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Research Article

Radiation risk assessment for the population from C-14 emissions of the World's first NPP and Smolensk NPP*

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Abstract

The results of the internal radiation dose calculations for the population and the assessment of the radiation risk from radioactive carbon C-14 during the normal operation of the World's First Nuclear Power Plant in Obninsk and Smolensk NPP are presented. Calculations were carried out using two methods, taking into account the inhalation and oral intake of C-14 with food into the human body. Radiation doses are $5.69 \cdot 10^{-9}$ Sv/year and $5.95 \cdot 10^{-9}$ Sv/year (for Obninsk NPP), $3.77 \cdot 10^{-7}$ Sv/year and $3.96 \cdot 10^{-7}$ Sv/year (for Smolensk NPP), which is orders of magnitude less than the established minimum significant dose (10 µSv). The assessed levels of radiation risk for the population does not exceed the risk established by NRB 99/2009 ($1 \cdot 10^{-5}$). It was found that the main contribution to the formation of the dose and risk of internal radiation of the population from C-14 radiation, released by the respective NPP, was the incorporation of radionuclide with locally produced food products, which is confirmed by the results of calculations using two methods, taking into account the influence of two nuclear power plants.

Keywords

carbon-14, nuclear power plant, internal radiation dose, radiation risk, inhalation, food consumption

Introduction

After the World's First NPP was put into operation in Obninsk in 1954, and in the course of introducing nuclear technologies, public safety of radiation facilities was of paramount importance. In the early days of the nuclear industry evolution, however, the regulatory framework in the field of health physics was not so perfect which caused difficulties in assessing operating safety of radiologically hazardous facilities for the public. Currently, a comprehensive framework has been established for the radiological safety regulation, and technologies have been developed for its implementation. One of the key radiation safety criteria is a constraint, that is, a pre-introduced value of individual risk involved in the radiation from the given source (risk constraint), which is used in situations with scheduled exposure as one of the parameters for optimizing protection and safety as applied to

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the source in question, and serves as a constraint for determining the range of options in the process of optimization (IAEA 2014). Radiation safety of the public from potential exposure sources is achieved via engineering measures for reducing the probability of events that may lead to the constraint of generalized risk ($1 \cdot 10^{-5}$) (NRB-99/2009, 2009), defined in NRB-99/2009, being exceeded (SP 2.6.1.2612-10, 2009). Therefore, assessing the public exposure risk in the course of the NPP operation allows characterizing the implementation of the optimization principle for ensuring radiation safety of the population residing in the NPP affected area.

The accumulated knowledge makes it possible to assess retrospectively the radiation situation in the observation area of the World's First NPP (with the AM-1 reactor: AM is the Russian abbrevation for *Peaceful Atom*) in the course of its operation years. For comparion, we shall characterize the radiological hazard for the population currently residing in the observation area of the Smolensk NPP with RBMK-1000 reactors.

In this paper, the radiological hazard from radioactive carbon (C-14) generated in NPPs in appreciable quantities will be chosen for comparison and demonstration of the NPP public safety. İt should be noted that expert studies show that gas and aerosol C-14 emissions account for much of the contribution to the exposure dose for the population residing in the vicinity of nuclear power and industry sites (Germansky 2009; Kryshev et al. 2020). The C-14 half-life is long (5730 years) which contributes to the accumulation of C-14 in the environment, while, according to some estimates (Rublevskii and Yatsenko 2019), it accounts for 96% of the exposure dose for the public residing in the NPP observation area. Recently, therefore, increased attenion has been given to monitoring the radioactive carbon emissions from NPPs and determining the exposure dose they form.

The purpose of the study is to assess comparatively the radiation risk from radioactive carbon emissions for the Obninsk population in the course of operating the World's First NPP and for the population residing in the Smolensk NPP observation area.

Investigation targets

The purpose of the study is to investigate C-14 emissions from the Obninsk and Smolensk NPPs. The Obninsk NPP with the AM-1 pressure-tube graphite-water reactor was in operation in 1954–2002. Along with electricity and heat production, the AM-1 reactor with an electric power of 5 MW and a thermal power of 30 MW was used for generation of isotopic products, neutronic and solid body physics studies, and many other investigations, specifically for in-core detectors and reactivity control rods (The World's First NPP 2023). According to data from JSC Rosenergoatom Concern (Smolensk NPP Website 2023), the Smolensk NPP's annual electricity generation amounts to about 20 billion kW·h. The NPP has three operating units with RBMK-1000 pressure-tube uranium-graphite reactors. The electric power of the Smolensk NPP's unit 1 is 212 times as high as that of the World's First NPP.

Investigation methods

The internal exposure doses and risks were estimated using a number of methods to minimize the risk estimation uncertainties.

The C-14 emission data required for the calculations were borrowed from (Rublevskii and Yatsenko 2016; Kryshev et al. 2020). The emission for all reactors is only in the form of CO_2. The emission for the Obninsk NPP was 0.5 GBq/day, while, as shown by data from a radiation engineering survey, the annual emission of C-14 and the calculated volumetric activity of this nuclide at critical points of the Smolensk NPP deployment locality are 12.1 TBq/g and $2.15 \cdot 10^{-2}$ Bq/m^3 respectively (Kryshev et al. 2020).

Further estimates require determining the C-14 volumetric activity in the Obninsk NPP affected area. The yearly averaged Obninsk NPP emissions amount to 0.18 TBq/g.

The C-14 volumetric activity in the atmospheric air is assumed to depend linearly on the radionuclide annual emission:

$$\frac{\text{C-14 volumetric activity for the Smolensk NPP}}{\text{C-14 volumetric activity for the Obninsk NPP}} = \frac{\text{Total C-14 emission for the Smolensk NPP}}{\text{Total C-14 emission for the Obninsk NPP}}$$

The calculated volumetric activity of C-14 in the Obninsk NPP affected area is assumed to be equal to $3.24 \cdot 10^{-4}$ Bq/m^3.

Calculation of the public internal exposure dose

Method 1 for calculating the public internal exposure dose in the NPP observation area is based on data contained in Kryshev et al. 2020, Garnier-Laplace and Roussel-Debet 2010.

A number of assumptions were made to calculate the committed annual internal dose and estimate the public radiation risk from C-14 emissions.

The annual internal exposure dose for C-14 emissions is calculated based on assumed inhalation and ingestion human exposure pathways.

The current methodologies for calculating the committed annual exposure dose based on calculated volumetric activities of radionuclides in atmospheric air rely on the assumption that equilibrium of the radionuclide specific activity in air and biological tissue is achieved (Kryshev et al. 2020). To minimize the calculation errors, it is assumed in this paper that no equilibrium is achieved in the radionuclide content between atmospheric air and human body. Such assumption is possible due to the fact that the population in the NPP deployment locality consumes the minimum amount (approximately 10%) of local food products (Kryshev et al. 2020). In connection with the foregoing, the annual internal exposure dose, given the C-14 inhalation and ingestion intake, was calculated using formula Kryshev et al. 2020, SC030162/SR2 2006

$$D_{\text{C-14}} = \varepsilon_{\text{inh}} U C_{\text{C-14\_a}} + \varepsilon_{\text{f}} \Sigma a_i R_i C_{\text{C-14\_p},i}, \tag{1}$$

where ε_{inh} is the dose conversion factor for the C-14 inhalation equal to $2.0 \cdot 10^{-9}$ Sv/Bq (SC030162/SR2 2006); U is the inhalation rate equal to $8.1 \cdot 10^{3}$ m^3/year (MU 2.6.5.010-2016.2.6.5 2016); $C_{\text{C-14\_a}}$ is the volumetric activity in the observation area air, Bq/m^3; ε_{f} is the dose conversion factor for the C-14 radionuclide intake with food equal to $5.8 \cdot 10^{-10}$ Sv/Bq (SC030162/SR2 2006); a_i is the share of the i^{th} local product in the population diet; R_i is the annual public consumption of the i^{th} product, kg (diary products, meat and potato were taken into account); and $C_{\text{C-14\_p},i}$ is the specific activity of C-14 in the i^{th} local food product, Bq/kg.

Most of the models take into account only atmospheric carbon pollution as the result of gas and aerosol emissions. In the process of photosynthesis, CO_2 is incorporated into the plant organic substance. Equilibrium is achieved then between the specific activity of radioactive carbon in CO_2 and C-14 as part of the plant organic substance being "built" (Garnier-Laplace and Roussel-Debet 2010). The key assumption is that the transport of small C-14 radionuclide quantities is identical to the C-12 atom transport. Further, via nutritional chains, C-14 enters the animal biomass and human bodies. It also needs to be taken into account that traditional estimates for the radiological effects from C-14 emissions on land ecosystems are of an empiric nature while there is an implied C-14 equilibrium in the atmosphere-plant or atmosphere-animal system.

In connection with the foregoing, the content of C-14 in plant products was estimated using formula Kryshev et al. 2020, Garnier-Laplace and Roussel-Debet 2010

$$C^{\text{p}}_{\text{C-14\_p},i} = f_{\text{v},i} C_{\text{C-14\_a}} / C_{\text{C-12\_a}}, \tag{2}$$

where $f_{\text{v},i}$ is the share of carbon in the i^{th} plant product, kgC/kg (in accordance with Garnier-Laplace and Roussel-Debet 2010, the following values of the carbon share are assumed: 0.059 for vegetables, 0.062 for fruits, 0.39 for cereals, 0.046 for potato and root vegetables); $C_{\text{C-14\_a}}$ is the volumetric activity of C-14 in the residence area air, Bq/m^3; and $C_{\text{C-12\_a}}$ is the mass of carbon in the form of CO_2 per air volume unit ($1.8 \cdot 10^{-4}$ kg/m^3).

The content of radioactive carbon in plant products is calculated using formula Kryshev et al. 2020, Garnier-Laplace and Roussel-Debet 2010

$$C_{\text{C-14\_p},i} = f_{\text{ap},i} f_{\text{cont},i} C_{\text{C-14\_a}} / C_{\text{C-12\_a}}, \tag{3}$$

where $f_{\text{ap},i}$ is the share of carbon in the i^{th} animal product, kgC/kg (in accordance with Garnier-Laplace and Roussel-Debet 2010, 0.065 is for milk, and 0.2 is for meat); $f_{\text{cont},i}$ is the share of contaminated animal fodder equal to 1; and $C_{\text{C-14\_a}}$ is the C-14 volumetric activity in the animal food production area air, Bq/m^3.

Method 2 for estimating the exposure dose formed by the C-14 radionuclide incorporated into the human body is based on the IAEA publication (IAEA 2001). The following assumptions are introduced for the calculations:

a) only the C-14 emission into the atmospheric air during the NPP operation is taken into account;
b) the C-14 that has entered the atmosphere by way of photosynthesis is incorporated into the plant biomass and moves into the human body through the food chains;
c) only the human internal exposure dose in the event of intake with food products (milk, potato, meat) is calculated.

The effective annual dose from beta radiation of the C-14 contained in food products is calculated using the formula below

$$E = A f_{\text{C},a} g, \tag{4}$$

where E is the effective dose, Sv/year; A is the specific activity of C-14 (Bq/gC) in local food products; $f_{\text{C},a}$ is the share of carbon in locally produced foods (assumed to be equal to 1); and g is the effective dose factor (the ratio between the annual dose rate (Sv/year) and the concentration of C-14 per g of carbon in human body) assumed to be equal to $5.6 \cdot 10^{-5}$ Sv/year per Bq/gC.

The value of the C-14 specific activity in atmospheric air is calculated using formula

$$A = C_{\text{C-14\_a}} / C, \tag{5}$$

where A is the C-14 specific activity value, Bq/gC; $C_{\text{C-14\_a}}$ is the volumetric activity of C-14 in the NPP deployment area air, Bq/m^3; and C is the average concentration of carbon in atmospheric air (equal to 0.18 g/m^3) which fits the average concentration of CO_2 in the atmosphere equal to 330 ppm.

The contribution to the human exposure via the inhalation intake of C-14 was estimated in the same way as with Method 1.

The calculated specific activities of C-14 in food products are: 0.12 and 7.76 Bq/kg for milk, 0.36 and 23.89 Bq/kg for meat, and 0.08 Bq/kg and 5.49 Bq/kg for potato for Obninsk and Desnogorsk respectively.

Estimation of the radiation risk from C-14 emission

The public radiation risk for the NPP affected area was estimated based on recommendations contained in the methodology provided in R 52.18.787-2013 2014. This also took into account the recommendations in IAEA 2001 where the following is noted. If there are no radiation monitoring data for the full-scale description of the radiation situation in the particular locality or these are insufficient, then models that take into account the regional radiation situation parameters are used to estimate the lacking information.

According to the classical definition, the lifetime risk magnitude is directly proportional to the effective exposure dose with the radiation risk factor taken into account

$$r_i = E_i r_{E,i}, \tag{6}$$

where r_i is the individual lifetime risk, person^{-1}; E_i is the effective exposure dose, Sv; and $r_{E,i}$ is the lifetime risk factor, Sv^{-1}.

The risk was estimated taking into account the assumptions formulated for the public exposure dose calculation. The lifetime risk factor is determined for the human inhalation intake of C-14 and for the ingestion intake with locally produced foods.

The radiation risk for the human inhalation intake of C-14 during the year was calculated using formula R 52.18.787-2013 2014

$$r_{E,\mathrm{inh}} = r_{\mathrm{inh}} U C_{\mathrm{C\text{-}14\_a}}, \tag{7}$$

where r_{inh} is the radiation risk factor for inhalation of the C-14 carbon, risk/Bq ($r_{\mathrm{inh}} = 1.3\cdot10^{-10}$ risk/Bq (R 52.18.787-2013 2014); U is the inhalation rate, m^3/year ($U = 8.1\cdot10^3$ m^3/year [14]; and $C_{\mathrm{C\text{-}14\_a}}$ is the volumetric activity of C-14 in atmospheric air, Bq/m^3.

The radiation risk from the C-14 beta radiation during the C-14 dietary intake is determined using the following formula

$$r_{E,\mathrm{ing}} = r_{\mathrm{ing}} \Sigma C_{f,i} R_i B_i, \tag{8}$$

where r_{ing} is the radiation risk factor for the C-14 intake with food assumed to be equal to $7.9\cdot10^{-11}$ risk/Bq (R 52.18.787-2013 2014); $C_{f,i}$ is the specific activity of C-14 in the i^{th} food product, Bq/kg; R_i is the annual public consumption of the i^{th} product, kg/year (300 for milk, 60 for meat, and 138 for potato (SC030162/SR2 2006); and B_i is the coefficient that allows for the loss of C-14 as the result of the i^{th} product cooking (1 for milk, 0.9 for meat, and 0.8 for potato (SC030162/SR2 2006).

Results and discussion

The estimated internal exposure dose for adult population from the C-14 emission in the event of the human radionuclide intake when inhaling contaminated air and with local food products is presented in Table 1.

The major contributor to the public internal exposure dose from the C-14 radiation is the radionuclide intake with food products which is confirmed by the results of the calculations based on two methods, taking into account the effects from two NPPs (Table 1). The calculated annual cumulative internal exposure doses from the C-14 radiation are several orders of magnitude smaller than the minimum significant dose of 10 μSv specified for the NPP normal operating mode in the event of the public emission effects (SanPiN 2.6.1.24-03.2.6.1 2003) and amount to $5.69\cdot10^{-9}$ and $5.95\cdot10^{-9}$ Sv (for the Obninsk NPP), and $3.77\cdot10^{-9}$ and $3.96\cdot10^{-9}$ Sv (for the Smolensk NPP). It should be noted that the biggest contributor to the internal exposure dose is the human ingestion intake of the radionuclide which is explained by the calculated annual exposure doses being two orders of magnitude larger than the respective inhalation intake values. At the same time, no critical difference is observed in the calculations obtained using different methods.

Table 1. Annual exposure dose from the NPP C-14 emissions

NPP	Calculated annual exposure dose from C-14, Sv (Method 1)		Calculated annual exposure dose from C-14, Sv (Method 2)	
	Inhalation intake of C-14	Ingestion intake of C-14	Inhalation intake of C-14	Ingestion intake of C-14
Obninsk	$1.63\cdot10^{-11}$	$5.67\cdot10^{-9}$	$1.63\cdot10^{-11}$	$5.93\cdot10^{-9}$
Smolensk	$1.08\cdot10^{-9}$	$3.76\cdot10^{-7}$	$1.08\cdot10^{-9}$	$3.95\cdot10^{-7}$

The calculated values of the annual internal exposure doses were taken into account to estimate the individual radiation risk from the C-14 radionuclide emissions (Table 2).

Table 2. Individual lifetime radiation risk from C-14 emissions for Desnogorsk and Obninsk residents

NPP	Risk, person^{-1}			Cumulative risk (Method 1)	Cumulative risk (Method 2)
	Inhalation	For food products (Method 1)	For food products (Method 2)		
Obninsk	$5.55\cdot1^{-21}$	$3.50\cdot10^{-17}$	$3.65\cdot10^{-17}$	$3.50\cdot10^{-17}$	$3.65\cdot10^{-17}$
Smolensk	$2.45\cdot10^{-17}$	$1.54\cdot10^{-13}$	$1.61\cdot10^{-13}$	$1.54\cdot10^{-13}$	$1.61\cdot10^{-13}$

Most of the risk from the C-14 internal beta radiation for the public in the NPP observation area adjoining localities is formed via the consumption of locally produced foods.

No excessive values of the risk constraint ($1\cdot10^{-5}$ (NRB-99/2009 2009) is observed in an analysis of the cumulative radiation risk and the risk in the event of the radionuclide incorporation with food products or with inhaled air. Also noteworthy are very small values of lifetime radiation risks from one of the key NPP-emitted dose forming radionuclides.

Conclusions

It has been found based on the obtained estimates for the exposure dose from the NPP-emitted atmospheric C-14 radiation that the annual effective public internal exposure dose in the normal operation mode of the World's First Nuclear Power Plant in Obninsk and the Smolensk NPP is much below the minimum significant dose of 10 μSv.

The value of the total individual lifetime risk (from inhalation and ingestion of food products contaminated with C-14) for the public is much smaller than the specified constraint of the generalized public radiation risk ($1 \cdot 10^{-5}$ person^{-1} (NRB-99/2009 2009) (by 12 and 8 orders of magnitude for Obninsk and Desnogorsk respectively). The public radiation safety within the observation areas of the NPPs under consideration, with regard for the internal exposure dose from the emitted C-14 radiation, was therefore achieved in accordance with the optimization principle. It should be noted that the estimates were obtained with a number of assumptions only for the C-14 radionuclide inhaled by humans or ingested with local plant and animal food products.

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