1871
ИнБЮМ – IBSS

Морской биологический журнал
Marine Biological Journal
2023, vol. 8, no. 4, pp. 94–105
https://marine-biology.ru

UDC [504.5:620.267](268.45)

ASSESSMENT OF RADIATION EFFECT OF ^{137}Cs, ^{134}Cs, AND ^{90}Sr ON BIOTA OF THE BARENTS SEA IN THE VICINITY OF HYPOTHETICAL ACCIDENT WITH THE SUNKEN NUCLEAR SUBMARINE K-159

© 2023 **T. G. Sazykina and A. I. Kryshev**

Research and Production Association "Typhoon," Obninsk, Russian Federation
E-mail: *ecomod@yandex.ru*

Received by the Editor 30.11.2022; after reviewing 18.01.2023;
accepted for publication 04.08.2023; published online 01.12.2023.

Radiation effect of ^{137}Cs, ^{134}Cs, and ^{90}Sr on marine biota was modelled for early period of a hypothetical accident with the sunken nuclear submarine K-159 during its surfacing and transportation in the Barents Sea. Dynamics of radioactivity in seawater was described, using analytical 2-dimensional model of radionuclide dispersion from an instantaneous point release in seawater. Radioactive contamination of seawater and bottom sediments with ^{137}Cs, ^{134}Cs, and ^{90}Sr was calculated for distances from 200 m to 30 km from the source. Estimated dose of acute exposure accumulated within the first 10 days was close to 100 mGy for bottom fish at a 200-m distance from the accidental source of contamination. The probability of lethal effects for fish at this dose was estimated to be below 1%. Chronic exposures from ^{137}Cs, ^{134}Cs, and ^{90}Sr at a distance of 200 m from the accidental source of contamination during the first year after the accident were as follows: for bottom fish, 9.7 mGy·day^{-1}; molluscs, 11 mGy·day^{-1}; and aquatic plants, 6.3 mGy·day^{-1}. These dose rates exceed the reference level ensuring safety of marine biota. Therefore, in the vicinity of the accident site, the radiation situation cannot be considered safe for bottom fish, molluscs, and aquatic plants. At distances of more than 500 m from the accidental source of contamination, expected dose rates of chronic exposure to marine biota were below reference level. Dose rates for biota resulting from a hypothetical accident in the Barents Sea were caused mainly by external exposure from contaminated sediments and also by accumulation of long-lived radionuclides from sediments by bottom biota.

Keywords: Arctic, Barents Sea, radiation accident, modelling, marine biota, dose, acute exposure, chronic exposure

In the Arctic seas, there are a significant number of radiation hazard facilities: radioactive waste containers, dumped/sunken nuclear submarines, a nuclear-powered icebreaker, *etc.* Various scenarios of accidents during surfacing of sunken radiation hazard facilities for their transportation and disposal were developed [Sarkisov et al., 2015]. To calculate the results of radionuclide dispersion from an instantaneous point release in the Arctic marine environment, several models were used:

- NAOSIM ocean model with a grid of 28 × 28 km [Hosseini et al., 2017];
- regional model with a grid of 3 × 3 km [Antipov et al., 2015];
- ECOMOD-ARCTIC radioecological box model [Kryshev et al., 2022b; Sazykina, 1998];
- ARCTICMAR box model [Iosjpe et al., 2020].

In all the models listed, the dimensions of spatial grid and camera boxes turned out to be too large, and it was impossible to directly examine the nearest zone of radioactive contamination – the one with the highest levels of exposure to marine organisms. The methodological objective of this study is to develop techniques for assessing acute exposure to marine biota in the early period of a radiation accident. The analysis of its radioecological consequences, including radionuclide accumulation in bottom sediments and hydrobionts, was carried out using dynamic models, since in the acute period of an accident, it is incorrect to apply equilibrium coefficients of transition from seawater to bottom sediments and fish [Kryshev et al., 2022a, b; Sazykina et al., 2022].

Radiation effects on marine biota were modelled for a scenario of a hypothetical accident with a spontaneous chain reaction on the sunken submarine K-159 during its transportation in the Barents Sea to a disposal site. The nuclear submarine K-159 of the project 627A (now, B-159) sank on 30.08.2003 in the southern Barents Sea because of an emergency during its transportation for disposal. The site is in approximately 6 km from Kildin Island, on the slope of the Kildin part of the Murmansk Trench, at the entrance to the Kola Bay, at a depth of 246 m [Sarkisov et al., 2015]. For this nuclear and radiation hazard facility, there is a hypothetical possibility of a radiation accident with a spontaneous chain reaction, both when the submarine is at the bottom and when it is being surfaced for transportation, which could lead to the release of long-lived radionuclides into the marine environment [Antipov et al., 2015; Hosseini et al., 2017; Sarkisov et al., 2018]. Predictive estimates were made of radioactivity spread in seawater under different scenarios of accident, obtained using a gridpoint model with 3-km horizontal resolution [Antipov et al., 2015].

This work models the contribution of long-lived radionuclides (^{137}Cs, ^{134}Cs, and ^{90}Sr) to exposure to marine biota during the initial period of radioactive contamination of the marine environment in the nearest zone of the accident – from 200 m to 30 km from the source. The analysis is based on estimates of the release of long-lived radionuclides into the marine environment, which were obtained within the scenario of a spontaneous chain reaction in the K-159 reactor after the submarine surfacing for transportation. The following long-lived radionuclides are expected to be released into seawater: ^{137}Cs, $2.48 \cdot 10^{13}$ Bq; ^{134}Cs, $1.4 \cdot 10^{9}$ Bq; and ^{90}Sr, $5.72 \cdot 10^{12}$ Bq [Sarkisov et al., 2015]. The release of short-lived radionuclides into seawater was not assessed in this scenario. Determining their potential contribution to exposure to marine biota requires additional research.

The levels of radioactive contamination of seawater and bottom sediments during the movement and dispersion of the primary spot of radioactive contamination were calculated using an analytical model for distances up to 30 km from the source. The model of accidental contamination of the marine environment made it possible to determine the dose rate and absorbed dose for 10 days of exposure to marine biota and to estimate the probability of lethal effects for marine organisms in the acute period of a radiation accident from exposure to ^{137}Cs, ^{134}Cs, and ^{90}Sr near the source. In the immediate vicinity of the accident site, radioactive contamination of bottom sediments can persist for a long time. Therefore, along with the dose of acute exposure, the dose rate of chronic exposure of benthic organisms was assessed.

MATERIAL AND METHODS

When surfacing a dumped radiation hazard facility, an emergency may arise associated with radionuclide release into the marine environment. The scenario of a hypothetical accident during surfacing of the sunken nuclear submarine K-159 for its transportation and disposal is described in the work [Sarkisov et al., 2015]. After an accident, a spot of radioactively contaminated seawater is formed near the facility and is spread with sea currents. The volumetric activity of radionuclides in the contamination spot decreases with distance from the accident site.

To describe seawater contamination during the acute period of a radiation accident, a two-dimensional model of radionuclide dispersion in seawater from an instantaneous point release was used. The dynamics of depth-averaged volumetric radionuclide activity in seawater, Bq·m^{-3}, was calculated by the formula:

$$C_w(x,y,t) = \frac{A_0}{H} \cdot G(x,y,t) \cdot \exp\left(-\frac{w}{H} \cdot t\right), \tag{1}$$

where A_0 is the radionuclide activity released into seawater during an accident, Bq;

H is the depth at the accident site, m;

w is the hydraulic particle size, m·s^{-1};

t is the time from the moment of emergency (point) radionuclide release into seawater, s.

G(x,y,t) is the dynamic function of scattering in the marine environment of a single one-time source, which is assessed by the formula [Yurezanskaya, Koterov, 2011]:

$$G(x,y,t) = \frac{1}{2 \cdot \pi \cdot \sigma_x \cdot \sigma_y} \cdot \exp\left(-\frac{(x-u_x \cdot t)^2}{2 \cdot \sigma_x^2} - \frac{(y-u_y \cdot t)^2}{2 \cdot \sigma_y^2}\right), \tag{2}$$

where x, y are the distances along coordinate axes with the center at the location of the source of contamination, m;

u_x, u_y are speeds of currents along X- and Y-axis, respectively, m·s^{-1};

σ_x, σ_y are dispersion coefficients of the impurity distribution.

Dispersion coefficients of the impurity distribution were calculated by the formulas:

$$\sigma_x^2 = \alpha \cdot t^3 + \sigma_{0,x}^2\,; \quad \sigma_y^2 = \alpha \cdot t^3 + \sigma_{0,y}^2\,, \tag{3}$$

where $\alpha = 8 \cdot 10^{-9}$ m^2·s^{-3} for distances up to 10 km, and $\alpha = 2 \cdot 10^{-9}$ m^2·s^{-3} for distances more than 10 km;

σ_0 is the initial size of the radioactive contamination spot, m [Yurezanskaya, Koterov, 2011].

For a hypothetical accident with K-159, σ_0 value is taken to be equal to the submarine length, *i. e.*, $\sigma_0 = 107.4$ m [Sarkisov et al., 2015]. In the southern Barents Sea, the speed of the current $u_x = 0.4$ m·s^{-1}; the speed of the cross-current u_y is assumed to be zero (we consider contamination along the axis of the accident trail spread).

The specific activity of the radionuclide in the upper layer of bottom sediments, Bq·kg^{-1}, at time t_s was determined by the formula:

$$C_s(x,y,t_s) = \int_0^{t_s} \frac{w}{\rho_s \cdot h} \cdot C_w(t)dt\,, \tag{4}$$

where ρ_s is the density of bottom sediments taken equal to 1,250 kg·m^{-3};

h is the thickness of the upper (effective) layer of bottom sediments, h = 0.1 m [MARINA II, 2003].

Large suspended particles (1 mm or more) are characterized by turbulent settling; their hydraulic size does not depend on the viscosity of the fluid and is calculated by the formula [Koterov, Yurezanskaya, 2009]:

$$w = \sqrt{\frac{4 \cdot g \cdot d_p \cdot \rho_p}{3 \cdot r \cdot \rho_w}}\,, \tag{5}$$

where g = 9.8 m·s^{-2};

d_p is the suspended particle diameter, m;

r is the coefficient of water resistance for a spherical particle moving in it, r = 0.45 [Shilova, Studenov, 2017];

ρ_p is the density of suspended particles, ρ_p = 2,600 kg·m^{-3};

ρ_w is the density of seawater, ρ_w = 1,020 kg·m^{-3}.

The settling of large particles formed during an accident at a radiation hazard facility in the sea occurs in its nearest zone, at a distance of approximately $2 \cdot \sigma_0$. When suspended particles decrease in size from 10^{-3} to 10^{-6} m, the sedimentation speed in seawater drops from 10^0 to 10^{-4} m·s^{-1}. Small particles of radioactive contamination, comparable in size to particles of natural suspension in seawater, settle at rates corresponding to natural sedimentation. ^{137}Cs, ^{134}Cs, and ^{90}Sr can also be absorbed on natural suspension and settle together with the suspension into bottom sediments. Due to the settling of radioactive particles, in the upper layer of bottom sediments, a distributed source of radiation is formed; it affects the bottom biota both in the acute and long-term periods after accidental contamination. For the scenario under consideration, the value of w was calculated by formula (5) at $d_p = 10^{-3}$ m for distances up to 200 m from the site of the submarine K-159 sinking: w = 0.27 m·s^{-1}. For larger distances, w was taken equal to 10^{-4} m·s^{-1}.

The estimated time for passage of a seawater contamination spot near an accidental source is short in the presence of a sea current and amounts to about 30 min for distances up to 200 m. With a hydraulic particle size, w, of 0.27 m·s^{-1} and a depth of 246 m, this time is sufficient for the formation of a contamination spot in bottom sediments. The specific activity of long-lived radionuclides in bottom sediments remains high for a long time after an accident. Therefore, when considering the effect on marine biota, it is advisable to select benthic organisms associated with benthic food chains as reference objects. As assumed in this work, the accumulation of radionuclides in benthic hydrobionts in this case is caused to a greater extent by contamination of the upper layer of bottom sediments, rather than seawater.

To determine the specific activity of a radionuclide in small hydrobionts (molluscs, zoobenthos, and aquatic plants) C_b, Bq·kg^{-1}, one can conservatively use the linear dependence $C_b = CF_{b,s} \cdot C_s$, where $CF_{b,s}$ is the equilibrium coefficient of radionuclide transfer from bottom sediments to a hydrobiont. To calculate the dynamics of ^{137}Cs contamination of bottom fish after an accident, the equilibrium approach is not applicable [Kryshev, Ryabov, 2000]. The specific activity of a radionuclide in benthic fish C_f, Bq·kg^{-1}, assuming that the main source of its contamination is the trophic chain associated with bottom sediments, is calculated by the equation:

$$\frac{dC_f}{dt} = -(\lambda + \varepsilon + \mu) \cdot C_f + (\varepsilon + \mu) \cdot CF_{f,s} \cdot C_s\,, \tag{6}$$

where λ is the radioactive decay constant, day^{-1};

μ is the relative increase in fish mass, day^{-1};

$CF_{f,s}$ is the equilibrium coefficient of radionuclide transfer from bottom sediments to fish;

ε is the parameter characterizing the metabolism and exchange of ^{137}Cs in the fish body, day^{-1}.

The procedure for ε calculation depending on fish mass and seawater temperature is described in [Kryshev, Ryabov, 2000; Sazykina et al., 2022].

For a short time after the accident, we can neglect the radioactive decay of ^{137}Cs and the decrease in its content in bottom sediments due to its penetration into deeper layers; so, we can consider the parameters μ and ε to be constant values. Then, the equation (6) has an analytical solution:

$$C_f = CF_{f,s} \cdot C_s \cdot (1 - \exp(-(\mu + \varepsilon) \cdot t)) \,. \tag{7}$$

As a reference species of bottom fish, the European plaice *Pleuronectes platessa* Linnaeus, 1758 was chosen. With fish mass of 500 g, the calculated μ value is $6.45 \cdot 10^{-4}$ day^{-1} [European Plaice, 2021], and $\varepsilon = 1.5 \cdot 10^{-3}$ day^{-1}. The equilibrium coefficients of ^{137}Cs transfer from bottom sediments to the Barents Sea biota are 0.22 for fish, 0.12 for molluscs, and 0.16 for aquatic plants. The values for ^{90}Sr are as follows: 0.027 for fish, 0.047 for molluscs, and 0.043 for aquatic plants [Rosnovskaya et al., 2022].

The dose rate of exposure to marine biota, mGy·day^{-1}, was determined by the formula:

$$d_i = \beta_{int,i} \cdot C_i + \beta_{ext,i} \cdot (C_{w,i} + 0.5 \cdot \tau_s \cdot C_{s,i}) \,, \tag{8}$$

where $\beta_{int,i}$ is the dose coefficient of internal exposure to a hydrobiont, (mGy·kg)/(Bq·day);

C_i is the specific activity of the *i*-th radionuclide in a hydrobiont, Bq·kg^{-1};

$\beta_{ext,i}$ is the dose coefficient of external exposure to a hydrobiont, (mGy·kg)/(Bq·day);

$C_{w,i}$ is the specific activity of the *i*-th radionuclide in seawater, Bq·kg^{-1};

$C_{s,i}$ is the specific activity of the *i*-th radionuclide in bottom sediments, Bq·kg^{-1};

τ_s is the fraction of time during which a hydrobiont is exposed to radiation from bottom sediments, taken equal to 1 for bottom fish and molluscs and 0.5 for aquatic plants.

The values of the dose coefficients were determined using the BiotaDC calculator, v.1.5.1 (http://biotadc.icrp.org), an annex to [ICRP Publication 136, 2017]. Marine organisms were approximated by ellipsoids with the following mass and ratios between axes: fish (the European plaice), 0.5 kg and 1 / 0.6 / 0.04; bivalves, $1.64 \cdot 10^{-2}$ kg and 1 / 0.5 / 0.5; and aquatic plants, $6.5 \cdot 10^{-3}$ kg and 1 / 0.01 / 0.01. The calculated values of dose coefficients for estimating internal and external exposure to marine organisms from ^{137}Cs, ^{134}Cs, and ^{90}Sr are given in Table 1.

Table 1. Dose coefficients for calculation of exposure to marine organisms, (mGy·day^{-1})/(Bq·kg^{-1})

Radionuclide	The European plaice	Molluscs	Aquatic plants
Internal exposure			
^{137}Cs	$3.77 \cdot 10^{-6}$	$3.62 \cdot 10^{-6}$	$3.1 \cdot 10^{-6}$
^{134}Cs	$3.34 \cdot 10^{-6}$	$2.95 \cdot 10^{-6}$	$2.28 \cdot 10^{-6}$
^{90}Sr	$1.34 \cdot 10^{-5}$	$1.37 \cdot 10^{-5}$	$1.07 \cdot 10^{-5}$
External exposure			
^{137}Cs	$7.49 \cdot 10^{-6}$	$7.63 \cdot 10^{-6}$	$8.16 \cdot 10^{-6}$
^{134}Cs	$2.04 \cdot 10^{-5}$	$2.08 \cdot 10^{-5}$	$2.15 \cdot 10^{-5}$
^{90}Sr	$2.12 \cdot 10^{-6}$	$1.82 \cdot 10^{-6}$	$4.8 \cdot 10^{-6}$

Doses of acute exposure were assessed as total absorbed doses accumulated by marine biota during the first 10 days after the accident. The distribution of the probability of lethal effects was determined by the formula [Finney, 1971]:

$$P = \frac{1}{\sqrt{2 \cdot \pi}} \cdot \int\limits_{-\infty}^{Pr} \exp\left(-\frac{t^2}{2}\right) dt\,, \tag{9}$$

where the upper limit of integration of the Gauss error function is the so-called probit function which reflects the correlation between the probability of lethal effects and the absorbed dose.

The value of the probit function was calculated by the formula:

$$Pr = a_{Pr} + b_{Pr} \cdot \ln D\,, \tag{10}$$

where D is the dose of acute exposure, mGy.

To determine the parameters of the probit function for fish and molluscs, we used literature data on lethal effects for these hydrobionts after acute exposure at different doses [Effects of Ionizing Radiation, 1976; Polikarpov, 1964; Polikarpov, Egorov, 1986] (Table 2).

Table 2. Lethal effects of acute exposure to marine biota in relation to the absorbed dose and the calculated probit function, (mGy·day^{-1})/(Bq·kg^{-1})

Dose, D, mGy	Ln(D)	% of lethality	Value of probit function
Fish (adult)			
100	4.605	0.1	1.5
1,000	6.907	2.5	3.12
3,500	8.161	30	4.48
5,000	8.517	50	5
10,000	9.210	90	5.52
Marine molluscs			
10,000	9.210	50	4.75
20,000	9.903	70	5.5
40,000	10.596	90	6.28

Graphs of the probit function dependence on the logarithm of the absorbed dose were approximated by a linear function (Fig. 1). The values for parameters in formula (10) were as follows: $a_{Pr} = -2.74$ for fish and $a_{Pr} = -5.42$ for molluscs; $b_{Pr} = 0.89$ for fish and $b_{Pr} = 1.1$ for molluscs. The probability of lethal effects for marine organisms depending on the dose received in the first 10 days after the accident was calculated by formula (9) using standard tables [Finney, 1971; Metodika modelirovaniya, 2015].

During chronic exposure to marine biota from contaminated bottom sediments, the criterion for the occurrence of adverse radiobiological effects is the excess of the reference level of radiation dose rate for a given ecological group [ICRP Publication 108, 2008; ICRP Publication 124, 2014; Sazykina et al., 2022]. The reference level is 1 mGy·day^{-1} for fish and aquatic plants and 10 mGy·day^{-1} for molluscs. When the reference level is exceeded under chronic exposure throughout life of marine organisms, their health and reproductive capacity are impaired, and their lifespan is reduced [Sazykina, Kryshev, 2003; Sazykina et al., 2009].

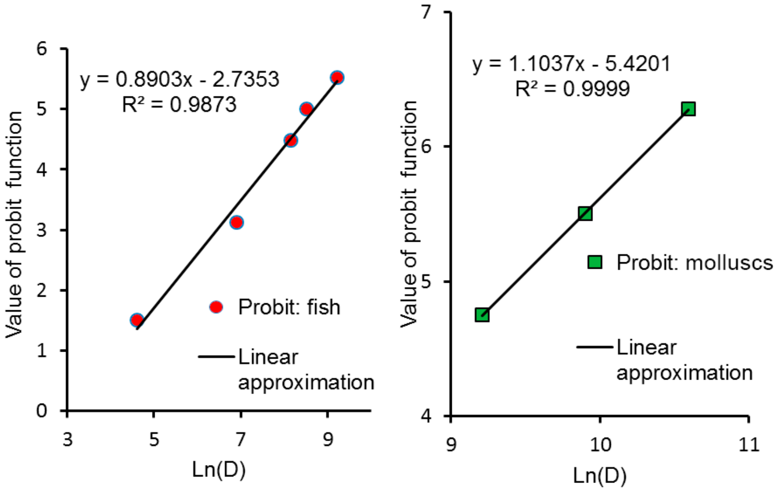

Fig. 1. Relationship between the probit function and logarithm of the acute dose (mGy) for fish (left side) and marine molluscs (right side)

RESULTS AND DISCUSSION

The calculated dynamics of water contamination with ^{137}Cs at a distance from 200 m to 30 km from the accidental source is shown in Fig. 2. In 200 m from the source, the time of passage of a contamination spot is no more than 30 min, and the maximum volumetric activity of ^{137}Cs in seawater during this period does not exceed 10^6 Bq·m^{-3}. At a distance of 30 km, the volumetric activity of ^{137}Cs in seawater is maximum in 17 h after the accident and amounts to $6.3 \cdot 10^3$ Bq·m^{-3}. It is worth noting as follows: during the acute period of a radiation accident, comparison of calculated values for volumetric activity of ^{137}Cs in seawater with the control levels of radionuclide content in it [Poryadok rascheta, 2016] is incorrect due to the lack of equilibrium in radionuclide dispersion between the components of the marine ecosystem.

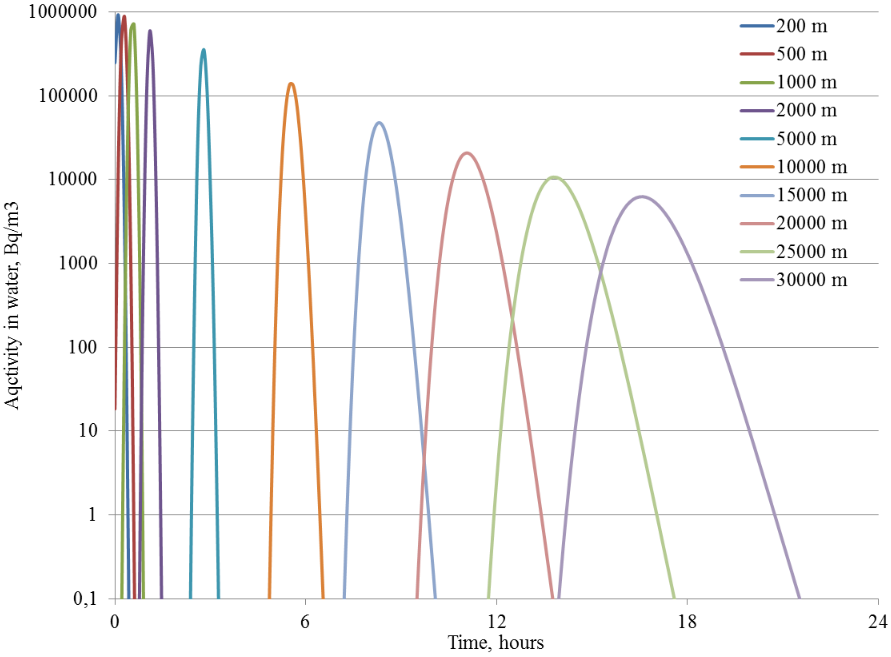

Fig. 2. Calculation of ^{137}Cs volume activity in seawater at different distances from the accidental source of contamination

The calculated dynamics of bottom sediment contamination with ^{137}Cs depending on the distance from the accidental source is presented in Fig. 3. Near the accident site (200 m), the specific activity of ^{137}Cs in the upper layer of bottom sediments can reach $1.2 \cdot 10^6$ Bq·kg^{-1}, and this exceeds the criterion for classifying this radionuclide as solid radioactive waste by 120 times. When moving away from the accident site, the estimated contamination of bottom sediments decreases significantly, since an assumption is made that the largest radionuclide-containing particles settle near the source of contamination. At a distance of 10 km from the accident site, the calculated specific activity of ^{137}Cs in bottom sediments does not exceed 150 Bq·kg^{-1}. Unlike seawater contamination, bottom sediment contamination with ^{137}Cs slowly decreases over time, being a long-term source of exposure to benthic biota.

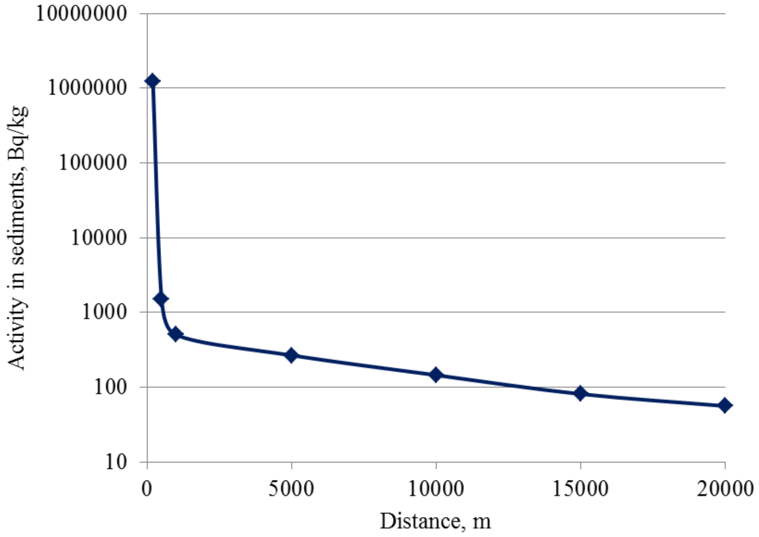

Fig. 3. Maximum activity concentrations of ^{137}Cs in bottom sediments at different distances from the accidental source of contamination

According to calculated estimates, the maximum volumetric activity of ^{90}Sr in seawater at a distance of 200 m from the accident site during the passage of the contamination spot does not exceed $2 \cdot 10^5$ Bq·m^{-3}. Contamination of bottom sediments with ^{90}Sr at a distance of 200 m from the accident site will be $2.8 \cdot 10^5$ Bq·kg^{-1}. The maximum volumetric activity of ^{134}Cs in seawater and its specific activity in bottom sediments will be 50 Bq·m^{-3} and 65 Bq·kg^{-1}, respectively. The initial emergency release of ^{134}Cs into the marine environment is estimated to be 18,000 times lower than that of ^{137}Cs and 4,000 times lower than the value for ^{90}Sr [Sarkisov et al., 2015].

The accumulation of ^{137}Cs in benthic organisms is associated with its content in the upper layer of bottom sediments. The calculated specific activity of ^{137}Cs in molluscs at a distance of 200 m from the accident site is $2.6 \cdot 10^5$ Bq·kg^{-1}; in aquatic plants, the value is $1.9 \cdot 10^5$ Bq·kg^{-1}. When moving away from the accident site, their contamination decreases in proportion to the contamination of bottom sediments. As follows from formula (7), during the first 30 days after the accident, the specific activity of ^{137}Cs in benthic fish increases almost linearly; at a distance of 200 m from the source of contamination, the value rises from 400 to 6,000 Bq·kg^{-1}. Under the conservative assumption that fish constantly occur there for several years, and the specific activity in bottom sediments does not decrease with time, the maximum (equilibrium) value of $2.4 \cdot 10^5$ Bq·kg^{-1} is achieved no earlier than in two years after the accident.

The dose of acute exposure to bottom fish in the first 10 days after the accident is estimated at almost 100 mGy. The value of the probit function according to formula (10) is 1.36. The probability of lethal effects for fish equal to 1% is achieved with the value of the probit function of 2.67. Thus, the probability of death of bottom fish from exposure with ^{137}Cs, ^{134}Cs, and ^{90}Sr over 10 days of the acute period of the hypothetical accident under consideration is < 1%.

The estimated dose rate of chronic exposure to the Barents Sea hydrobionts from long-lived radionuclides during the first year after the accident at different distances from the source of contamination is given in Table 3. In 200 m, the dose rate of chronic exposure to hydrobionts from an emergency release of ^{137}Cs is estimated to be 9.0 mGy·day^{-1} for fish, 9.7 mGy·day^{-1} for molluscs, and 5.5 mGy·day^{-1} for aquatic plants, with the main contributor being external exposure. The maximum dose rate of chronic exposure to hydrobionts from an emergency release of ^{90}Sr is estimated to be 0.7 mGy·day^{-1} for fish, 0.7 mGy·day^{-1} for molluscs, and 0.8 mGy·day^{-1} for aquatic plants. ^{134}Cs makes an insignificant contribution to the dose rate of exposure to hydrobionts, both in acute and chronic periods: no more than $1.4 \cdot 10^{-3}$ mGy·day^{-1} for fish, $1.5 \cdot 10^{-3}$ mGy·day^{-1} for molluscs, and $8.2 \cdot 10^{-4}$ mGy·day^{-1} for aquatic plants.

Table 3. Dose rate of chronic exposure to marine organisms with ^{137}Cs, ^{134}Cs, and ^{90}Sr at different distances from the accidental source of contamination, mGy·day^{-1}

Distance, m	Fish	Molluscs	Aquatic plants
200	$9.7 \cdot 10^{0}$	$1.1 \cdot 10^{1}$	$6.3 \cdot 10^{0}$
500	$1.4 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	$7.9 \cdot 10^{-3}$
1,000	$4.5 \cdot 10^{-3}$	$4.3 \cdot 10^{-3}$	$2.6 \cdot 10^{-3}$
5,000	$2.4 \cdot 10^{-3}$	$2.4 \cdot 10^{-3}$	$1.4 \cdot 10^{-3}$
10,000	$1.3 \cdot 10^{-3}$	$1.3 \cdot 10^{-3}$	$7.6 \cdot 10^{-4}$
20,000	$7.2 \cdot 10^{-4}$	$6.9 \cdot 10^{-4}$	$4.3 \cdot 10^{-4}$

As follows from Table 3, at a distance of 500 m or greater from the source of contamination, the dose rate of exposure for all reference species is significantly lower than the reference level of safe chronic exposure (1 mGy·day^{-1}). Therefore, we can conclude about the local nature of the radioecological effect of a hypothetical accident with the nuclear submarine K-159 to the Barents Sea biota.

For benthic organisms that permanently inhabit the area of maximum contamination of bottom sediments (up to 200 m from the accident site), the dose rates indicated in Table 3 persist for several years. Due to the excess of the reference level of chronic exposure, these dose rates cannot be considered safe for the development of populations of bottom fish, molluscs, and aquatic plants in the immediate vicinity of the accident site.

Conclusion. The contribution of ^{137}Cs, ^{134}Cs, and ^{90}Sr to radioactive contamination of the marine environment was calculated, and dose rates on marine biota in the early period of contamination were determined for a hypothetical scenario of a radiation accident with the sunken nuclear submarine K-159.

The dose of acute exposure to bottom fish from ^{137}Cs, ^{134}Cs, and ^{90}Sr at a distance of 200 m from the accident site in the first 10 days is almost 100 mGy. The probability of lethal effects for bottom fish at such an absorbed dose is estimated to be less than 1%. Assessment of the release of short-lived radionuclides into the marine environment and their contribution to acute exposure to marine biota requires additional research within the framework of the scenario of an accident.

Contamination of bottom sediments with long-lived radionuclides slowly decreases over time, being a long-term source of exposure to benthic biota. The dose rate of chronic exposure to marine biota within the first year after the accident at a distance of 200 m from the source of contamination is estimated to be 9.7 mGy·day^{-1} for bottom fish, 11 mGy·day^{-1} for molluscs, and 6.3 mGy·day^{-1} for aquatic plants. These levels are higher than the reference value for dose rate of chronic exposure that ensure the safety of marine biota.

At a distance of 500 m and greater from the source of contamination, the dose rate of chronic exposure to marine biota is significantly lower than the reference level. This makes it possible to predict the local nature of the effect of a hypothetical accident on the Barents Sea ecosystem.

REFERENCES

1. Antipov S. V., Bilashenko V. P., Vysotskii V. L., Kalantarov V. E., Kobrinskii M. N., Sarkisov A. A., Sotnikov V. A., Shvedov P. A., Ibraev R. A., Sarkisyan A. S. Prediction and evaluation of the radioecological consequences of a hypothetical accident on the sunken nuclear submarine B-159 in the Barents Sea. *Atomnaya energiya*, 2015, vol. 119, iss. 2, pp. 106–113. (in Russ.)
2. Koterov V. N., Yurezanskaya Y. S. Simulation of suspended substance dispersion on the ocean shelf: Effective hydraulic coarseness of polydisperse suspension. *Zhurnal vychislitel'noi matematiki i matematicheskoi fiziki*, 2009, vol. 49, no. 7, pp. 1245–1256. (in Russ.)
3. Kryshev A. I., Sazykina T. G., Katkova M. N., Kryshev I. I., Buryakova A. A., Pavlova N. N. Assessment of ecological risk to biota of the Stepovogo Bay of the Kara Sea after the hypothetical accidental contamination. *Radiatsionnaya biologiya. Radioekologiya*, 2022a, vol. 62, no. 4, pp. 424–433. (in Russ.)
4. *Metodika modelirovaniya rasprostraneniya avariinykh vybrosov opasnykh veshchestv. Rukovodstvo po bezopasnosti.* Utverzhdeno prikazom Federal'noi sluzhby po ekologicheskomu, tekhnologicheskomu i atomnomu nadzoru ot 20.04.2015 no. 158. Moscow : ZAO "NTTs PB", 2015, 125 p. (Normativnye dokumenty v sfere deyatel'nosti Federal'noi sluzhby po ekologicheskomu, tekhnologicheskomu i atomnomu nadzoru. Series 27. Deklarirovanie promyshlennoi bezopasnosti i otsenka riska ; iss. 11). (in Russ.)
5. Polikarpov G. G. *Radioekologiya morskikh organizmov.* Moscow : Atomizdat, 1964, 295 p. (in Russ.). https://repository.marine-research.ru/handle/299011/12748
6. Polikarpov G. G., Egorov V. N. *Morskaya dinamicheskaya radiokhemoekologiya.* Moscow : Energoatomizdat, 1986, 176 p. (in Russ.). https://repository.marine-research.ru/handle/299011/7683
7. *Poryadok rascheta kontrol'nykh urovnei soderzhaniya radionuklidov v morskikh vodakh* : rekomendatsii R-52.18.852-2016 / Rosgidromet. Obninsk : FGBU "NPO "Taifun", 2016, 28 p. (in Russ.)
8. Rosnovskaya N. A., Kryshev A. I., Kryshev I. I. Determination of control levels of radionuclides ensuring acceptable environmental risk in the Barents Sea water and bottom sediments. *Morskoj biologicheskij zhurnal*, 2022, vol. 7, no. 4, pp. 70–80. (in Russ.). https://marine-biology.ru/mbj/article/view/360
9. Sazykina T. G., Kryshev A. I., Kryshev I. I. *Modelirovanie radioekologicheskikh protsessov v okruzhayushchei srede.* Moscow : OOO "Maska", 2022, 638 p. (in Russ.)
10. Sarkisov A. A., Antipov S. V., Vysotsky V. L., Kobrinsky M. N., Shvedov P. A., Bilashenko V. P., Khokhlov I. N. Forecast of the radioecological consequences of hypothetical accidents in nuclear and radiation hazardous objects located at the bottom of the Barents and Kara seas. *Atomnaya energiya*, 2018, vol. 125, iss. 6, pp. 343–351. (in Russ.)
11. Sarkisov A. A., Sivintsev Yu. V., Vysotskii V. L.,

Nikitin V. S. *Atomnoe nasledie kholodnoi voiny na dne Arktiki. Radioekologicheskie i tekhniko-ekonomicheskie problemy radiatsionnoi reabilitatsii morei.* Moscow : IBRAE RAN, 2015, 699 p. (in Russ.)

12. Shilova N. A., Studenov I. I. Peculiarities of calculation of hydraulic particle size to simulate the initial concentration of suspended substances in the estuarine areas of the Arctic seas (the case of the White Sea). *Arctic Environmental Research*, 2017, vol. 17, no. 4, pp. 295–307. (in Russ.). https://doi.org/10.17238/issn2541-8416.2017.17.4.295
13. Yurezanskaya Y. S., Koterov V. N. *Modelirovanie perenosa vzveshennykh veshchestv na okeanicheskom shel'fe.* Moscow : Lambert Academic Publishing, 2011, 116 p. (in Russ.)
14. *Effects of Ionizing Radiation on Aquatic Organisms and Ecosystems.* Vienna : IAEA, 1976, 131 p. (IAEA Technical Report Series ; no. 172).
15. *European Plaice (Pleuronectes platessa) of the Barents Sea: A Retrospective Review of Fishing and Research Activities for the Period 2016–2020 and a Modern Assessment of the State of Its Reserves.* Report on the Research Work. Agreement no. 18/2021 between the Polar Branch of the VNIRO (PINRO) and GELA Ltd. Murmansk : PINRO, 2021, 25 p.
16. Finney D. J. *Probit Analysis.* 3rd edition. New York : Cambridge University Press, 1971, 333 p.
17. Hosseini A., Amundsen I., Brown J., Dowdall M., Dyve J. E., Klein H. *Radiological Impact Assessment for Hypothetical Accident Scenarios Involving Russian Nuclear Submarine K-159.* Østerås : Statens Strålevern, 2017, 145 p. (Strålevern Rapport ; no. 12).
18. ICRP Publication 108. Environmental protection: The concept and use of reference animals and plants. *Annals of the ICRP*, 2008, vol. 38, nos 4–6, 242 p.
19. ICRP Publication 124. Protection of the environment under different exposure situations. *Annals of the ICRP*, 2014, vol. 43, no. 1, 58 p.
20. ICRP Publication 136. Dose coefficients for non-human biota environmentally exposed to radiation. *Annals of the ICRP*, 2017, vol. 46, no. 2, 136 p.
21. Iosjpe M., Amundsen I., Brown J., Dowdall M., Hosseini A., Strand P. *Radioecological Assessment After Potential Accidents with the Russian Nuclear Submarines K-27 and K-159 in the Arctic Marine Environment.* Østerås : Norwegian Radiation and Nuclear Safety Authority, 2020, 78 p. (DSA Report ; no. 7).
22. Kryshev A. I., Ryabov I. N. A dynamic model of ^{137}Cs accumulation by fish of different age classes. *Journal of Environmental Radioactivity*, 2000, vol. 50, iss. 3, pp. 221–233. https://doi.org/610.1016/S0265-931X(99)00118-6
23. Kryshev A. I., Sazykina T. G., Katkova M. N., Buryakova A. A., Kryshev I. I. Modelling the radioactive contamination of commercial fish species in the Barents Sea following a hypothetical short-term release to the Stepovogo Bay of Novaya Zemlya. *Journal of Environmental Radioactivity*, 2022b, vols 244–245, art. no. 106825 (9 p.). https://doi.org/10.1016/j.jenvrad.2022.106825
24. *MARINA II. Update of the MARINA Project on the Radiological Exposure of the European Community from Radioactivity in North European Marine Waters.* Vol. 2. Luxembourg : Office for Official Publications of the European Communities, 2003, 364 p. (Radiation Protection ; 132).
25. Sazykina T. G. The regional radioecological model “Arctic” for predictions of radioactive contamination of the Barents and Kara seas. In: *International Symposium on Marine Pollution*, Monaco, 5–9 October, 1998 : Extended Synopses. [Vienna] : International Atomic Energy Agency, 1998, pp. 339–340.
26. Sazykina T. G., Kryshev A. I. EPIC database on the effects of chronic radiation in fish: Russian/FSU data. *Journal of Environmental Radioactivity*, 2003, vol. 68, iss. 1, pp. 65–87. https://doi.org/10.1016/S0265-931X(03)00030-4
27. Sazykina T. G., Kryshev A. I., Sanina K. D. Non-parametric estimation of thresholds for radiation effects in vertebrate species under chronic low-LET exposures. *Radiation and Environmental Biophysics*, 2009, vol. 48, iss. 4, pp. 391–404. https://doi.org/10.1007/s00411-009-0233-0

ОЦЕНКА РАДИАЦИОННОГО ВОЗДЕЙСТВИЯ ^{137}Cs, ^{134}Cs, ^{90}Sr НА БИОТУ БАРЕНЦЕВА МОРЯ ВБЛИЗИ ИСТОЧНИКА ЗАГРЯЗНЕНИЯ ПРИ ГИПОТЕТИЧЕСКОЙ АВАРИИ С ЗАТОНУВШЕЙ АТОМНОЙ ПОДВОДНОЙ ЛОДКОЙ К-159

Т. Г. Сазыкина, А. И. Крышев

Научно-производственное объединение «Тайфун», Обнинск, Российская Федерация
E-mail: *ecomod@yandex.ru*

Выполнено моделирование воздействия излучения ^{137}Cs, ^{134}Cs, ^{90}Sr на морскую биоту для гипотетической аварии с самопроизвольной цепной реакцией на затонувшей подводной лодке К-159 при её подъёме и транспортировке в Баренцевом море. Для описания загрязнения морской воды в острый период аварии использована двумерная модель рассеивания радионуклидов в морской воде от мгновенного источника. Рассчитано радиоактивное загрязнение ^{137}Cs, ^{134}Cs, ^{90}Sr морской воды и донных отложений на расстояниях от 200 м до 30 км от источника. Доза острого облучения придонной рыбы от ^{137}Cs, ^{134}Cs, ^{90}Sr на расстоянии 200 м от места аварии за первые 10 дней составляет почти 100 мГр. Согласно оценке, вероятность летальных эффектов для придонной рыбы при такой поглощённой дозе — менее 1 %. Мощность дозы хронического облучения морской биоты ^{137}Cs, ^{134}Cs, ^{90}Sr в течение первого года с момента аварии на расстоянии 200 м от источника загрязнения оценена в 9,7 мГр·сут$^{-1}$ для придонной рыбы, 11 мГр·сут$^{-1}$ для моллюсков и 6,3 мГр·сут$^{-1}$ для водных растений. Эти уровни выше референтного значения мощности дозы хронического облучения, обеспечивающего безопасность морской биоты, поэтому нельзя рассматривать такие дозовые нагрузки как безопасные для развития популяций придонной рыбы, моллюсков и водных растений в непосредственной близости от места аварии. При удалении от источника загрязнения на 500 м и более мощность дозы хронического облучения морской биоты значительно ниже референтного уровня. Дозовые нагрузки на биоту Баренцева моря для аварийного сценария обусловлены преимущественно внешним облучением от донных отложений, а также переходом долгоживущих радионуклидов из донных отложений в придонные организмы.

Ключевые слова: Арктика, Баренцево море, радиационная авария, моделирование, морская биота, доза, острое облучение, хроническое облучение