Atmospheric emission of $^{137}$Cs$_{82}$ from Beloyarsk nuclear power plant

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Abstract. Citing Beloyarsk nuclear power plant (Russia) as an example, the problem of remote detection of radioactivity in the atmospheric pollution is examined. The comparative analysis of injected radionuclides into the atmosphere from the nuclear power plant with advanced fast neutron reactor is carried out. The main radionuclides throw out into the atmosphere from the nuclear power plant are beta-radionuclides. The secondary and tertiary spectra of beta-electrons decay for artificial radionuclide $^{137}$Cs$_{82}$ is calculated, using Spencer-Fano’s equation. The averaged parameters of initial beta–electrons generated by $^{137}$Cs$_{82}$ decay in the atmosphere is calculated.

1. Introduction
The actuality of this research concludes in accumulation of the huge amount of radioactive materials, only spent fuel more than 270000 tons, safety time defined by thousand years. Time decay of radionuclides and their mobility in the environment allow a component of radioactive waste to distribute widely in the natural food chain [1, 2]. Existing decisions could be divided on; building a new nuclear waste storage or recycle recovered fuel. For example, countries that do not possess the latest nuclear technologies are planning to build additional radioactive waste storage facilities, while in Russia this problem is solved by designing and launching nuclear power plants (NPPs) with fast neutron reactors (BN reactor). To implement the agreement on the disposition of plutonium, signed in 2000 between Russia and the United States, Russia is developing and commissioning fast neutron reactors for burning MOX fuel. The work of such NPPs is highly expected since they will increase the efficiency of the use of uranium, $^{238}$U and $^{232}$Th may be involved in the fuel cycle, which in nature is much larger than $^{235}$U, the main fuel for thermal neutron reactors. The nuclear reactors work with great expectations on fast neutrons, as it would: increase the efficiency of the use of uranium, $^{238}$U and $^{232}$Th stocks may be involved in the fuel cycle, which of nature is much greater than $^{235}$U - the main fuel for thermal reactors. Including can be used and so-called "depleted uranium" remaining after enrichment of nuclear fuel $^{235}$U. It is interesting and relevant to consider the gas-aerosol radioactive emissions and theoretically justify the possibility of remote detection of increased radioactivity in air emissions from the Beloyarsk power plant with nuclear reactor BN (BAES) [3, 4].

2. Analysis of averaged gas-aerosol emission in the atmosphere by BAES working in the normal mode
Beloyarsk nuclear power plant is located in 42 km east of Yekaterinburg city and 3 km north of Zarechny town. In the event of hypothetic accident situation, it could be thrown from the tube out a bulk of radioactivity in the atmosphere and the radioactivity composition of which are not known. The
The purpose of the given work was the estimate of electron density formed in the emission plume from Beloyarsk nuclear power plant. Despite the main part of radioactivity in an emission plume are β-active radionuclides named in the paper radioactive inert gases (RIG) we consider separate isotope $^{137}$Cs, $^{14}$C, $^{89}$Sr, $^{90}$Sr from a plume of Beloyarsk nuclear power plant. In the example of calculation of electron density in the emission plume was chosen $^{137}$Cs.

It is necessary to note that radioactive inert gases are Ar, Kr, Xe and etc. consists in an emission plume from enterprises of nuclear fuel cycle constantly. The nuanced analysis of radionuclides content in emission plume from enterprises of nuclear fuel cycle consists in [5].

The amount of radioactivity and the composition of radionuclides in emissions depend on the type of reactor. Radioactive noble gases (RBG) are manifested through radioactive decay of products in fuel. Moreover, RBGs can appear as a result of neutron activation. Thus, $^{41}$Ar can also be contained in the air. The main elements contained in the emissions of nuclear power plants with a BN reactor: $^{24}$Na (33%), $^{137}$Cs (33%), $^{134}$Cs (16%). Some radionuclides with a small half-life are not included in the table.

### Table 1. Annual estimation of the atmospheric emissions from various nuclear reactors.

| Radionuclide | BWR, Bq∙y$^{-1}$ [6] | PWR, Bq∙y$^{-1}$ [6] | FBR, Bq∙y$^{-1}$ [7] | BAES, Bq∙y$^{-1}$ [8-10] |
|--------------|------------------------|------------------------|----------------------|--------------------------|
| $^{41}$Ar    | 9.25⋅10$^{11}$         | 9.25⋅10$^{11}$         | —                    | —                        |
| $^{83m}$Kr  | < 3.7⋅10$^{10}$        | 3.7⋅10$^{10}$          | —                    | —                        |
| $^{85m}$Kr  | 5.55⋅10$^{12}$         | 5.2⋅10$^{11}$          | —                    | —                        |
| $^{85}$Kr   | 1.073⋅10$^{13}$        | 1.739⋅10$^{13}$        | —                    | —                        |
| $^{87}$Kr   | 7.4⋅10$^{12}$          | 1.11⋅10$^{11}$         | —                    | —                        |
| $^{89}$Kr   | 8.88⋅10$^{12}$         | 8.51⋅10$^{11}$         | —                    | —                        |
| $^{131m}$Xe | 6.66⋅10$^{11}$         | 3.034⋅10$^{12}$        | —                    | —                        |
| $^{133m}$Xe | < 3.7⋅10$^{10}$        | 4.44⋅10$^{12}$         | —                    | —                        |
| $^{133}$Xe  | 1.184⋅10$^{14}$        | 4.44⋅10$^{14}$         | —                    | —                        |
| $^{135m}$Xe | 2.738⋅10$^{13}$        | < 3.7⋅10$^{10}$        | —                    | —                        |
| $^{135}$Xe  | 4.07⋅10$^{13}$         | 3.182⋅10$^{12}$        | —                    | —                        |
| $^{138}$Xe  | 5.18⋅10$^{13}$         | < 3.7⋅10$^{10}$        | —                    | —                        |
| $^{131}$I   | 1.11⋅10$^{10}$         | 9.25⋅10$^{8}$          | 9⋅10$^{2}$           | —                        |
| $^{133}$I   | 9.07⋅10$^{10}$         | 8.51⋅10$^{8}$          | —                    | —                        |
| $^{14}$C    | 3.515⋅10$^{11}$        | 2.96⋅10$^{11}$         | 1.2⋅10$^{5}$         | 7.72⋅10$^{11}$            |
| $^{3}$H     | 1.591⋅10$^{12}$        | 4.07⋅10$^{13}$         | 9.7⋅10$^{7}$         | —                        |
| $^{89,90}$Sr| —                      | —                      | —                    | 3.28⋅10$^{6}$            |
| $^{60}$Co   | —                      | —                      | —                    | 4.04⋅10$^{6}$            |
| $^{137}$Cs  | —                      | —                      | —                    | 9.2⋅10$^{6}$ + 3.94⋅10$^{7}$ |
| RIG         | —                      | —                      | —                    | 4.39⋅10$^{12}$ + 3.14⋅10$^{14}$ |
| Total activity | 2.7⋅10$^{14}$     | 5.2⋅10$^{14}$          | 1.5⋅10$^{8}$         | 3.3⋅10$^{14}$            |

The Symbol “—” doesn’t mean that aforementioned radionuclides are not completely emitted from a nuclear reactor with a fast breeder reactor, which means that we do not have sufficient information about radionuclide composition of the emissions. Main radionuclides release in the atmosphere by a nuclear power plant in a normal working regime. Taking into account the summary radioactive noble gases activity and the proven ability to remotely detect an increased concentration of radioactivity in the emissions of nuclear power plants and RCP, we can conclude that existing radiometric systems are able to detect emissions from a nuclear power plant with a BN reactor.
3. Calculation of spectrum radionuclide $^{137}\text{Cs}_{82}$

Table 1 data shows that significant proportion of emitted radionuclides are radioactive inert gases (RIG): Ar, Kr, Xe. In this paper, we will consider only $^{137}\text{Cs}$ because of its radiological hazard. The probability of beta-electron appearance in the result of decay radionuclide $^{137}\text{Cs}_{82}$ is shown below in the table 2.

| E, keV | $N_0(E)$ | E, keV | $N_0(E)$ | E, keV | $N_0(E)$ |
|--------|----------|--------|----------|--------|----------|
| 0      | 3.41·10^-3 | 391    | 9.33·10^-4 | 782    | 8.78·10^-6 |
| 20     | 3.37·10^-3 | 411    | 7.30·10^-4 | 802    | 7.39·10^-6 |
| 39     | 3.27·10^-3 | 430    | 5.36·10^-4 | 821    | 6.15·10^-6 |
| 59     | 3.18·10^-3 | 450    | 3.56·10^-4 | 841    | 5.06·10^-6 |
| 78     | 3.09·10^-3 | 469    | 2.06·10^-4 | 860    | 4.11·10^-6 |
| 98     | 3.00·10^-3 | 489    | 9.77·10^-5 | 880    | 3.30·10^-6 |
| 117    | 2.92·10^-3 | 508    | 4.73·10^-5 | 899    | 2.60·10^-6 |
| 137    | 2.83·10^-3 | 528    | 4.25·10^-6 | 919    | 2.01·10^-6 |
| 156    | 2.74·10^-3 | 547    | 3.89·10^-6 | 939    | 1.53·10^-6 |
| 176    | 2.65·10^-3 | 567    | 3.54·10^-5 | 958    | 1.14·10^-6 |
| 196    | 2.54·10^-3 | 587    | 3.22·10^-5 | 978    | 8.22·10^-7 |
| 215    | 2.43·10^-3 | 606    | 2.90·10^-5 | 997    | 5.78·10^-7 |
| 235    | 2.31·10^-3 | 626    | 2.61·10^-5 | 1017   | 3.92·10^-7 |
| 254    | 2.18·10^-3 | 645    | 2.33·10^-5 | 1036   | 2.56·10^-7 |
| 274    | 2.04·10^-3 | 665    | 2.07·10^-5 | 1056   | 1.59·10^-7 |
| 293    | 1.89·10^-3 | 684    | 1.83·10^-5 | 1075   | 9.30·10^-7 |
| 313    | 1.72·10^-3 | 704    | 1.60·10^-5 | 1095   | 5.04·10^-8 |
| 332    | 1.53·10^-3 | 723    | 1.40·10^-5 | 1115   | 2.44·10^-8 |
| 352    | 1.34·10^-3 | 743    | 1.21·10^-5 | 1134   | 9.67·10^-9 |
| 372    | 1.14·10^-3 | 762    | 1.03·10^-5 | 1154   | 2.28·10^-9 |

To calculate the averaged parameters of beta decay electrons and thermalized electrons we use Spencer-Fano’s equation (1, 2):

$$
\Sigma(E)\Phi(E) - \int_E^\infty \Sigma_s(E')\Phi(E')dE' = S(E)
$$

(1)

where $\Sigma, \Sigma_s$ are the integral and differential energy transmission macroscopic cross section, derived by multiplying of appropriate microscopic cross section on atomic concentration in a homogeneous medium:

$$
\Sigma_s(E'\rightarrow E) = \frac{d\sigma}{d\varepsilon} N
$$

(2)

where $\varepsilon = E' - E$ is the energy lost by a particle in one act of interaction; $S(E)$ - the spectrum of beta, el·cm$^{-3}$·s; $\Phi(E)$ - the electron-flux density, having energy $E$ (decision function), el·cm$^{-2}$·s.

The solution (1) was carried out with use of the numerical method on the following recurrence relations (3):

$$
\Phi_n = \frac{S_n + \Delta E}{\Sigma_n} \sum_{i=1}^{\infty} \left[ \sum_{m=1}^{\infty} \Phi_i \right] + \frac{1}{2} \Sigma_n \Phi_0
$$

(3)
where \( n \) changes from 1 up to \( M \); \( M \) is the amount of intervals in width \( \Delta E \) on which the area of energy change \( (E_{\text{min}}, E_0) \) is broken. Energy \( E_0 \) corresponds to the peak energy of the beta –electrons spectrum; \( E_{\text{min}} \) is the minimal energy, when particle energy loss is missing (it insufficiently even for excitation of the first level of atoms). The coefficient \( n \) designates the left-hand boundary of the energy interval. In our case \( \Phi_0 \) is the density of the electron stream, having energy \( E_0 \); \( S_0 \) is the density of electrons generation at the beta –decay, having energy \( E_0 \); \( \Sigma_0 \) is the macroscopic integral cross section of the energy transfer, providing transition of an electron from an energy interval with the left-hand boundary \( E_2 = E_0 - 2\Delta E \) (and \( \Sigma_i \) at \( i = n \) are equal 0).

Major factor effecting components of the air in the emission plume are high energy electrons formed in the result of beta –decay radio nuclides. For the atmosphere \( 95.5\,\text{N} + 95.5\,\text{O} \approx \delta_\text{N}+\delta_\text{O} \) eV, where \( \delta_\text{N} \) and \( \delta_\text{O} \) are the parts of nitrogen and oxygen atoms in the air, respectively. Dissociation energies of molecules are for \( \text{N}_2 \) is 9.78 eV, for \( \text{O}_2 \) of 5.12 eV that is on the order less than average ionization potential of the air. Ionization potential of oxygen molecule is \( I_{\text{O}_2} = 12.15 \) eV, nitrogen molecule is \( I_{\text{N}_2} = 56 \) eV, oxygen atom is \( I_{\text{O}} = 13.57 \) eV, nitrogen atom is \( I_{\text{N}} = 14.6 \) eV. Concentration of oxygen atoms is of \( 11.4 \cdot 10^{18} \) atoms \( \cdot \) cm\(^{-3} \), nitrogen atoms is of \( 42.6 \cdot 10^{18} \) atoms \( \cdot \) cm\(^{-3} \).

In table 3 averaged parameters describing the thermalization of fast electrons, formed by beta-decay are shown.

| Radionuclide \( ^{137}\text{Cs}_{82} \) | Initial | Secondary | Tertiary |
|----------------------------------------|---------|-----------|----------|
| The mean free path of electrons, cm    | 0.014   | 3.592 \cdot 10^{-3} | 1.703 \cdot 10^{-3} |
| Time of run, between acts of energy transfer, s | 7.752 \cdot 10^{-13} | 1.995 \cdot 10^{-13} | 9.459 \cdot 10^{-14} |
| Frequency of energy transfer, 1 \cdot s\(^{-1} \) | 1.29 \cdot 10^{12} | 5.012 \cdot 10^{12} | 1.057 \cdot 10^{13} |
| The average kinetic energy of the electrons formed, keV | 40.841 | 13.613 | 4.319 |

4. Results and discussion

Below presents the results of resolve of Spencer-Fano’s equation.

![Figure 1. Spectrum of secondary electron of beta decay (\( S_0 \)) and flux density of beta secondary electron (\( \Phi_0 \)).](image1.png)

![Figure 2. Spectrum of tertiary electron of beta decay (\( S_{\delta\delta} \)) and flux density of beta tertiary electron (\( \Phi_{\delta\delta} \)).](image2.png)
The averaged parameters of initial beta – electrons generated by $^{137}\text{Cs}$ decay in the atmosphere and results on the figure 1 and 2 show that averaged energy of primary, secondary and tertiary electrons of $^{137}\text{Cs}$ decay are exceeding considerably potential of the air ionization. In such manner, the process of ionization will be continued. Further research will be continued to solve the problem remote monitoring of nuclear power plant with fast neutron reactor.

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