the additional doses from artificial radionuclides are considerably lower than the doses from the natural background radiation.

4.2 Current dose levels to marine biota near RW disposal in the Kara Sea

The current radiological situation at RW dumping sites was inspected during the cruises of the Joint Russian-Norwegian expeditions in 1993 - 1994 [8-9]. In these cruises samples of water, sediments and biota were collected, and concentrations of specific radionuclides were measured. These data forms the database for calculating the current doses to marine organisms in the vicinity of RW dumping sites.

The expeditions to the sites of the radioactive waste disposals near the Novaya Zemlya didn't reveal any difference in the radiological situation as compared to the open Kara Sea [8-9]. The internal doses to the local biota are the same as for the Kara Sea biota. External exposure from sediments in the Tsivolki Fjord was estimated to be about $110\cdot10^{-9}$ Gy$\cdot$day^{-1}. During the survey to the Abrosimov Fjord [9], small local spots of bottom contamination were found in the vicinity of some dumped containers with radioactive wastes (but not near containers with the spent fuel). The highest levels of man-made radionuclides in bottom sediments within these spots were as follows: ^{137}Cs - about 2000 Bq/kg w.w.; ^{60}Co - up to 15-21 Bq/kg w.w. A general increase in the ^{137}Cs levels in bottom sediments of the Abrosimov Fjord was observed (13±8 Bq/kg w.w., which is approximately two times higher as compared with the sediments from the open Kara Sea). Small concentrations of ^{60}Co (2-5 Bq/kg w.w.) were also detected in the top layer (0-2 cm) of bottom sediments. The concentration of ^{137}Cs in water of the Abrosimov Fjord (about 3 Bq/m^3) did not differ from that in water of the open Kara Sea.

The calculated dose rates to mollusks inhabiting the contaminated spots of bottom sediments can be as great as $8.5 \cdot 10^{-6}$ Gy day^{-1}, whereas the average external exposure to molluscs in the Abrosimov Fjord is about $1 \cdot 10^{-7}$ Gy day^{-1}.

So, the doses to marine biota calculated using the current levels of radioactive contamination of the fjords, are very low, with the exception of some local contaminated spots, and cause no damage to marine biota.

Table 2. The estimated internal exposures for Arctic marine biota, 10^{-9} Gy/day

Marine biota	Barents Sea	Kara Sea	Natural background
Crustaceans	2	3	3500
Mollusks	3	5	2700
Fish	20	30	800

4.3 Dose assessment to the Arctic biota based on the potential release scenario

Potential doses to marine organisms inhabiting the radioactive waste (RW) dumping sites in the bays of Novaya Zemlya were calculated using predicted levels of future environmental contamination, associated with potential radionuclide releases from the containers with radioactive materials [10-11].

Model scenarios for the potential radionuclide releases patterns from the dumped containers with radioactive materials were developed within the framework of the International Arctic Seas Assessment Project (IASAP) under the auspices of the International Atomic Energy Agency [12]. These IASAP source term scenarios provided predictions of annual release rates for a wide set of radionuclides from each site of RW dumpings over the period of 1000 years in the future. To evaluate the highest potential doses to marine biota, we used the release rates predicted for the so-called 'plausible worst case scenario', based on the assumption of an accidental disruption in 2050 AD of dumped fuel containers in the Tsivolki Fjord, with a release 'spike' of 110,000 GBq followed by much smaller releases in the subsequent years.

4.4 Potential doses to marine biota in the Tsivolki Fjord

The highest levels of radioactive contamination of the fjord are expected in the case of realization of the so-called 'plausible worst case scenario' developed by the IASAP experts. The calculated concentrations of the most important radionuclides in water and bottom sediments of the Tsivolki Fjord during the period of highest releases (2050 AD) are given in Table 3 [11].

Table 3. Predicted levels of radionuclide concentrations in the Tsivolki Fjord in the case of realization of the IASAP 'plausible worst case scenario'[10,11]

Year	2050 AD	2050 AD
Radionuclide	Water, Bq/m^3	Sediments (0-5 cm), Bq/kg dw
^{137}Cs	0.42E+05	0.17E+03
^{90}Sr	0.37E+05	0.49E+02
^{63}Ni	0.11E+05	0.12E+05
^{239}Pu	0.14E+04	0.11E+03
^{240}Pu	0.62E+03	0.49E+02
^{241}Am	0.28E+03	0.49E+02

The calculated dose rates to different types of marine biota are presented in Table 4. Because of the presence of great amounts of actinides in the releases, their contribution to potential dose rates is dominating for mollusks and zooplankton. The contribution of internal exposure to the total dose rate for all types of organisms is greater than 90 %. No quality factors were used to estimate the relative biological effectiveness of alpha and beta emitters.

Table 4. Predicted dose rates to local marine biota in the fjord of Novaya Zemlya during the year of highest releases (2050 AD, Tsivolki Fjord) in the case of realization of the IASAP 'plausible worst case scenario'

Organism	Total dose rate, mGy day^{-1}	Contribution of actinides, %
	Year: 2050 AD	
Mollusc	0.48	100
Zooplankton	0.07	89.8
Small fish	0.026	26.3
Big fish	0.029	24
Sea mammal	0.033	20

According to [13], summarizing the effects of radiation on aquatic organisms, dose rates no greater than 10 mGy day^{-1} should ensure the survival of populations, although some damage to individuals may occur. By analysing the predicted dose rates to marine biota in the Tsivolki Fjord (see Table 4), one can conclude that the dose limit to some marine species will not be exceed; however, the calculations were made without consideration of quality factors for alpha and beta particles, so the actual impact of the actinides can be much higher than predicted levels. It should be also taken into account that the calculations were made on the assumption of a uniform distribution of the released radionuclides in water and uniform contamination of the seabed. However, some local spots of much higher contamination will certainly be formed in the vicinity of ruined containers.

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References

1. R. Loevinger, J.G. Holt, G.J. Hine In: *Radiation Dosimetry* (Eds. G.J. Hine & G.L. Brownell) (chapter 17). New York, Academic Press, 1956.
2. D.S. Woodhead In: IAEA Technical Report Series N 172, pp. 5-54 (1976).
3. D.S. Woodhead In: IAEA Technical Report Series N 190, pp. 43-96 (1979).
4. V.P. Mashkovich. *Protection from Ionizing Radiation.* Moscow, Energoatomizdat, 1982. (in Russian).
5. I.I. Kryshev & T.G. Sazykina. *Simulation Models for Ecosystem Dynamics Under Anthropogenic Effects of Heat Electric Generation and Nuclear Power Plants.* Moscow: Energoatomizdat, 1990. (in Russian).
6. A.I. Kryshev, T.G. Sazykina, I.I. Kryshev, P.Strand & J.E. Brown. *Environmental Modeling and Software* (2001). (in press).
7. I.I. Kryshev & T.G. Sazykina. *Journal of Environmental Radioactivity*, 29 (3), 213-223 (1995).
8. NRPA – Norwegian Radiation Protection Authority. *Results from Norwegian-Russian 1993 expedition to the Kara Sea.* Osteras, Norway, 1994.
9. NRPA - Norwegian Radiation Protection Authority. *Report from the Joint Norwegian/ Russian expedition to the dumping sites for radioactive waste in the Abrosimov Fjord and the Stepovogo Fjord, August-September 1994.* Osteras, Norway, 1995.
10. N. Lynn, S. Timms, J. Warden et al. In: *Environmental Radioactivity in the Arctic* (Eds. P. Strand & A. Cooke) (pp. 135-138). Osteras, Norway, 1995.
11. T.G. Sazykina, I.I. Kryshev & A.I. Kryshev. *Radiation Protection Dosimetry.* 75 (1-4), 253-256 (1998).
12. K.-L. Sjoeblom & G.S. Linsley. In: *Environmental Radioactivity in the Arctic* (Eds. P. Strand & A. Cooke) (pp. 15-20). Osteras, Norway, 1995.
13. NCRP - National Council on Radiation Protection and Measurements. *Effects of Ionizing Radiation on Aquatic Organisms.* NCRP Report N 109, Bethesda, USA, 1991.