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Original Article

Optimization of radiation shields made of Fe and Pb for the spent nuclear fuel transport casks

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ABSTRACT

Recommendations are given to improve the efficiency of radiation protection of transport casks for SNF transportation. The attenuation of γ-quanta of long-lived isotopes ^{134}Cs, ^{137m}Ba(^{137}Cs), ^{154}Eu and ^{60}Co by optimizing the thicknesses and arrangement of layers of Fe and Pb radiation shields of transport casks is studied. The fixed radiation shielding mass (fixed mass thickness) is chosen as the main optimization criterion. The effect of the placement order of Fe and Pb layers in a combined two-layer radiation shield with an equivalent thickness of 30 cm is studied in detail. It is shown that with the same mass thicknesses of the Fe and Pb layers, the placement of Fe in the first layer, and Pb - in the second one provides more than twofold attenuation of γ-quanta compared to the reverse placement: Pb - in the first layer, Fe - in the second. The increase in the efficiency of attenuation of γ-quanta for TC with combined shielding of Fe and Pb is shown to be achieved by designing the first layer of radiation shielding around the canister with SNF from Fe of the maximum possible thickness.

1. Introduction

Operation of dry storage of spent nuclear fuel (SNF) foresees transportation of the significant part of the SNF in transport casks (TCs) [1] by railway. TCs must ensure safe railway transportation as well as radiation safety. Radiation shield of a TC is a massive thick-walled layered structure made of a metal, which provides gamma radiation shielding, as well as materials in the form of rubber, plastic, etc., which provide neutron radiation shielding. The efficiency of radiation shield determines the number of spent fuel assemblies (SFAs) transported in the TC, the level of burnup and the duration of SNF cooling in the nuclear power plant (NPP) spent fuel pools. The weight of the TC is 100–140 tons, and the main contribution to the weight is made by the shielding from gamma rays. In the most cases, iron or various types of steels as well as cast iron up to 30 cm thick are used as the material for radiation shield of TCs [2]. To transport 26–31 SFAs with a burnup of 45–55 MW day/kg and a cooling time of 5–7 years TCs with combined shield from lead and steel are used. Thicknesses of radiation shield from γ - quanta of the NAC-STC cask developed by NAC International is 10.5 cm of Fe and 9.4 cm of Pb [2]. In the case of the HI-STAR 190 UA cask developed by HOLTEK the thickness of Fe is 14.4 cm and thick of Pb is 14.1 cm [3].

Radiation shields made of layers of various materials were the subject of studying in many papers. In particular, combinations of multilayer protective screens were considered in the review [4], based on the analysis of 27 original papers published up to 2018. The studies were focused on the effect of material types and arrangement on shielding properties and on build-up factors. Most of the papers were devoted to the study of the attenuation of neutron fluxes. The attenuation of γ-quanta fluxes was studied for multilayer shields of small thickness. In particular, the effectiveness of shielding from layers of 2 cm thick lead and iron was studied in Ref. [5]. The passage of γ-quanta from ^{60}Co and ^{137}Cs was considered. The shield efficiency was shown in Refs. [4,5] to be independent from the arrangement order of thin layers of Fe and Pb. In Ref. [6], a method for optimizing shielding against neutron and gamma radiation was developed. In particular, the attenuation of γ - quanta of ^{60}Co by a three-layer 20 cm thick shield made of Fe + Polyamine + Pb with an element ratio of 2.5: 6: 1.5 was studied. In extension of the investigation [6] combined thick shields were optimized in Ref. [7] to attenuate the radiation generated from the fission of ^{235}U, in which neutrons and gamma quanta are mixed. The following optimized three-layer shields were under

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consideration: 1st layer made of Fe, 2nd layer made of polyethylene (PE) or a mixture of boron carbide B_4C and polyethylene, 3rd layer made of Pb. Multicriteria optimization of the problem was applied in Refs. [6,7]. The thickness, weight, and composition of composite materials in each of the layers varied within a certain range. However, the main emphasize of the optimization was done on obtaining new effective materials for the combined neutrons and gamma rays radiation shield in designing the shielding for new generation compact nuclear reactors. In Ref. [8], the shielding properties of materials with various combinations of elements, such as PE, Pb, and boron compounds, were studied. The main goal was to develop effective combined neutrons and gamma radiation shield. The goal was suggested to be achieved by combining heavy layers of lead and light layers of polyethylene and boron carbide. The arrangement order of heavy and light layers was optimized for the most effective neutrons and secondary gamma quanta shield. The use of composite layers of lead, polyethylene and boron carbide in various proportions in a three-layer shield was considered as well. The results of modeling and experimental data were compared for the fixed total thickness of the shield.

The weight and sizes are the main criteria for optimization of the combined shield of TCs. Therefore, the optimization to be carried out in the present paper is a one-parameter problem, in which the total thickness of the shield and the weight of the materials (Fe and Pb) are fixed. The only optimization parameter is the arrangement order of the layers while the original dimensions and weight of the TCs are given. That is why the data given in Refs. [4–8] cannot be considered as sufficient for optimizing the parameters of combined radiation shield against γ-quanta in TCs for SNF transportation.

The objective of the present work is to optimize the thicknesses of the Fe and Pb layers, the order of their placement in the radiation shield with fixed mass thickness, providing maximum shielding from gamma radiation of long-lived SNF isotopes.

2. Method of calculation

An analysis of the effectiveness of combined shield from Fe and Pb layers of different thicknesses and the order of their placement is carried out for the fixed shield weight, i.e. for the constant mass thickness of the shield $t_M = const.$, g/cm^2 [9]. Mass thickness t_M is determined as follows:

$$t_M = t_{Fe} \cdot \rho_{Fe} + t_{Pb} \cdot \rho_{Pb}, \tag{1}$$

where t_{Fe}, and t_{Pb} are the thicknesses of the Fe and Pb layers, ρ_{Fe}, and ρ_{Pb} are the mass densities of Fe and Pb. The mass thickness of the radiation shield for the TC NAC-STC is $t_M \approx 189$ g/cm^2, and $t_M \approx 273$ g/cm^2 for TC HI-STAR 190UA. For clarity of illustration of the numerical results, the mass thicknesses of the combined radiation shielding is replaced by the equivalent thickness t_{eq} (that is the thickness of the shield with the same mass but made of one Fe layer) in the form:

$$t_{eq} = t_{Fe} + t_{Pb} \cdot \rho_{Pb} / \rho_{Fe}. \tag{2}$$

Then for TC NAC-STC the equivalent thickness is $t_{eq} \approx 24$ cm, and $t_{eq} \approx 35$ cm for TC HI- STAR 190 UA. Note that the thickness of the radiation shielding against γ-quanta for the majority of steel (cast iron) transport casks used for the transportation of SNF with high level of burnup is about 30 cm [2].

Calculations of γ-quanta transport, as well as that of SNF neutrons through layered shields are realized by the Monte Carlo method in the PHITS package [10]. The radiation source is modeled as a cylinder with 1.8 m in diameter and 4.5 m in length, filled with SNF, surrounded by a layered cylindrical shielding. The zone of fuel intended for dry storage is modeled by homogeneous SNF with a density of 3.5 g/cm^3 containing 52.3% of ^{238}U, 25.8% of ^{40}Zr, 14.6% of ^{26}Fe, and 7.3% of ^{16}O.

Transport of γ-quanta through the layered shield is calculated in the following model. Gamma-radiation from an outer layer of homogenized SNF with a thickness of ≈10 cm only [7] is taken into account. In calculations of the effectiveness of the layered shield during the passage of neutrons, radiation from the entire volume of the source is accounted for.

Two approaches are applied for the detailed analysis of the influence of the thicknesses of the Fe and Pb layers on the characteristics of the transmitted radiation. The cylindrical shape of the TC is modeled in the first approach as a set of discs which include the flat layered shield with 2 m and 1 m in diameter respectively. The TC is modeled as the set of flat surface sources of γ-quanta in the second approach. Both models are realized in PHITS package. The data obtained in the result of calculations from the source in the form of a cylindrical layer of homogenized SNF are used as the initial spectral composition and angular distributions of the surface source of γ-quanta. However, it is significant to note that the results of calculations of external radiation in the models of cylindrical and flat sources of γ-quanta differ by 1–2%. Calculations based on the approach of a point source, as it was done in Ref. [11], with such dimensions of shields lead to the underestimation in the dose rate, for example, generated by γ - quanta of ^{60}Co, by 1.5 times. And it is reasonable to apply the model of the flat source, since the computational speed in this case is 3–5 times higher than in the model of a cylindrical source, which provides a statistical error of less than 5% for large shield thicknesses.

2.1. Source of gamma radiation

To analyze the effectiveness of layered shield against γ-radiation, long-lived SNF isotopes with a half-life of more than 1 year are selected. At cooling times of more than five years, the isotopes ^{134}Cs, ^{137m}Ba (^{137}Cs), ^{154}Eu, and ^{60}Co make the maximum contribution to γ-radiation outside a cask [12]. Note, that well-known parent beta-emitters for given γ-emitters are indicated here in brackets. Table 1 shows the main characteristics of these isotopes: half-lives $T_{1/2} > 1$ year, γ-quanta energies for which quantum yields are greater than 5% of the total yield Yi.

2.2. Source of neutrons

The spontaneous fission of ^{244}Cm, whose half-life is 18.1 years [13], is the dominant source of neutrons produced in SNF (about 97.4%).

The neutron spectrum of spontaneous fission of actinides is similar to the spectrum of stimulated fission of ^{235}U and is approximated by the relation [14]:

$$N(E) = \frac{2\sqrt{E}}{\sqrt{\pi\theta^3}} \exp(-E/\theta), \tag{3}$$

where E is the energy, MeV, and θ is the hardness parameter equal to 1.33 MeV for ^{244}Cm. The average energy of such neutrons is approximately 1.995 MeV.

3. Calculation results

The attenuation of γ-quanta fluxes of long-lived SNF isotopes during the passage through Fe and Pb layers is investigated. Spectral distributions of radiation passing through the layers of different

Table 1
The main characteristics of ^{134}Cs, ^{137m}Ba (^{137}Cs), ^{154}Eu, and ^{60}Co isotopes.

No.	Isotope	$T_{1/2}$ (year)	Eγ, MeV, (yield/1 Bq, > 5% of the total yield)	Y_i, yield/1Bq, total (Eγ>0.2 MeV)
1	^{60}Co	5.27	1.17 (0.999); 1.33 (0.9998)	2
2	^{134}Cs	2.06	0.57 (0.15); 0.60 (0.975); 0.8 (0.851)	2.224
3	^{137m}Ba (^{137}Cs)	30	0.662 (0.9)	0.9
4	^{154}Eu	8.6	0.6 (0.061); 0.72 (0.2); 0.87 (0.115); 1.0 (0.28); 1.27 (0.355)	1.22

thicknesses and combined shields with an equivalent thickness of 30 cm are calculated. The detector is placed at the distance of 60 cm from the surface of the radiation source.

This equivalent thickness is taken as a model reference observable, which corresponds to the average magnitude of the thicknesses of TCs NAC-STC, HI-STAR 190 UA and CASTOR. In the following, the 15 cm Fe thickness in the composite material is applied which is the shield half-thickness of indicated TCs (see Fig. 4.)

To determine the quality of γ-quanta shield against individual isotopes, the dose attenuation coefficients K_{dose} are used. The dose attenuation coefficient is defined as the ratio of the dose rate produced by γ-quanta in the detector without shielding t = 0 to the dose rate behind the shielding of thickness t

$$K_{dose} = \mathrm{Dose}(t = 0)/\mathrm{Dose}(t). \quad (4)$$

As the other criterion for the effectiveness of combined shields $R_{mat}(t)$ made of Fe and Pb layers, the ratio of the dose rate behind the combined shield to the dose rate behind the shield of iron of the same mass thickness is taken:

$$R_{mat}(t) = \mathrm{Dose}_{Fe}(t) \,/\, \mathrm{Dose}_{mat}(t). \quad (5)$$

3.1. Shields made of Fe and Pb

Fig. 1 shows dose attenuation factors K_{dose} of the γ-quanta for isotopes ^{60}Co, ^{134}Cs, ^{137}Cs, and ^{154}Eu subject to the equivalent thickness of Fe and Pb shields.

It follows from the data shown in Fig. 1 that for both Fe and Pb shields, γ-quanta of ^{60}Co have the maximum penetrating power. The increase in the thickness of Fe shields from 12 to 30 cm (as well as increase in the thickness of Pb which is equivalent to the thickness of iron) causes the decrease in the dose rate by more than 10^3 times for the ^{60}Co isotope, and more than 10^4 times for ^{134}Cs. Fig. 2 shows the dependences of the efficiency of Pb shielding $R_{Pb}(t)$, compared to the Fe shielding, on the shielding thickness *t* for γ-quanta of ^{60}Co, ^{134}Cs, ^{137}Cs, and ^{154}Eu isotopes. It follows from the data presented in Fig. 2 that the increase in the thickness of the Pb shield results in the increase of its efficiency due to the attenuation of high-energy γ-quanta from the isotopes ^{60}Co (their average energy is E_{Co60} = 1.25 MeV) and ^{154}Eu (their average energy is $E_{Eu154} \approx$ 1.0 MeV). Note that the average energies are calculated with taking into account of the γ-quanta with the energy higher than 0.4 MeV, since those with E_γ < 0.4 MeV are effectively absorbed. The effectiveness of Pb shielding against the γ-quanta from ^{134}Cs isotope (the average energy is $E_{Cs134} \approx$ 0.7 MeV) is practically independent of the shielding thickness. As far as the ^{137}Cs isotope (average energy is E_{Cs137} = 0.662 MeV) is concerned, the shielding efficiency of Pb against this isotope is larger than 250 already at t_{eq} = 15 cm, and larger than 1000 at t_{eq} = 20 cm.

Fig. 3 shows the spectra of gamma radiation that passes through the Fe shield of 15 cm thick and Pb, with a thickness equivalent to the Fe thickness of 15 cm. Gamma-quanta from the isotopes ^{60}Co, ^{137}Cs and ^{154}Eu are considered. Fig. 3 illustrates the well-known fact that Pb shields effectively absorb the low-energy photons.

3.2. Combined Fe and Pb shields

It follows from the data presented in Fig. 3 that for shields made of Fe and Pb with a total thickness equivalent to the iron thickness of 30 cm, the arrangement order of layers made of different materials is essential. In the following, the combined shield with equivalent thickness of 30 cm (the respective mass thickness is 235.8 g/cm^2) is considered. The schemes of two versions for placing a two-layer shield and the version of a three-layer shield are presented on Fig. 4. The radiation protective properties of the combined shield (options A and B), in which the weights of iron and lead are the same, i.e. the thickness of the Fe layer is 15 cm, and the

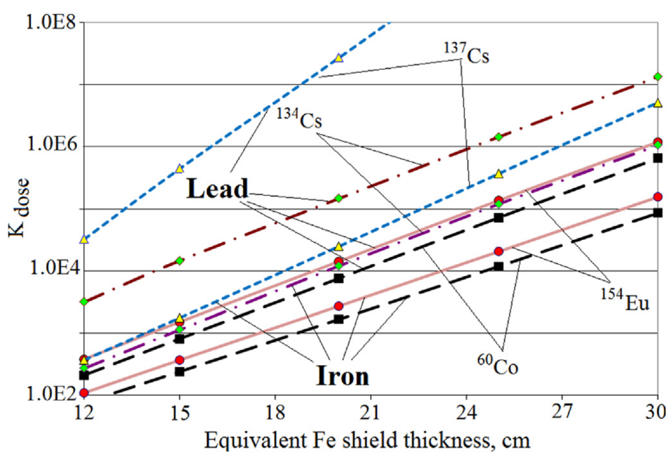

Fig. 1. Dependences of the dose attenuation coefficients K_{dose} for isotopes ^{60}Co, ^{134}Cs, ^{137}Cs, and ^{154}Eu subject to the equivalent thickness.

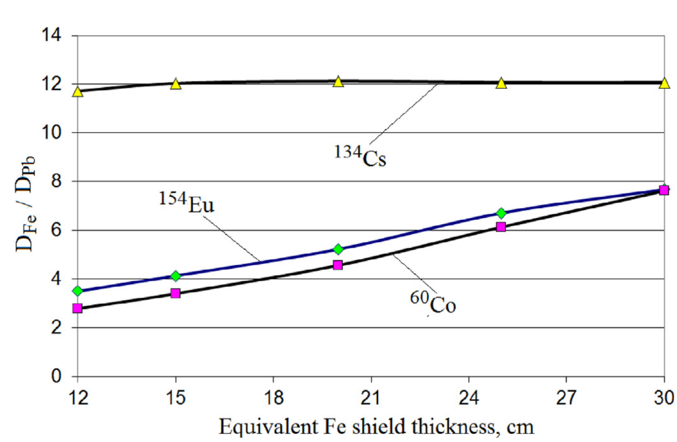

Fig. 2. Shield efficiency R_{Pb} (t) subject to the thickness t of Pb shield for γ-quanta from ^{60}Co, ^{134}Cs, and ^{154}Eu isotopes.

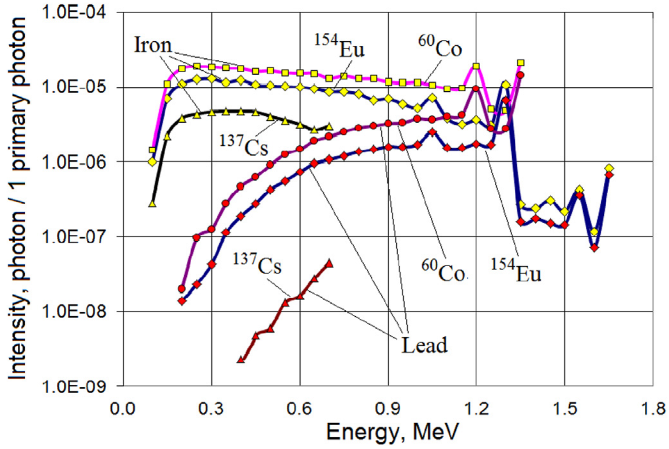

Fig. 3. Emission spectra for γ-quanta from ^{60}Co, ^{137}Cs, and ^{154}Eu isotopes passed through Fe shields of 15 cm thick and Pb with the thickness equivalent to the thickness of 15 cm of iron.

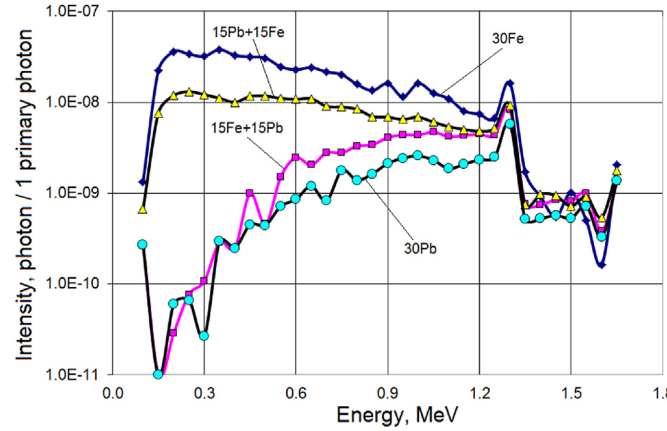

Fig. 5. Emission spectra of γ-quanta from ^{154}Eu isotope which pass through 30 cm thick mono-layers of Fe and Pb shields, as well as through two-layer shields in versions A and B with the same equivalent thickness.

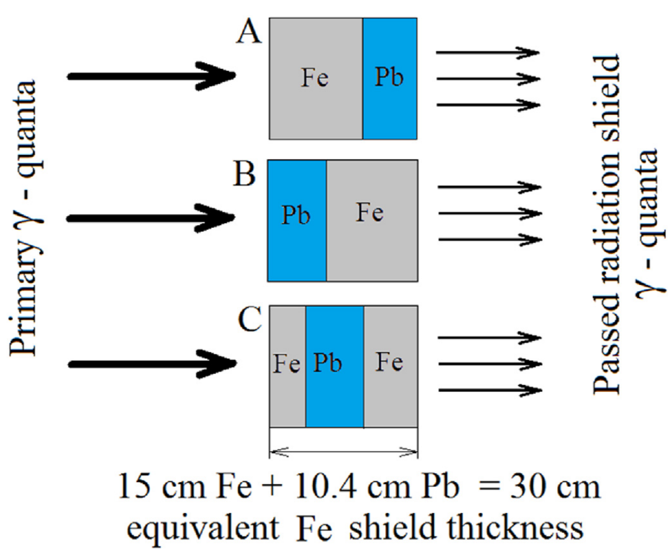

Fig. 4. Schemes of two-layer and three-layer shield made of Fe and Pb.

equivalent thickness of the Pb layer is 15 cm as well (in this case its physical thickness is 10.4 cm) are considered.

Table 2 presents the dependences of the attenuation coefficients and efficiency of γ-shield against γ-quanta from ^{60}Co,^{134}Cs, and ^{154}Eu isotopes on the arrangement order of Fe and Pb shield layers. Row 3 of Table 2 shows the shield characteristics when the 1st layer is made of Fe, and the 2nd layer is made of Pb (version A); in the row 4, the 1st layer is Pb, and the 2nd layer is Fe (version B).

It follows from the data given in Table 2, that the attenuation coefficients are ~ 2 times higher, and the shield efficiency with respect to iron is also ~ 2 times higher for the version A compared to version B. Three-layer material was considered in Ref. [7]. Specifically, Fe, PE, and Pb from left to right, respectively, were studied. The first layer of Fe was set to attenuate the gamma rays and slow down the fast neutrons to moderate energy via inelastic scattering. The second layer of PE was put to further moderate the neutrons to thermal energy via elastic scattering. And the third layer of Pb was set to attenuate the secondary gamma rays and the original gamma rays [7]. The present study demonstrates that a significant part of the primary photons from the ^{60}Co, ^{134}Cs, ^{154}Eu isotopes, when passing through the first layer of Fe 15 cm thick, significantly reduce their energy due to inelastic scattering (Compton effect), see Fig. 3, and then low-energy gamma rays are effectively absorbed in the second layer of Pb. Fig. 5 shows the spectra of ^{154}Eu photons after passing through Fe layer of 30 cm thick, as well as three other layers with the same equivalent thickness: that made of Pb, and combined shields in versions A and B. One can see from the data shown in Fig. 5, that the number of photons which pass the combined shield in version A is significantly smaller than the number of photons which pass the combined shield in the version B.

The effect of the thickness of the first Fe layer on the shield efficiency is studied for the three-layer shield with keeping the total thickness of the first and third Fe layers, that is $t1_{Fe} + t3_{Fe} = 15$ cm. The equivalent thickness of the Pb layer is 15 cm (version C). Fig. 6 shows the shield efficiency for three layers (2 layers of iron and 1 layer of lead) subject to the thickness of the first Fe layer. Note that the dependence of attenuation efficiency for the γ-quanta from ^{60}Co is similar to the attenuation dependence for the case of ^{154}Eu shown in Fig. 6; the difference does not exceed 1–2%.

Within the versions of the combined shields considered above, the mass thicknesses of the layers of lead and iron are the same. Let's define the ratio of the mass thicknesses of Fe to Pb as the mass coefficient $K_{mass} = t_{Fe} \cdot \rho_{Fe}/(t_{Pb} \cdot \rho_{Pb})$. The mass coefficient is as

Table 2
Dependences of the attenuation coefficients and efficiency of γ-shield against γ-quanta from ^{60}Co, ^{134}Cs, and ^{154}Eu isotopes on the arrangement order of Fe and Pb shield layers, the equivalent thickness of the shield layers is 15 cm.

No	Shielding material, equivalent thickness, cm	^{60}Co		^{154}Eu		^{134}Cs	
		$K_{dose}(30)$	$R_{mat}(30)$	$K_{dose}(30)$	$R_{mat}(30)$	$K_{dose}(30)$	$R_{mat}(30)$
1	30Fe	8.52E+4	1	1.55E+5	1	1.06E+6	1
2	30 Pb	6.49E+5	7.62	1.19E+6	7.68	1.34E+7	12.70
3	15Fe + 15 Pb (A)	3.67E+5	4.31	6.76E+5	4.36	8.27E+6	7.82
4	15 Pb+15Fe (B)	1.75E+5	2.06	3.26E+5	2.11	3.53E+6	3.33

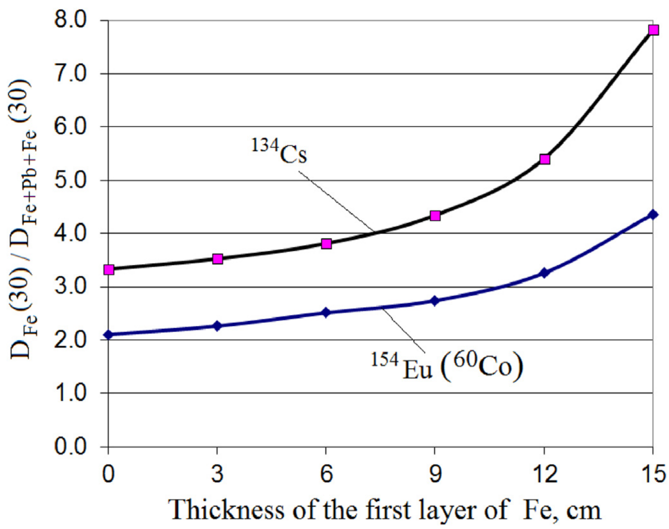

Fig. 6. Dependences of the shield efficiency for the version C on the thickness of the first Fe layer. The total thickness of two layers of Fe is 15 cm, and the equivalent thickness of the entire shield (including Pb) is 30 cm.

Table 3
Dependences of the neutron attenuation coefficients of the ^{244}Cm isotope and the shield efficiency of shields made of Fe, Pb and combined shields with an equivalent thickness of 30 cm.

	30Fe	30 Pb	15Fe + 15 Pb	15 Pb+15Fe
K_{dose}	3.87	2.29	3.38	3.09
$R_{mat}(30)$	1.00	0.59	0.87	0.80

follows for existing transport casks with combined shield. For example, $K_{mass} = 0.77$ for TC NAC-STC, and $K_{mass} = 0.71$ for TC HI-STAR 190 UA [2]. In the other words, the weight of lead exceeds the weight of iron in the radiation shields of these TCs. The attenuation of γ-quanta by two-layer combined shields with an equivalent 30 cm thickness of Fe in the version A and the mass coefficient $K_{mass} < 1$ is calculated. The versions 13.33Fe + 16.67 Pb ($K_{mass} = 0.8$) and 11.25Fe + 18.75 Pb ($K_{mass} = 0.6$) are considered as shields. Calculations show that the attenuation coefficient for γ-quanta from ^{154}Eu isotope when passing through such shields is 1.06 times larger for the version 13.33Fe + 16.67 Pb and 1.15 times larger for the version 11.25Fe + 18.75 Pb as compared to the case: $K_{dose}(30) = 6.76 \times 10^5$, version A, $K_{mass} = 1$ given in Table 2.

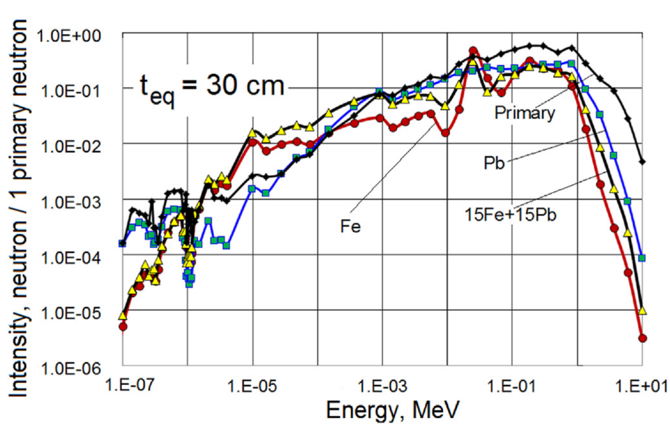

Fig. 7. Dependences of the neutron intensity on the energy behind the shields made of Fe, Pb and the combined shield with an equivalent thickness of 30 cm.

Neutron transport through the combined shields is also calculated. Table 3 shows the dependences of the neutron attenuation coefficients of the ^{244} *Cm* isotope and the shield efficiency of shields made of Fe, Pb and combined shields, options (A) and (B) with an equivalent thickness of 30 cm.

It follows from the data given in Table 3, that the best attenuation of the neutron flux is observed for the purely iron shield, and the worst attenuation takes place for purely lead shield. Fig. 7 shows the dose rates generated by the initial neutrons, those neutrons which pass through the shield made of Fe, Pb and the combined shield (version A) subject to the neutron energy.

The data presented in Fig. 7 illustrate the fact that the scattering of neutrons by relatively light Fe atoms significantly reduces their energy, compared to the scattering by Pb atoms. The neutron dose rate behind the Fe shield decreases, respectively. The change in arrangement order of the Fe and Pb layers in the combined shield reduces the attenuation coefficient for neutrons by ~10%, in contrast to the attenuation of the γ-quanta flux when the flux is attenuated twice.

4. Conclusions

A model of the gamma radiation source in the form of a cylinder surrounded by a layered cylindrical shield, similar to the cask for transporting SNF by railway, is developed.

The characteristics of γ-quanta from long-lived SNF isotopes: ^{134}Cs, $^{137m}Ba(^{137}Cs)$, ^{154}Eu, and ^{60}Co, passed through Fe and Pb shields, are studied by the Monte Carlo method. The attenuation coefficients of the γ-quanta flux are calculated subject to the shield thickness. The effectiveness of Pb shields is determined in comparison with the effectiveness of shield made of Fe with the same weight. It is shown for the ^{154}Eu and ^{60}Co isotopes that the effectiveness of Pb shields increases with the thickness of the shields. For the ^{134}Cs and $^{137m}Ba(^{137}Cs)$ isotopes, the shielding efficiency of Pb practically does not change with increasing the lead thickness.

The influence of the arrangement order of Fe and Pb layers in a combined two-layer radiation shield with a mass thickness of 235.8 g/cm^2, equivalent to 30 cm of Fe, is considered. The mass thicknesses of the iron and lead layers are the same: physical thickness of Fe is 15 cm, and that of the Pb layer is 10.4 cm (which is equivalent to 15 cm of Fe). It is shown that when the arrangement is such that the first layer is that of Fe and the second layer is that of Pb, the attenuation coefficients and the effectiveness of the combined shield are more than twice larger than when the arrangement is reversed: the first layer is of Pb and the second layer is of Fe. This is explained as follows. The significant part of the high-energy γ-quanta passed through the first Fe layer is transformed into low-energy γ-quanta, which are effectively absorbed by the Pb layer.

The influence of the thickness of the first layer $t1_{Fe}$ made of Fe on the characteristics of a three-layer Fe + Pb + Fe shield with the total thickness $t_{Fe+Pb+Fe} = 30$ cm, where $t_{Fe+Fe} = 15$ cm, is studied. It is shown that the maximum attenuation of the photon flux is observed for the protection, in which all the iron is concentrated in the first layer and $t1_{Fe} = 15$ cm. That is, not a three-layer, but a two-layer protection of Fe + Pb is optimal.

The influence of an increase in the proportion (mass) of lead in a two-layer combined shield at a fixed total weight on the attenuation of the γ-quanta flux is studied. It is shown that the absorption efficiency of γ-quanta increases with an increase in the proportion (mass) of lead in the combined shield, and the attenuation is maximum when the first protection layer is made of Fe.

The transport of SNF neutrons emitted by the ^{244}Cm isotope through combined Fe and Pb shields is studied. It is shown that the maximum attenuation of the neutron flux is provided by the shield from pure Fe. If to place Fe as the first layer and Pb as the second layer, the effectiveness of such shield is ~10% higher compared to the combined shield, within which Pb is the first layer and Fe is the second layer.

Summarizing all mentioned above, one can conclude the following. Arrangement order of Fe and Pb layers causes a significant influence on the protective properties of TC. To increase the efficiency of γ-quanta attenuation, one should construct the first layer of radiation shield around the canister with SNF from iron of the maximum possible thickness.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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