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## Radiation changes of concrete aggregates under the influence of gamma radiation

**A.V. Denisov**

National Research Moscow State Civil Engineering University, Moscow, Russia

\* E-mail: [den-al-v@inbox.ru](mailto:den-al-v@inbox.ru)

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**Abstract.** The work (in connection with the small study of the effects of gamma ray on concretes and their components) contains the results of calculation and analysis of radiation changes of concrete aggregates under the influence of gamma ray on the basis of analytical methods developed previously during the neutron irradiation process. The possibility of using these analytical methods in the case of exposure to gamma ray was substantiated. The relationship of the absorbed doses of gamma ray of different energies with the number of atoms displaced during irradiation was established. There is an assessment of radiation changes in the volume and strength of the main types of rocks - aggregates of concrete (igneous, sedimentary rocks and ores) under the influence of gamma ray with an average energy of 2 MeV and 5 MeV after irradiation to absorbed doses of  $10^5$  to  $10^{11}$  Gy at 30 °C, 100 °C and 300 °C. For this, from the beginning, the radiation changes of the main rock-forming minerals were calculated, and on the ground of them, the radiation changes of rocks of concrete aggregates were calculated. It has been established that noticeable radiation changes of considered minerals and rock aggregates will occur only at absorbed doses of gamma ray of more than  $1 \cdot 10^9$ – $1 \cdot 10^{10}$  Gy of gamma rays with an energy of 5 MeV and of  $3 \cdot 10^9$ – $3 \cdot 10^{10}$  Gy for gamma rays with an energy of 2 MeV. The number of radiation changes grows with a rise in the absorbed dose and significantly decrease with an increase in the irradiation temperature for silicate class minerals and silicate rocks. The greatest radiation changes under the influence of gamma ray at 30 °C are observed in silicate minerals and rocks, especially olivine pyroxenes, hornblende, dunite, peridotite, pyroxenite, and gabbro. Moreover, even with an absorbed dose of gamma ray of  $10^{11}$  Gy, the radiation changes are not large (increase in volume is not more than 0.36 %, decrease in strength is not more than 8.7 %). As the temperature increases, the ratio in the magnitude of radiation changes of different materials changes.

### 1. Introduction

Significant radiation changes in concrete could occur under the influence of ionizing radiation. In this regard, the radiation resistance of concrete used in buildings with various nuclear facilities determines the safety of operation of these buildings for both the operating staff and the environment as a whole.

The most significant radiation changes in concrete occur under the influence of neutrons of nuclear reactors. In this connection the influence of neutron radiation in concrete and their components (aggregates, minerals, cement stone) was investigated and adequately described in literature, for example in [1-22]. There are methods for the analytical determination of radiation changes in the following materials described in [8, 9, 10, 11, 12, 14, 22]:

- minerals of concrete aggregate [8, 14, 22] and cement stone [11,14] under the influence of neutrons according to the data on the fluence and neutron spectrum, irradiation temperature;
- materials of concrete aggregate according to data on radiation changes in crystals of the composing minerals them [9, 14];
- concretes according to data on radiation changes in their components (aggregates and cement stone) [10, 12, 14].



At the same time, significant volumes of concrete in buildings with nuclear facilities are exposed to gamma radiation. However, the effect of gamma ray on concrete is less studied. There are only a few data on the effect of gamma radiation on concrete obtained in [1, 2, 21, 23–27], discussed in the reviews [6, 7, 13, 15, 21] and on the effect of gamma radiation on the cement stone [25, 26, 28–31], indicating that they have small radiation changes under the influence of gamma radiation.

The effect of gamma ray on concrete aggregates and the contribution of radiation-induced changes in aggregates to radiation-induced changes in concrete under the influence of gamma ray have hardly been studied. This is due to the opinion based on the results of the study of ceramic materials [32, 34] that gamma ray does not cause noticeable changes in the properties of inorganic materials. This view was confirmed in the works of [33, 35], which show that the ability to displace atoms under the influence of gamma ray is 100 to 10,000 times lower than under the influence of neutrons.

However, the studies described in the papers [1, 2, 6, 7, 13, 15, 21, 23–31] were performed after exposure to the absorbed dose of gamma radiation no more than  $1.5 \cdot 10^9$  Gy. The result of a study of the effects of higher absorbed doses has not been found in literature. At higher absorbed doses, the number of displaced atoms and changes in material properties may be more significant. In addition, studies of the aggregate materials, which are more radiation-sensitive than ceramics, are not available in the literature. In this regard, studies of radiation changes in concrete aggregate materials under the influence of gamma ray are of considerable practical interest.

The purpose of this work is to assess radiation changes in the main varieties of concrete aggregates under the influence of gamma ray in a wide range of absorbed doses and radiation temperatures.

Due to the lack of data in the literature on significant radiation changes of the aggregates and their minerals under the influence of gamma ray, radiation changes of these materials were evaluated by calculation.

In achieving the goal, the following known provisions in accordance with [8, 9, 14], were taken into account:

- Changes in the basic properties of concrete aggregate materials are caused by the displacement of atoms in their minerals, leading to the accumulation of radiation defects in them.
- Changes in volume and strength are of greatest interest.
- Radiation changes in the volume and strength of concrete aggregate materials can be calculated by radiation changes in the size and volume of the minerals that compose them on the basis of the analytical method tested during neutron irradiation, described in the works [9, 14].
- Radiation changes in the volume and size of mineral crystals can be calculated on the base of the number of displaced atoms and the radiation temperature. This analytical method based on neutron radiation, is described in the works [8, 14].

In order to achieve this goal, the following objectives of the study were set and solved:

- To justify the possibility of using the existing analytical methods listed above, which have been tested under the influence of neutrons, to determine the results of gamma radiation exposure.
- To establish the dependence of the number of displaced atoms in minerals of concrete aggregates under the action of gamma radiation on the absorbed dose and the energy of gamma quanta.
- To calculate, using the well-known analytical method presented in [8, 14] for neutron irradiation, radiation changes in the volume and size of crystals of the main minerals of concrete aggregates after irradiation with gamma radiation to various absorbed doses.
- To calculate, using the available analytical method presented in [9, 14] for neutron irradiation, the radiation changes of the volume and strength of the main materials of concrete aggregates after irradiation with gamma radiation to various absorbed doses.
- To analyze the results obtained and establish the absorbed doses and conditions under which it is necessary to take into account the radiation changes in the materials of concrete aggregates under the influence of gamma radiation.

## *2. Methods*

When substantiating the possibility of using the above existing analytical methods tested under the influence of neutrons, the following circumstances were taken into account for the results of exposure to gamma ray:

- In accordance with the existing method for the analytical determination of radiation changes in minerals under the influence of neutrons, radiation changes in the volume and size of minerals, although they are not the same for different minerals, are determined by the calculated number of displaced atoms and the

irradiation temperature. In this regard, the most important for substantiating the possibility of using this analytical method when exposed to gamma ray is the condition that the same number of displaced atoms when irradiated with neutrons and gamma ray cause approximately equal radiation changes.

- Although atom displace efficiency in gamma radiation is 100 to 10,000 times lower than that of neutrons, the number of basic radiation defects (vacancies, interstitial atoms), their distribution in the crystal lattice and the effect on the properties for equal values of number of displaced atoms and irradiation temperature should be approximately the same. For neutrons of different energies, the efficiency of atomic displacement also differs significantly from each other. However, differences in the results of irradiation of minerals with neutron fluxes with different proportions of neutrons of different energies are quite well excluded when the radiation changes are linked to the calculated number of displaced atoms in [14].

- However, there is an opinion [37], that the number and distribution of radiation defects in the space may depend on the speed of displacement of atoms, which is less under the influence of gamma ray than under the influence of neutrons. However, this was not found in existing studies when irradiating minerals with neutrons at different neutron flux densities.

- In accordance with the existing method for the analytical determination of radiation changes in concrete aggregates, radiation changes in the volume and mechanical properties are determined by changes in the size and volume of minerals, their moduli of elasticity, grain size of minerals, and the modulus of elasticity of the material. The reasons for the change in the size and volume of minerals do not play a significant role. This is shown by the results of a positive-used of this method when heating the rocks presented in [36]. In this regard, this analytical method can be used when exposed to gamma ray.

To calculate the number of displaced atoms under the influence of gamma ray, we used the cross sections for the formation of displaced atoms  $\sigma_d(E_g)$ , calculated in [33] for atoms of building materials (mainly with the atomic number  $4 \div 14$ ):

- $\sigma_d(E_g) = 0.1 \cdot 10^{-24} \text{ cm}^2$  for gamma rays with an energy of 2 MeV;

- $\sigma_d(E_g) = (0.2 - 0.5) \cdot 10^{-24} \text{ cm}^2$  for gamma rays with an energy of 5 MeV

By analogy with neutron radiation, considered in [8, 14], the number of displaced atoms  $n_{CM}$  when irradiated by gamma ray in the minerals should be determined by the formulas:

$$n_d = \sum_{i=1}^m [\sigma_d(E_{gi}) F_g(E_{gi})] \quad (1)$$

- when exposed to gamma rays with different energies  $E_{gi}$  (for  $i = 1 - m$ );

$$n_d = \sigma_d(E_g) F_g(E_g) \quad (2)$$

- when exposed to gamma rays with one energy  $E_g$  or average energy  $E_g$ ,

- where  $\sigma_d(E_{gi})$  and  $\sigma_d(E_g)$  are the cross sections for the formation of displaced atoms upon exposure to gamma rays with energy  $E_{gi}$  and  $E_g$ ,  $\text{cm}^2$ ;

- $F_g(E_{gi})$  and  $F_g(E_g)$  are fluence of  $\gamma$ -quantum with energy  $E_{gi}$  and  $E_g$ ,  $\gamma$ -quantum/ $\text{cm}^2$ .

In accordance with [39] the following coefficients  $k_{D_g/F_g}(E_g)$  as the ratios of the dose-to-the-level gamma-quanta-dependent gamma-quanta energy  $E_g$ :

$$k_{D_g/F_g}(E_g) = (4.4 - 5.6) \cdot 10^{-12} \text{ Gy}/(\gamma\text{-quantum}/\text{cm}^2) \approx 5 \cdot 10^{-12} \text{ Gy}/(\gamma\text{-quantum}/\text{cm}^2) \text{ for gamma-rays with energy } E_g = 1 \text{ MeV};$$

$$k_{D_g/F_g}(E_g) = (7.5 - 9.2) \cdot 10^{-12} \text{ Gy}/(\gamma\text{-quantum}/\text{cm}^2) \approx 8 \cdot 10^{-12} \text{ Gy}/(\gamma\text{-quantum}/\text{cm}^2) \text{ for gamma rays with energy } E_g = 2 \text{ MeV};$$

$k_{D_g/F_g}(E_g) = (1.39 - 1.6) \cdot 10^{-11} \text{ Gy}/(\gamma\text{-quantum}/\text{cm}^2) \approx 1.5 \cdot 10^{-11} \text{ Gy}/(\gamma\text{-quantum}/\text{cm}^2)$  for gamma rays with energy  $E_g = 5 \text{ MeV}$ .

In accordance with [8, 14] the change in the volume of minerals under the influence of gamma ray was calculated by the formulas:

$$\frac{\Delta V}{V} = \begin{cases} \frac{a(T) \left( \frac{\Delta V}{V} \right)_{M.M} (e^{b(T)n_d} - 1)}{\left( \frac{\Delta V}{V} \right)_{M.M} + a(T) \cdot e^{b(T)n_d}} & \text{-- at } a(T) \neq \infty \text{ and } \beta(T) \neq 0 \\ \left( \frac{\Delta V}{V} \right)_{M.M} (1 - e^{-b(T)n_d}) & \text{-- at } a(T) = \infty \text{ and } \beta(T) = 0 \end{cases} \quad (3a)$$

$$\left( \frac{\Delta V}{V} \right)_{M.M} (1 - e^{-b(T)n_d}) & \text{-- at } a(T) = \infty \text{ and } \beta(T) = 0 \quad (3b)$$

where  $\frac{\Delta V}{V}$  is the relative increase in the volume of crystals or unit cells of the mineral, %.

$\left( \frac{\Delta V}{V} \right)_{M.M}$  increase in the volume of the crystal of the mineral in a state of saturation, %

$a(T)$  and  $b(T)$  are the parameters depending on the irradiation temperature, determined by the formulas:

$$a(T) = \alpha(T) / \beta(T) \quad (4)$$

$$b(T) = \beta(T) \left( \frac{\Delta V}{V} \right)_{M.M} + \alpha(T), \quad (5)$$

where  $\alpha(T)$  and  $\beta(T)$  are the parameters depending on the irradiation temperature.

Taking into account the work [8, 14], the change in the size of the crystals of minerals along various axes under the action of gamma ray was calculated by the formula:

$$\frac{\Delta \ell}{\ell} = a_1 + a_2 \frac{\Delta V}{V} + a_3 \left( \frac{\Delta V}{V} + a_4 \right)^{a_5}, \quad (6)$$

where  $a_1 - a_5$  are the parameters.

In this work, we used the parameters of equations (3a)–(6) obtained and presented in [8, 14].

In accordance with [9, 14], the change in the volume of rocks of concrete aggregates under the action of gamma ray was calculated by the formulas:

$$\frac{\Delta V_{AG}}{V_{AG}} = \left( \frac{\Delta V}{V} \right)_1 = 3 \left( \frac{\Delta \ell}{\ell} \right)_{M.M} - a_M \frac{E_0}{E_{M.M} \sqrt{d_{GR}}} \cdot \frac{1 - V_{M.RED}}{V_{M.RED}} \text{ -- at } \left( \frac{\Delta V}{V} \right)_1 \geq \left( \frac{\Delta V}{V} \right)_2 \quad (7a)$$

$$\frac{\Delta V_{AG}}{V_{AG}} = \left( \frac{\Delta V}{V} \right)_2 = \left( \frac{\Delta V}{V} \right)_{AD.M} + \frac{3 \Delta \varepsilon_{AVE}}{1 + 2.2 a_M / (\sqrt{d_{GR}} 3 \Delta \varepsilon_{AVE})} \text{ -- at } \left( \frac{\Delta V}{V} \right)_1 < \left( \frac{\Delta V}{V} \right)_2, \quad (7b)$$

where  $\left( \frac{\Delta \ell}{\ell} \right)_{M.M}$  is the maximum of the values of the radiation values of radiation-induced dimensional changes in the most expanding direction of the crystals composing the material of minerals, %;

$a_M = 3.4 \cdot 10^{-2} \% \text{ cm}^{0.5}$  is the complex parameter of the model;

$E_0$  is modulus of elasticity of the material at zero porosity, MPa;

$d_{GR}$  is average size of crystals composing the material of minerals, cm;

$E_{M.M}$  is the modulus of elasticity of crystals having an expansion  $\left(\frac{\Delta\ell}{\ell}\right)_{M.M}$  along the axis where the expansion  $\left(\frac{\Delta\ell}{\ell}\right)_{M.M}$  takes place, MPa;

$\Delta\varepsilon_{AVE}$  is the average difference between the deformations of the crystals along various axes composing the material of minerals, %;

$V_{M.RED}$  is the relative volumetric content of mineral crystals with expansion,  $\left(\frac{\Delta\ell}{\ell}\right)_{M.M}$ , reduced to the isotropic case, but taking into account the anisotropy of radiation deformations and the presence of crystals with expansion  $\left(\frac{\Delta\ell}{\ell}\right)_{M.i}$ , (differing by a value of no more  $\xi_p = a_M / \sqrt{d_{AVE}}$ ), rel. units;

$\left(\frac{\Delta V}{V}\right)_{AD.M}$  is an increase in the volume of material (in %) associated with a free change in the volume of mineral crystals composing it, determined by the formula:

$$\left(\frac{\Delta V}{V}\right)_{AD.M} = \sum_{i=1}^n \left[ \left(\frac{\Delta V}{V}\right)_i V_i \right], \quad (8)$$

where  $\left(\frac{\Delta V}{V}\right)_i$  and  $V_i$  is the radiation change in volume (in %) and the relative volume content of the minerals composing the material (in rel. units).

Values  $\Delta\varepsilon_{AVE}$  and  $V_{M.RED}$  by [9, 14] were determined by the formulas:

$$\Delta\varepsilon_{AVE} = \sum_{i=1}^n \sum_{j=1}^3 \left[ \left(\frac{\Delta\ell}{\ell}\right)_{ij} - \frac{1}{3} \left(\frac{\Delta V}{V}\right)_{AD.M} \left| \frac{V_i}{3} \right| \right] \quad (9)$$

$$V_{M.RED} = \frac{n_{M.M} \cdot V_{M.M}}{3} + \sum_{i=1}^n \left[ \frac{n_{M.i} \cdot V_{M.i}}{3} \frac{\left(\frac{\Delta\ell}{\ell}\right)_{M.i} E_{M.i}}{\left(\frac{\Delta\ell}{\ell}\right)_{M.M} E_{M.M}} \right] \leq 1 \quad (10)$$

where  $\left(\frac{\Delta\ell}{\ell}\right)_{ij}$  is the increase in the size of the crystals of the i-th mineral along the j-th axis ( $j = 1 \dots 3$  along the axes a, b and c) of the crystal, %;

$n_{M.M}$  and  $n_{M.i}$  are the number of axes in the crystals along which the expansion occurs  $\left(\frac{\Delta\ell}{\ell}\right)_{M.M}$  and  $\left(\frac{\Delta\ell}{\ell}\right)_{M.i}$ ;

$V_{M.M}$ ;  $V_{M.i}$ ;  $E_{M.M}$ ;  $E_{M.i}$  are the relative volume content (in rel. units) and the moduli of normal elasticity (in MPa) of mineral crystals having an expansion of  $\left(\frac{\Delta\ell}{\ell}\right)_{M.M}$  and  $\left(\frac{\Delta\ell}{\ell}\right)_{M.i}$ .

The elastic moduli of mineral crystals along various axes were taken according to [39].

The radiation changes in the indicators of the mechanical properties of the aggregates were calculated by the formula [9, 14]:

$$\frac{R_{AG}}{R_{AG0}} = \exp \left[ - \frac{\left( \frac{\Delta V_{AG}}{V_{AG}} \right)_{CR}}{A_{AG} \left( \frac{\Delta V_{AG}}{V_{AG}} \right)_{CR} + B_{AG}} \right], \quad (11)$$

where  $\frac{R_{AG}}{R_{AG0}}$  is the residual value of the mechanical property  $R_{AG}$  after radiation exposure relative to the strength before irradiation  $R_{AG0}$ , rel. units;

$A_{AG}$  and  $B_{AG}$  are the complex parameters of the model, the values are given in the works [9, 14].

$\left( \frac{\Delta V_{AG}}{V_{AG}} \right)_{CR}$  is an increase in the volume of material due to the formation of cracks is determined by the formula:

$$\left( \frac{\Delta V_{AG}}{V_{AG}} \right)_{CR} = \frac{\Delta V_{AG}}{V_{AG}} - \sum_{i=1}^n \left[ \left( \frac{\Delta V}{V} \right)_i V_i \right] + \sum_{i=1}^n \left[ \left( \frac{\Delta V}{V} \right)_i V_i u_i \right], \quad (12)$$

where  $u_i$  is the fraction of the increase in mineral crystals due to the formation of microcracks in the crystal, taken according to the data of [9, 14].

Relative changes in strength are calculated by the formula:

$$\frac{\Delta R_{AG}}{R_{AG0}} = \left( \frac{R_{AG}}{R_{AG0}} - 1 \right) \cdot 100\% , \quad (13)$$

where  $\frac{\Delta R_{AG}}{R_{AG0}}$  are the relative changes in strength, as the ratio of the absolute change in strength  $\Delta R_{AG}$  to strength before irradiation  $R_{AG0}$ , %.

The calculations of radiation changes were carried out for the following main rock-forming minerals:

- silicate class minerals - quartz, potassium feldspar-microcline, plagioclases (oligoclase and labrador), pyroxenes (enstatite, diopside), hornblende, olivine, serpentine;
- carbonate class minerals - calcite, dolomite;
- oxide-ore class minerals (hematite, magnetite).
- quartz glass.

The radiation changes in minerals were used to calculate the radiation changes in aggregate rocks: granite, diorite, gabbro, basalt, pyroxenite, peridotite, dunite, sandstone, limestone, and enriched hematite and magnetite ore.

When choosing the rocks, the following circumstances were taken into account:

- granites, diorites, gabbros, basalts, sandstones, limestones are the most common rocks;
- pyroxenites, peridotites, dunites, hematite and magnetite ore are examples of the most radiation-resistant rocks when irradiated with neutrons;
- sandstones and limestones were used as aggregates of concrete investigated after exposure to gamma ray in [1, 2, 24];
- hematite and magnetite ores are used for the preparation of particularly heavy concrete, effective for protection against radiation.

The characteristics of the mineral composition, the average size of the crystals of minerals and the elastic modulus of the rocks considered in the work are shown in table 1.

Although the mineral composition, structure, and properties of these rocks can vary in a rather wide range, the use of the accepted average characteristics can be considered to estimate the values of their radiation changes under the influence of gamma ray.

**Table 1. The characteristics of the mineral composition, the average size of the crystals of minerals, and the modulus of elasticity of the rocks considered in this paper.**

No.	Name of the rock	Mineral composition in the form of mineral content in %	Average crystal size of minerals, cm	Modulus of elasticity, MPa
1	Granite	Quartz – 25 %, Microcline – 40 %, Oligoclase – 20 %, Hornblende – 15 %	0.3	$6 \cdot 10^4$
2	Diorite	Oligoclase – 70 %, Microcline – 5 %, Hornblende – 25 %	0.3	$8 \cdot 10^4$
3	Gabbro	Enstatite, Diopside – 50 %, Labrador – 50 %	0.3	$10 \cdot 10^4$
4	Basalt	Enstatite, Diopside – 50 %, Labrador – 40 %, Glass – 10 %	0.01	$10 \cdot 10^4$
5	Pyroxenite	Enstatite, Diopside – 90 %, Olivine – 10 %	0.1	$12 \cdot 10^4$
6	Peridotite	Enstatite, Diopside – 40 %, Olivine – 40 %, Serpentine – 20 %	0.1	$12 \cdot 10^4$
7	Dunitite	Enstatite, Diopside – 10 %, Olivine – 90 %	0.1	$12 \cdot 10^4$
8	Sandstone	Quartz – 50 %, Microcline – 25 %, Oligoclase – 25 %	0.03	$6 \cdot 10^4$
9	Limestone	Calcite – 75 %, Dolomite – 25 %	0.03	$8 \cdot 10^4$
10	Hematite ore (enriched)	Hematite – 100 %	0.01	$25 \cdot 10^4$
11	Magnetite ore (enriched)	Magnetite – 100 %	0.01	$27 \cdot 10^4$

First, using the formulas (1)–(6), the radiative changes in the volume and size of the crystals of the minerals that make up these rocks were calculated: quartz, microcline, oligoclase, hornblende, calcite and dolomite. Then, according to formulas (7)–(13), radiation changes in the volume and strength of granite, sandstone, and limestone with the accepted characteristics of the mineral composition, structure, and properties were calculated.

Considering the data of [14], the radiation changes of the considered minerals and rocks were calculated after the following exposure to gamma ray:

- gamma ray with an average energy of 2 MeV at absorbed doses from  $1 \cdot 10^5$  to  $1 \cdot 10^{11}$  Gy for materials of radiation protection of technological equipment of nuclear power plants;

- gamma ray with an average energy of 5MeV at absorbed doses from  $1 \cdot 10^5$  to  $1 \cdot 10^{11}$  Gy for radiation protection materials of nuclear reactors.

The radiation changes were calculated for cases of irradiation at temperatures of 30 °C, 100 °C, and 300 °C. In this case, changes in materials under the action of heating associated with irradiation (thermal changes) were not considered, since they are independent of radiation changes, they are determined and can be taken into account by other methods, for example, according to [36].

### 3. Results and Discussion

The dependences necessary for calculating the number of displaced atoms in concrete aggregate minerals were found based on the values of the atomic displacement cross sections  $\sigma_d(E_g)$ , calculated in [33] for atoms of building materials and the known relations  $k_{D_g/F_g}(E_g)$  between the absorbed dose and gamma-ray fluence, which depend on the energy of gamma-rays  $E_g$ .

Based on the values of  $\sigma_d(E_g)$  and  $k_{D_g/F_g}(E_g)$  and of formula (2) shown in the research methodology, the following dependence of the number of displaced atoms (in fractions of a unit) in aggregate minerals when irradiated with gamma ray on the absorbed dose in Gy of gamma ray of different energy was established and accepted for calculations:

$$n_d = 1.1 \cdot 10^{-14} \cdot D_g - \text{at gamma ray energy } E_g = 2 \text{ MeV}; \quad (14)$$

$$n_d = 3.3 \cdot 10^{-14} \cdot D_g - \text{at gamma ray energy } E_g = 5 \text{ MeV.} \quad (15)$$

It can be seen that the absorbed dose of gamma ray with an energy of 5 MeV corresponds to a 3 times larger number of displaced atoms than gamma ray with an energy of 2 MeV. In this connection, the absorbed dose of gamma quanta with an average energy of 2 MeV is equivalent to 1/3 of the absorbed dose of gamma quanta with an energy of 5 MeV in the efficiency of atomic displacement. This circumstance was taken into account when graphically presenting the calculation results. All calculation results are presented depending on the absorbed dose equal to the absorbed dose of gamma rays with an energy of 5 MeV or equal to 1/3 of the absorbed dose of gamma rays with an energy of 2 MeV.

The calculation results according to formulas (1) - (5) taking into account formulas (14) and (15) of radiation changes in the volume of the examined minerals from the absorbed dose of gamma ray in the range of  $10^5$ – $10^{11}$  Gy and the irradiation temperature from 30 to 300 °C are given on Figures 1 to 5.

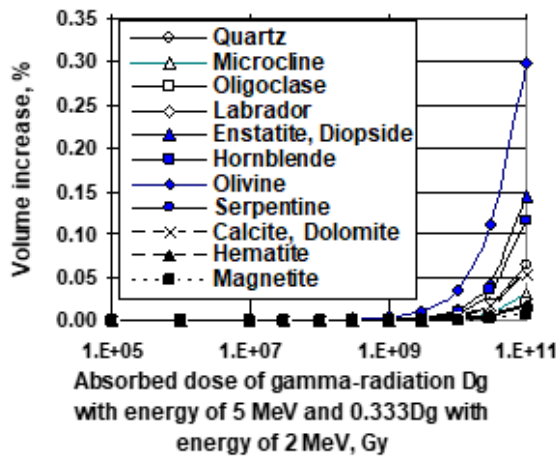


Figure 1. Dependence of the calculated radiation increase in the volume of various minerals on the absorbed dose of gamma ray with an average energy of 5 MeV and 2 MeV at an irradiation temperature of 30 °C.

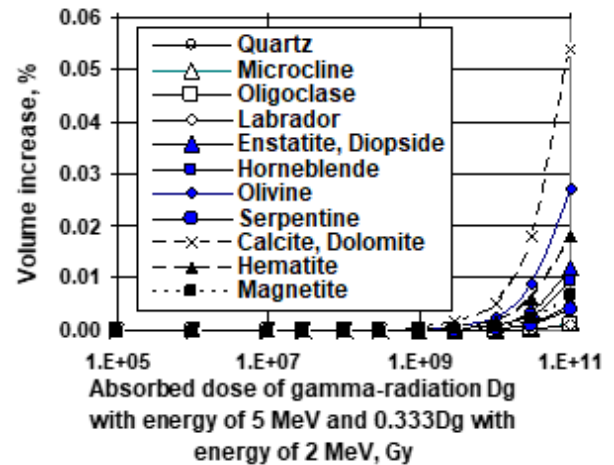


Figure 2. Dependence of the calculated radiation increase in the volume of various minerals on the absorbed dose of gamma ray with an average energy of 5 MeV and 2 MeV at an irradiation temperature of 100 °C.

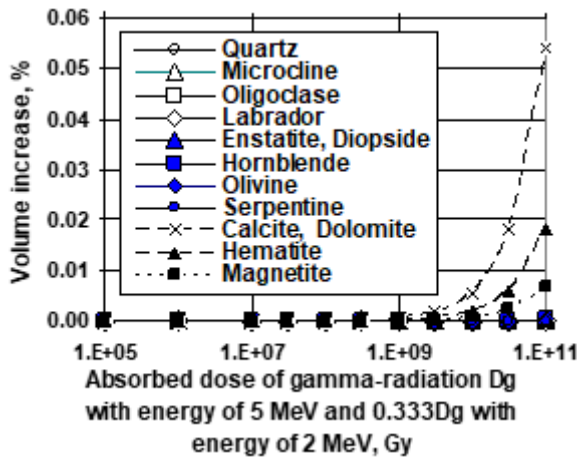


Figure 3. Dependence of the calculated radiation increase in the volume of various minerals on the absorbed dose of gamma ray with an average energy of 5 MeV and 2 MeV at an irradiation temperature of 300 °C.

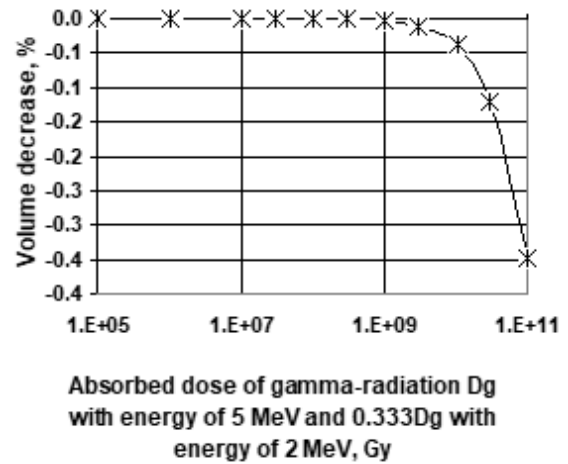
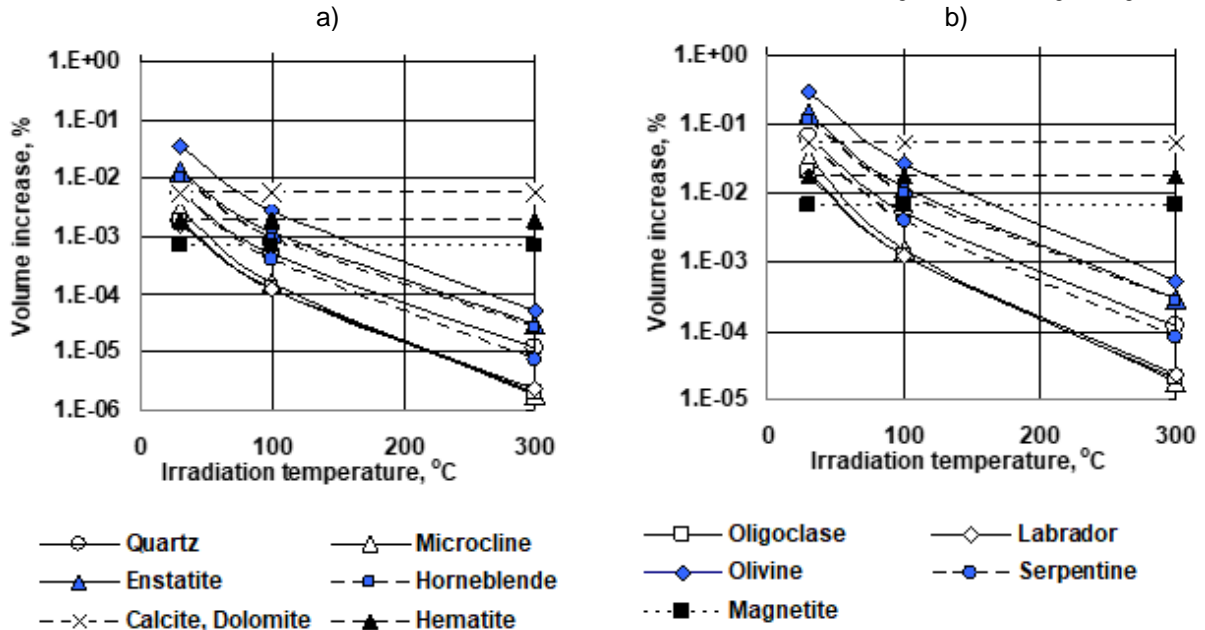


Figure 4. The dependence of the calculated radiation decrease in the volume of quartz glass on the absorbed dose of gamma ray with an average energy of 5 MeV and 2 MeV at irradiation temperatures from 30 to 300 °C.





**Figure 5. Dependence of the calculated radiation increase in the volume of various minerals on the irradiation temperature at an absorbed dose of gamma ray with an average energy of 5 MeV  $1 \cdot 10^{10}$  Gy (a) and  $1 \cdot 10^{11}$  Gy (b)**

The calculation results indicate that noticeable radiation changes in the considered minerals will occur only at absorbed doses of gamma ray greater than  $D_{g0} = 1 \cdot 10^9 - 1 \cdot 10^{10}$  Gy for gamma rays with an energy of 5 MeV and  $D_{g0} = 3 \cdot 10^9 - 3 \cdot 10^{10}$  Gy for gamma rays with an energy of 2 MeV. The radiation changes in volume rise with an increase in the absorbed dose and decrease in silicate class minerals with an increase in the irradiation temperature.

At 30 °C, according to the calculation results, the largest radiation increase in volume in the studied range of absorbed doses will occur in minerals of silicate class minerals.

The maximum increase in volume during irradiation at 30 °C will be observed in olivine (up to 0.3 %). A 2–2.5 times smaller increase in volume will occur in pyroxenes of diopside and enstatite (up to 0.15 %) and hornblende (up to 0.12 %). 4.6–5.5 times a smaller increase in volume will be observed in quartz (up to 0.065 %), serpentine, calcite, dolomite (up to 0.055 %). A 10–16 times smaller increase in volume will occur in the microcline minerals (up to 0.03 %) and oligoclase, labrador, hematite (up to 0.018–0.020 %). A minimal increase in volume will be observed in magnetite (up to 0.007 %). In quartz glass, regardless of the irradiation temperature, a decrease in volume will occur (up to -0.3 %).

With an increase in the irradiation temperature from 30 °C to 100 °C and 300 °C, the radiation changes in the silicates class minerals decrease, while the radiation changes of carbonate class minerals (calcite, dolomite) and iron oxides (hematite, magnetite) do not change. Moreover, the effect of temperature increases with the rise of irradiation temperature. At 100 °C the increase in the volume of silicates decreases by 11–18 times, and at 300 °C it decreases by 400–1800 times in comparison with a change in volume at 30 °C. In this regard, the ratio between radiation changes in the volume of various minerals changes, the upper and lower boundaries of the changes in volume decrease, and the increase in the volume of silicate class minerals becomes smaller than that of carbonates and iron oxides.

In the case of irradiation at 100 °C in the studied range of absorbed doses, the maximum volume increase will be observed in minerals of the carbonate class—calcite and dolomite (up to 0.055 %). An approximately twofold smaller increase in volume will occur in olivine (up to 0.027 %). A 3.7-fold smaller increase in volume will be observed in hematite (0.018 %). A 4.5–5.6 times smaller volume increase will occur in pyroxenes of enstatite, diopside (up to 0.012 %) and hornblende (up to 0.096 %). An 8-fold smaller increase in volume will be observed in magnetite (up to 0.0067 %). 10.8–13.5 times a smaller increase in volume will occur in quartz (up to 0.005 %) and serpentine (up to 0.004 %). A slight, 36–45 times smaller increase in volume will be observed in microcline, oligoclase and labrador (up to 0.0012–0.0015 %).

In the case of irradiation at 300 °C in the studied range of absorbed doses, a maximum increase in volume will also be observed in calcite and dolomite of carbonate class minerals (up to 0.055 %). A 3.7-fold smaller increase in volume will occur in hematite (0.018 %). An 8-fold smaller increase in volume will be observed in magnetite (up to 0.0067 %). For the remaining studied minerals, the increase in volume will not be significant (at 100–3000 times less) and will be 0.000018–0.00053 %.

The results of calculations by formulas (7)–(13) of radiation changes in the volume and compressive strength of the considered rocks - aggregates of the absorbed dose of gamma ray are shown in Figures 6–12.

The calculation results indicate that, as with minerals, noticeable radiation changes in the considered minerals will occur only at absorbed doses of gamma ray greater than  $D_{g0} = 1 \cdot 10^9 - 1 \cdot 10^{10}$  Gy for gamma rays with an energy of 5 MeV and  $D_{g0} = 3 \cdot 10^9 - 3 \cdot 10^9$  Gy for gamma rays with an energy of 2 MeV. The radiation changes in volume rise with an increase in the absorbed dose and decrease in rocks, consisting of silicates, with an increase in the irradiation temperature.

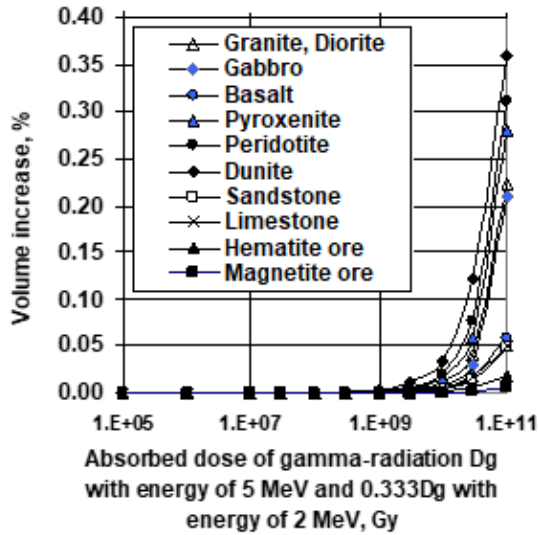


Figure 6. Dependence of the calculated radiation increase in the volume of various concrete aggregate rocks on the absorbed dose of gamma ray with an average energy of 5 MeV and 2 MeV at an irradiation temperature of 30 °C.

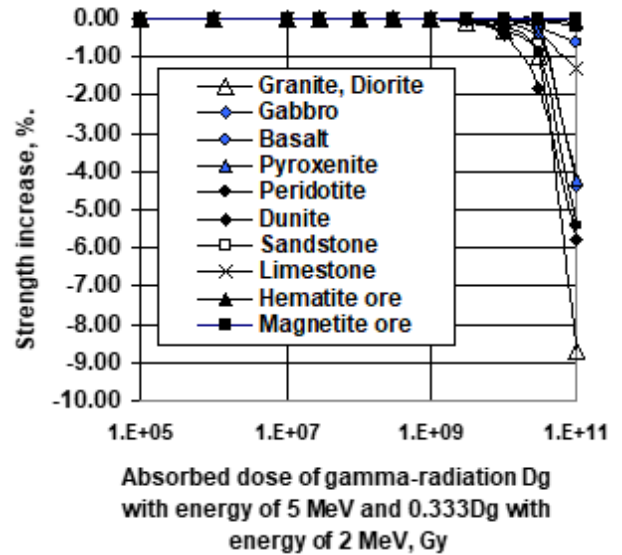


Figure 7. Dependence of the estimated residual strength of various concrete aggregate rocks on the absorbed dose of gamma ray with an average energy of 5 MeV and 2 MeV at an irradiation temperature of 30 °C.

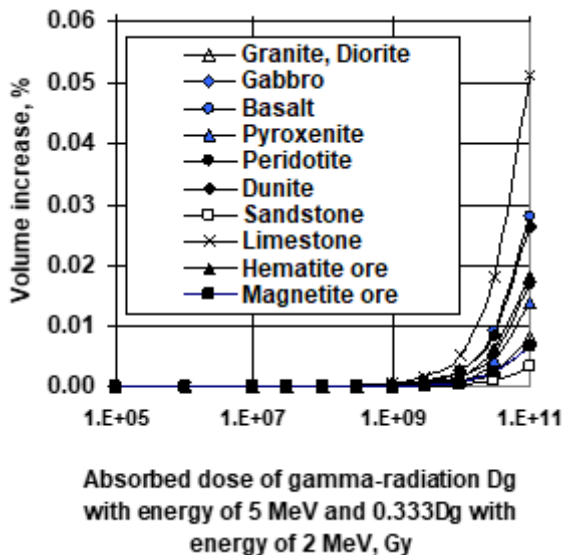


Figure 8. Dependence of the calculated radiation increase in the volume of various concrete aggregate rocks on the absorbed dose of gamma ray with an average energy of 5 MeV and 2 MeV at an irradiation temperature of 100 °C.

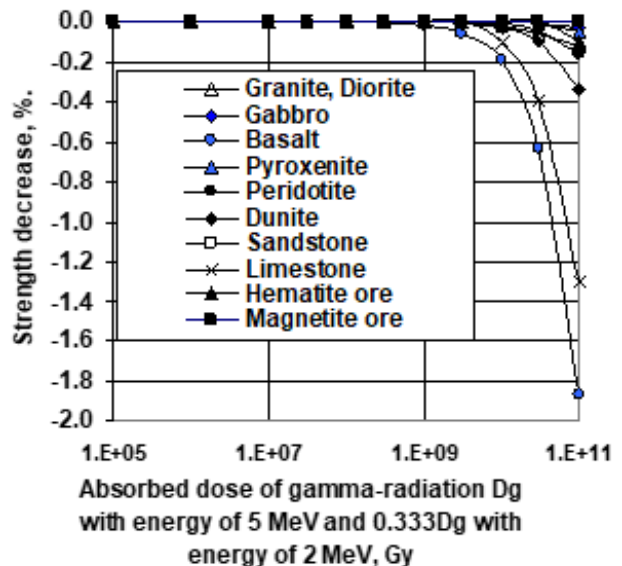


Figure 9. Dependence of the estimated residual strength of various concrete aggregate rocks on the absorbed dose of gamma ray with an average energy of 5 MeV and 2 MeV at an irradiation temperature of 100 °C.

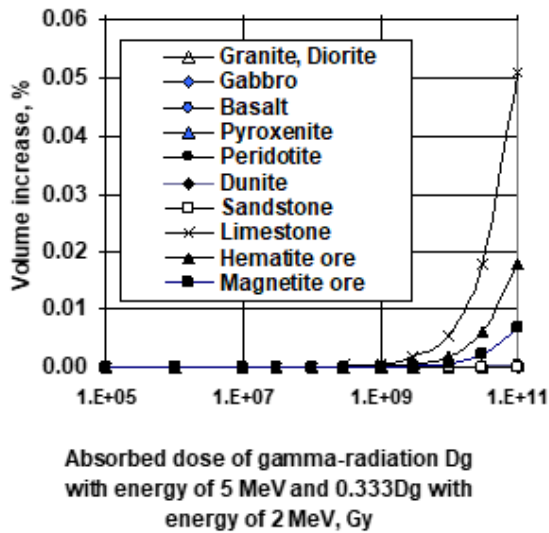


Figure 10. Dependence of the calculated radiation increase in the volume of various concrete aggregate rocks on the absorbed dose of gamma ray with an average energy of 5 MeV and 2 MeV at an irradiation temperature of 300 °C.

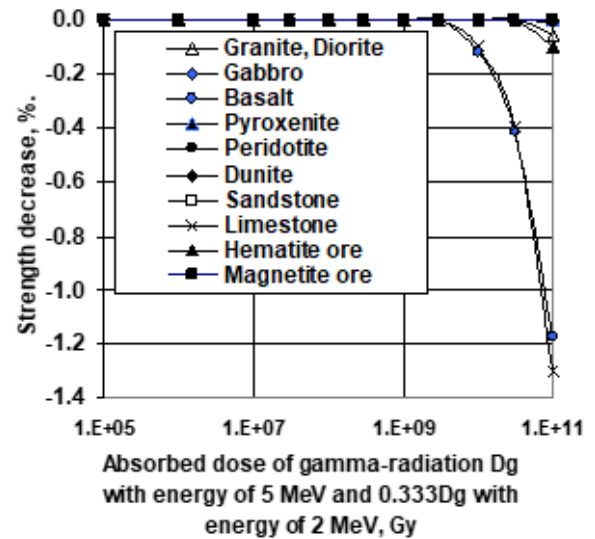


Figure 11. Dependence of the estimated residual strength of various concrete aggregate rocks on the absorbed dose of gamma ray with an average energy of 5 MeV and 2 MeV at an irradiation temperature of 300 °C.

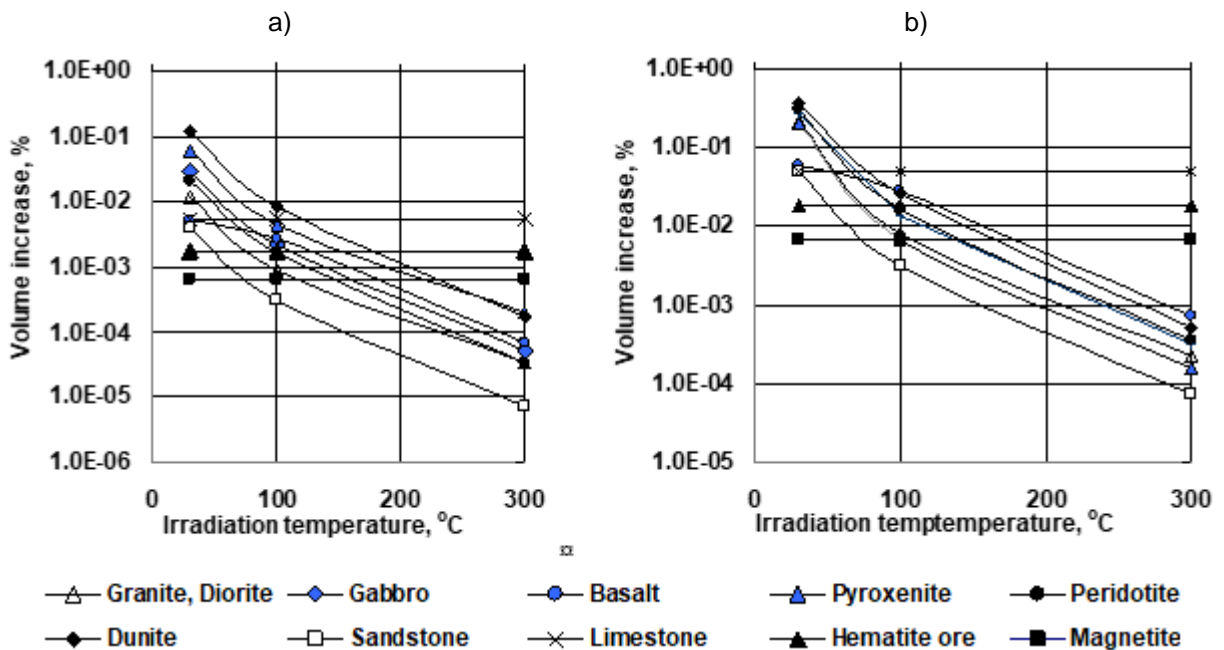


Figure 12. Dependence of the calculated radiation increase in the volume of various concrete aggregate rocks on the irradiation temperature for an absorbed dose of gamma radiation with an average energy of 5 MeV  $1 \cdot 10^{10}$  Gy (a) and  $1 \cdot 10^{11}$  Gy (b)

At 30 °C, according to the results of calculations, the greatest increase in volume and decrease in strength under the influence of gamma radiation in the studied range of absorbed doses will occur in rocks consisting of silicate class minerals.

The largest volume increase during irradiation at 30 °C will be observed in dunite (up to 0.36 %), peridotite (up to 0.31 %) and pyroxenite (up to 0.28 %). 1.4–1.7 times a smaller increase in volume will occur in granite, diorite (up to 0.22 %) and gabbro (up to 0.21 %). 4.7–7 times less a smaller increase in volume will be observed in basalt (up to 0.059 %), sandstone (up to 0.050 %), limestone and dolomite (up to 0.051 %). The smallest increase in volume will occur in hematite ore (up to 0.018 %) and magnetite ore (up to 0.0066 %).

The greatest decrease in strength during irradiation at 30 °C will be observed for granite (up to -8.7 %). Almost two times lesser decrease in strength will occur in dunite (up to -5.8 %), peridotite (up to -5.4 %), pyroxenite (up to -4.2 %) and gabbro (-4.3 %). In other rocks, the decrease in strength is not significant and amounts to -1.3 % or less, but decreases in the direction: limestone (up to -1.3 %) → basalt (up to -0.6 %) → hematite and magnetite ore (up to -0.1 %).

With an increase in the irradiation temperature from 30 °C to 100 °C and 300 °C, the radiation changes of silicate aggregate rocks decrease, but the radiation changes of carbonate and ore aggregate rocks do not change. Moreover, the effect of temperature increases with increasing irradiation temperature. At 100 °C, an increase in the volume of silicate rocks except for basalt decreases by 13–31 times, and at 300 °C it decreases by 300–970 times compared with a change in volume at 30 °C. In basalt, the decrease is  $\approx 2$  times at 100 °C and  $\approx 80$  times at 300 °C. In this regard, the ratio between radiation changes in the volume of various silicate and carbonate, ore rocks varies, the upper and lower boundaries of volume changes decrease, and the increase in the volume of silicate rocks becomes less than that of carbonate and ore rocks.

In the case of irradiation at 100 °C in the studied range of absorbed doses, the maximum increase in volume will be observed in limestone (up to 0.051 %). An approximately twofold smaller increase in volume will occur in basalt (up to 0.028 %) and dunite (up to 0.026 %). 2.8–3.7 times a smaller increase in volume will be observed in hematite ore (0.018 %), peridotite (up to 0.017 %) and pyroxenite (up to 0.014 %). In 6.2–7.3, a smaller increase in volume will occur in granite and diorite (up to 0.008 %), gabbro (up to 0.007 %) and magnetite ore (up to 0.007 %). A minimal and insignificant increase in volume will be observed in sandstone (up to 0.0032 %).

The decrease in strength during irradiation at 100 °C will be insignificant in all rocks, since it does not exceed -1.8 %. However, it decreases in the direction: basalt (up to -1.8 %)  $\rightarrow$  limestone (up to -1.3 %)  $\rightarrow$  dunite (up to 0.3 %)  $\rightarrow$  other rocks (up to -0.2 %).

In the case of irradiation at 300 °C in the studied range of absorbed doses, the maximum increase in volume will be observed in limestone (up to 0.051 %). A 2.8 times smaller increase in volume will occur in hematite ore (up to 0.018 %). A 7.3-fold smaller increase in volume will be observed in magnetite ore. In other rocks, the increase in volume is not significant and does not exceed 0.0007 %.

The decrease in strength during irradiation at 300 °C will be even less significant than during irradiation at 100 °C. The greatest decrease in strength will be -1.3 % for limestone and -1.2 % for basalt. In other rocks, the decrease in strength will not be significant (no more than -0.1 %).

Thus, the radiation changes of aggregates of concrete and their minerals under the influence of gamma ray at the considered absorbed doses can be significant only at absorbed doses of more than  $10^9$  Gy. Radiation changes increase with the absorbed dose. However, even with an absorbed dose of  $10^{11}$  Gy, the radiation changes are not large (an increase in volume of not more than 0.36 %, a decrease in strength of not more than 8.7 %). Since, in accordance with the existing analytical methods [10, 12, 14] the changes in concrete are close to changes in aggregates, the radiation changes in concrete under the influence of gamma ray at the considered absorbed doses will not be large either.

Since the available experimental data on concretes were obtained in [1, 2, 6, 7, 13, 15, 21, 23–27] at absorbed doses of less than  $1.5 \cdot 10^9$  Gy, the radiation-induced changes in concrete found in these works are mainly caused by changes in their cement stone.

It is important that the calculated radiation changes of minerals and aggregate rocks under the influence of gamma ray are much less than the maximum changes established by neutron radiation (increase in volume to 18–23 %, decrease in strength to 100 % in silicate materials, increase in volume to 3 % in carbonate and oxide materials). In this regard, it is of interest to evaluate what absorbed doses of gamma ray are necessary to achieve the same effects as under the influence of neutrons.

According to [14], the indicated maximum radiation changes in the aggregate rocks are observed at the following approximate values of the damaging neutron fluences (with an energy of more than 10 KeV):

- $1 \cdot 10^{20}$  neutron/cm<sup>2</sup> for silicate materials at 30 °C;
- $3 \cdot 10^{20}$  neutron/cm<sup>2</sup> for silicate materials at 100 °C;
- $10 \cdot 10^{20}$  neutron/cm<sup>2</sup> for silicate materials at 300 °C;
- $(1-10) \cdot 10^{20}$  neutron/cm<sup>2</sup> for carbonate materials and materials based on iron oxides.

For the neutron spectra of the main reactors used in these studies, the fluences of  $1 \cdot 10^{20}$  –  $10 \cdot 10^{20}$  neutron/cm<sup>2</sup> correspond to the fraction of displaced atoms  $n_{CM} = 0.14$ – $1.4$ , since the average cross section for atomic displacement is  $\sigma_{CM}(E_n) = 1400 \cdot 10^{-24}$  cm<sup>2</sup>. Then, to obtain under the action of gamma ray the same maximum effects as under the action of neutrons in accordance with formulas (14) and (15), the following absorbed to gamma ray are necessary:

$$D_g = n_{CM} / 1.1 \cdot 10^{-14} = (0.14 - 1.4) / 1.1 \cdot 10^{-14} = 1.3 \cdot 10^{13} - 1.3 \cdot 10^{14} \text{ Gy} - \text{at gamma ray energy } E_g = 2 \text{ MeV};$$

$$D_g = n_{CM} / 3.3 \cdot 10^{-14} = (0.14 - 1.4) / 3.3 \cdot 10^{-14} = 4.2 \cdot 10^{12} - 4.2 \cdot 10^{13} \text{ Gy} - \text{at gamma ray energy } E_g = 5 \text{ MeV}.$$

Such high absorbed doses of gamma ray to radiation protection concrete in modern nuclear facilities are not achievable. Therefore, radiation changes under the influence of gamma ray, commensurate with the maximum radiation changes under the influence of neutrons, are practically impossible at currently operating nuclear facilities.

It is also of interest to evaluate the contribution of radiation changes due to gamma ray to radiation changes in the radiation protection materials of nuclear reactors, which are simultaneously affected by neutrons and gamma ray.

It can be made in the following way:

According to [40], the ratio  $\varphi_n / \varphi_g$  of the density of the damaging neutron flux (with an energy of more than 10 KeV)  $\varphi_n$  (neutron/(cm<sup>2</sup>·s)) to the energy flux density of gamma ray  $\varphi_g$  (MeV/(cm<sup>2</sup>·s)) behind the nuclear reactor vessel is:

-  $\varphi_n / \varphi_g \approx 0.05 \text{ MeV}^{-1}$  – for uranium-graphite and water-cooled thermal neutron reactors;

-  $\varphi_n / \varphi_g \approx 3 \text{ MeV}^{-1}$  – for fast neutron reactors.

Then the ratio  $n_{d.g} / n_{d.n}$  of the number of displaced atoms under the action of gamma ray  $n_{d.g}$  with gamma ray energy  $E_g = 5 \text{ MeV}$  (average energy behind the reactor vessel) to the number of displaced atoms under the action of neutrons  $n_{d.n}$  with the cross sections for the formation of displaced atoms  $\sigma_d(E_g) = 0.5 \cdot 10^{-24} \text{ cm}^2$  and  $\sigma_d(E_n) = 1400 \cdot 10^{-24} \text{ cm}^2$  will be:

$$n_{d.g} / n_{d.n} = \varphi_n / \varphi_g \cdot \frac{\sigma_d(E_g)}{E_g \cdot \sigma_d(E_n)} = 0.05 \cdot \frac{0.5 \cdot 10^{-24}}{5 \cdot 1400} = 3.6 \cdot 10^{-6} \text{ – for uranium-graphite and water-cooled thermal neutron reactors;}$$

$$n_{d.g} / n_{d.n} = \varphi_n / \varphi_g \cdot \frac{\sigma_d(E_g)}{E_g \cdot \sigma_d(E_n)} = 3 \cdot \frac{0.5 \cdot 10^{-24}}{5 \cdot 1400} = 2.1 \cdot 10^{-4} \text{ – for fast-neutron reactors.}$$

Since  $n_{d.g} / n_{d.n}$  is much less than 1, the effect of gamma ray on the radiation changes of minerals and rock-aggregates of concrete, and hence concrete, radiation protection of nuclear reactors under the simultaneous exposure to neutrons and gamma ray can be neglected. In this regard, the radiation changes under the influence of gamma ray must be taken into account when gamma ray only is exposed to materials with absorbed doses of more than  $10^9 \text{ Gy}$ .

It is characteristic that the results of evaluating the gamma ray effect on minerals and rocks do not correspond to the opinion that silicate minerals and rocks receive the largest and smallest radiation changes upon exposure based on the results of irradiation of minerals and rocks with high neutron fluences. When irradiated with neutrons with the formation of a large number of displaced atoms, the largest radiation changes are obtained by quartz, feldspars and including them granites, diorites (with coarser grains especially), sandstones, and much smaller changes – by serpentine, pyroxenes, hornblende, olivine and including them gabbro, basalts, diabases, pyroxenites, peridotites and dunites. Under the gamma ray influence of the considered absorbed dose values, the maximum changes from silicate materials will occur in olivine, pyroxenes and including them dunite, peridotite, pyroxenite, and the minimum changes will occur in quartz, serpentine, feldspars (microcline, oligoclase, labrador) and including them sandstone and basalt. The intermediate radiation changes will be observed in granites, diorites and gabbro, to the compositional features of which the influence of their coarse-grained structure is added.

Further computational research should be devoted to:

- assessment of radiation changes in cement stone based on existing experimental data on concrete irradiation;
- assessment of radiation changes in concrete with various aggregates under the influence of gamma ray in a wide range of absorbed doses and radiation temperatures based on the results of the assessment of radiation changes in aggregates and cement stone.

Such an assessment can also be performed on the basis of the above considered methods for the analytical determination of radiation changes in concrete and its components.

## 4. Conclusion

1. The paper assesses the radiation changes of concrete aggregates under the influence of gamma ray based on analytical methods developed previously during the study of neutron radiation influence. The possibility of using these analytical methods in the case of exposure to gamma ray is discussed and justified in this paper.

2. For practical use of these analytical methods, the relationship between the absorbed dose of gamma radiation of different energies and the number of atoms displaced during irradiation has been established. It was found that the absorbed dose of gamma radiation with an energy of 5 MeV corresponds to 3 times more displaced atoms than the absorbed dose of gamma radiation with an energy of 2 MeV.

3. As a result of the calculations, the radiation changes of the main types of rocks - concrete aggregates (igneous, sedimentary rocks and ores) under the influence of gamma radiation with an average energy of 2 MeV and 5 MeV after irradiation to absorbed doses from  $10^5$  to  $10^{11}$  Gy at 30 °C, 100 °C and 300 °C were estimated. For this purpose, the radiation changes of the main rock-forming minerals were calculated, and the radiation changes of rocks of concrete aggregates were calculated from them.

4. It has been established that the noticeable radiation changes in the examined minerals and aggregate rocks will occur only at absorbed doses of gamma ray greater than  $D_{g0} = 1 \cdot 10^9 - 1 \cdot 10^{10}$  Gy for gamma rays with an energy of 5 MeV and  $D_{g0} = 3 \cdot 10^9 - 3 \cdot 10^{10}$  Gy for 2 MeV gamma rays. The radiation changes in the volume of minerals increase with a rise in the absorbed dose and decrease in silicate class minerals and silicate rocks with an increase in the irradiation temperature.

5. At 30 °C, the largest increase in volume under the influence of gamma radiation in the studied range of absorbed doses will occur in minerals of the silicate class. The maximum increase in volume during irradiation at 30 °C will occur in olivine (up to 0.3 %). A minimal and insignificant increase in volume will be observed in magnetite (up to 0.007 %). The radiation change in the volume of minerals decreases in the direction: olivine-pyroxenes (diopside, enstatite) →hornblende→quartz, serpentine, calcite, dolomite→microcline, oligoclase, labrador, hematite→magnetite.

6. With an increase in the irradiation temperature from 30 °C to 100 °C and 300 °C, the radiation changes of silicate class minerals decrease, while the radiation changes of carbonate class minerals (calcite, dolomite) and iron oxides (hematite, magnetite) do not change. Moreover, the effect of temperature increases with the rise of irradiation temperature. At 100 °C, the radiation increase in the volume of silicates decreases by 11–18 times and becomes insignificant and at 300 °C it decreases by 400–1800 times compared with the change in volume at 30 °C and becomes insignificant. In this regard, the ratio between radiation changes in the volume of various minerals changes, the upper and lower boundaries of the changes in volume decrease, and the increase in the volume of silicate class minerals becomes smaller than that of carbonates and iron oxides.

7. In quartz glass, regardless of the irradiation temperature, there will be a decrease in volume (up to -0.3%).

8. Radiation changes in the volume of rocks of concrete aggregates increase with an increase in the absorbed dose and decrease in rocks consisting of minerals of the silicate class with an increase in the irradiation temperature.

9. At 30 °C, according to the results of calculations, the greatest increase in volume and decrease in strength under the influence of gamma radiation in the studied range of absorbed doses will occur in rocks consisting of silicate class minerals.

10. The largest increase in volume under the influence of gamma radiation during irradiation at 30 °C will be observed in dunite (up to 0.36 %), peridotite (up to 0.31 %) and pyroxenite (up to 0.28 %). The smallest, insignificant increase in volume will occur in magnetite ore (up to 0.0066 %). The radiation change in the volume of rocks decreases in the direction of: dunite, peridotite and pyroxenite→granite, diorite and gabbro (up to 0.22 %)→basalt, sandstone, limestone and dolomite (up to 0.059%)→magnetite ore (up to 0.018 %)→hematite ore.

11. The greatest decrease in strength during irradiation at 30 °C will be observed in granite (up to -8.7 %). Almost half less reduction of strength will occur in dunite (up to -5.8 %), peridotite (up to -5.4 %), pyroxenite (up to -4.2 %) and gabbro (-4.3 %). In other rocks, the reduction of strength is not significant and is -1.3 % or less, but it decreases in the direction of: limestone (to -1.3 %)→basalt (to -0.6 %)→hematite and magnetite ore (to -0.1 %).

12. With an increase in the irradiation temperature from 30 °C to 100 °C and 300 °C, the radiation changes of silicate aggregate rocks decrease, while the radiation changes of carbonate and ore aggregate

rocks do not change. At 100 °C, the increase in the volume of silicate rocks in addition to basalt decreases by 13-31 times, and at 300 °C decreases by 300–970 times compared to the change in volume at 30 °C. In basalt, the decrease is about 2 times at 100 °C and about 80 times at 300 °C. In this regard, the ratio between the radiation changes in the volume of various silicate and carbonate, ore rocks changes, the upper and lower limits of volume changes are reduced, and the increase in the volume of silicate rocks become less than of carbonate and ore rocks. Radiation changes in strength with increasing irradiation temperature change similarly to changes in volume.

13. In general, it can be noted that even with the absorbed dose of  $10^{11}$  Gy gamma ray the changes of rocks-concrete aggregates are not great (an increase in volume is no more than 0.36 %, a decrease in strength is no more than 8.7 %). In this regard, the changes in concrete under the influence of gamma ray at the considered absorbed doses will not be significant.

14. The calculated radiation changes of minerals and rock aggregates of concrete under the action of gamma radiation are much smaller than the maximum changes established during neutron irradiation (an increase in volume is to 18–23 %, a decrease in strength is to 100 % in silicate materials, an increase in volume is to 3 % in carbonate and oxide materials). According to the results of calculations, the radiation changes under the action of gamma ray, commensurate with the maximum radiation changes under the action of neutrons in nuclear facilities operating at the present time are practically impossible.

15. The calculations have shown that the influence of gamma ray on the radiation changes of minerals and rock aggregates of concrete, and therefore concrete, the radiation protection of nuclear reactors with the simultaneous exposure to neutrons and gamma ray can be neglected. In this regard, the radiation changes under the influence of gamma radiation must be taken into account when only gamma ray is applied to materials and when absorbed doses are greater than  $10^9$  Gy.

## References

- Kelly, B., Brocklehurst, J., Mottershead, D., McNearney, S. The Effects of Reactor Radiation on Concrete. Proceedings of the Second Information Meeting on Pre Stress Concrete and Reactor Pressure Vessels and their Thermal Isolation. EUR-4531, 1969. Pp. 237–265.
- Gray, B.S. The Effect of Reactor Radiation on Cements and Concrete. Proceedings of an information exchange meeting on results of concrete irradiation programmes. EUR 4751 f-e Brussels (Belgium), April 19, 1971. Commission of the European Communities, Luxembourg, 1972. Pp. 17-39
- Elleuch, L., Dubois, F., Rappeneau, J. Effects of Neutron Radiation on Special Concretes and Their Components. Special Publication of The American Concrete Institute SP-34, 1972. Pp. 1071–1108.
- Dubrovskiy, V.B., Lavdanskiy, P.A., Pergamenshchik, B.K., Solovyev, V.N. Radiatsionnaya stoykost materialov [Radiation Stability of Materials Handbook]. Spravochnik. Pod obshey red. V.B. Dubrovskogo. Ed. V.B. Dubrovskiy. Moscow: Atomizdat, 1973. 264 p.(rus)
- Dubrovskiy, V. B. Radiatsionnaya stoykost stroitelnykh materialov [Radiation Stability of building materials] Moscow: Stroyizdat, 1977. 278 p.(rus)
- Hilsdorf, H.K., Kropp, J., Koch, H. J. The effects of nuclear radiation on the mechanical properties of concrete. Proceedings of the Douglas McHenry International Symposium on Concrete and Concrete Structures, ACI SP 55-10, American Concrete Institute, Mexico City, Mexico, 1978. Pp. 223–251.
- Kaplan, M.F. Concrete Radiation Shielding. Concrete Design and Construction Series. Harlow: Longman Scientific, 1989. 457 p.
- Denisov, A.V., Dubrovskiy, V.B., Krivokoneva, G.K. Radiatsionnyye izmeneniya mineralov zapolniteley betonov i ikh analiticheskoye opredeleniye [Radiation-induced changes in concrete aggregates minerals and analytical determination]. Voprosy atomnoy nauki i tekhniki. 1984. No 2 (18). Pp. 31–40. (rus)
- Denisov, A. V., Dubrovskiy, V.B. Analiticheskoe opredelenie radiatsionnogo izmeneniya svoystv materialov zapolniteley betonov [Analytical determination of radiation changes in the properties of concrete aggregate materials]. Voprosy atomnoy nauki i tekhniki. 1984. No. 2(18). Pp. 45–57. (rus)
- Muzalevskiy, L.P. Prognozirovaniye stepeni izmeneniya prochnosti i radiatsionnykh deformatsiy betona [Forecasting of degree of change of durability and radiating deformations of concrete]. Trudy Tretey Vsesoyuznoy nauchnoy konferentsii po zashchite ot ioniziruyushchih izlucheniye yaderno-tekhnicheskikh ustanovok [Works of the Third All-Union scientific conference on protection from ionising radiation of Nuclear-technical installations]. Vol. 5. Tbilisi: Iz-vo TGU, 1985. Pp. 116–125. (rus)
- Denisov, A.V., Dubrovskiy, V.B., Yershov, V.Yu. et. al. Radiatsionno -Temperaturnyye izmeneniya svoystv portlandcementnogo kamnya betona i avisimosti dlya ih prognozirovaniya [Radiation -thermal changes of properties of hardened cement paste and functions for their predictions]. Voprosy atomnoy nauki i tekhniki. 1989. No. 2. Pp. 20–35. (rus)
- Muzalevskiy, L.P. Radiatsionnyye izmeneniya tyazhelykh betonov i metod ikh analiticheskogo opredeleniya [Radiating changes of heavy concrete and method of their analytical definition]. Dissertatsiya na soiskaniye uchenoy stepeni kandidata tekhnicheskikh nauk [Candidate of technical sciences (PhD) dissertation]. Moscow, 1989. 240 p. (rus)
- Fillmore, D.L. Literature Review of the Effects of Radiation and Temperature on the Aging of Concrete. Technical Report INEL/EXT-04-02319. Idaho National Engineering and Environmental Laboratory. Bechtel BWXT Idaho, LLC. Prepared for the Central Research Institute of Electric Power Institute. September 2004.
- Denisov, A.V., Dubrovskiy, V.B., Solovev, V.N. Radiatsionnaya stoykost mineralnykh i polimernykh stroitelnykh materialov [Radiating stability of mineral and polymer c building materials]. Moscow: Izdatelskiy dom MEI, 2012. 284 p. (rus)
- William, K., Xi, Y., Naus, D. A review of the effects of radiation on microstructure and properties of concretes used in Nuclear Power Plants. Tech. Rep. NUREG/CR -7171 ORNL/TM - 2013/263, US Nuclear Regulatory Commission, Oak Ridge National Laboratory. 2013.
- Field, K.G., Remec, I., Le Pape, Y. Radiation effects in concrete for nuclear power plants – Part I: Quantification of radiation exposure and radiation effects. Nuclear Engineering and Design. 2015. 282. Pp. 126–143.

17. Le Pape, Y., Field, K.G., Remec, I. Radiation effects in concrete for nuclear power plants, Part II: Perspective from micromechanical modeling. *Nuclear Engineering and Design*. 2015. 282. Pp. 144–157.
18. Giorla, A., Vaitova, M., Le Pape, Y., Stemberk, P. Meso-scale modeling of irradiated concrete in test reactor. *Nuclear Engineering and Design*. 2015. Vol. 295. Pp. 59–73.
19. Pomaro, B. A Review on Radiation Damage in Concrete for Nuclear Facilities. Experiments to Modeling. *Modelling and Simulation in Engineering*. 2016. Pp 1-10. Article ID 4165746. <https://doi.org/10.1155/2016/4165746> (date of application: 19/01/2020)
20. Rosseel, T.M., Maruyama, I., Le Pape, Y., Kontani, O., Giorla, A.B., Remec, I., Wall, J.J., Sircar, M., Andrade, C., Ordonez, M. Review of the Current State of Knowledge on the Effects of Radiation on Concrete. *Journal of Advanced Concrete Technology*. 2016. 14(7), Pp. 368-383. DOI:10.3151/jact.14.368.
21. Maruyama, I., Kontani, O., Takizawa, M., Sawada, S., Ishikawa, S., Yasukouchi, J., Sato, O., Etoh, J., Igari, T. Development of the soundness assessment procedure for concrete members affected by neutron and gamma-irradiation. *Journal of Advanced Concrete Technology*. 2017. 15. Pp. 440–523. DOI:10.3151/jact.15.440.
22. Le Pape, Y., Alsaid, M.H.F., Giorla, A.B. Rock-forming minerals radiation induced volumetric expansion – revisiting the literature data. *Journal of Advanced Concrete Technology*. 2018. 16. Pp.191–209. DOI: 10.3151/jact.16.191
23. Sommers, J.F., Gamma radiation damage of structural concrete immersed in water. *Health Physics*. 1969. 16. Pp. 503–508.
24. McDowall, D.C. The Effect of Gamma Irradiation on the Creep Properties of Concrete. Proceedings of an information exchange meeting on results of concrete irradiation programmes. EUR 4751 f-e Brussels (Belgium), April 19, 1971. Commission of the European Communities, Luxembourg, 1972. Pp. 55–69
25. Vodák, F., Trtík, K., Sopko, V., Kapičková, O., Demo, P. Effect of  $\gamma$ -Irradiation on Strength of Concrete for Nuclear Safety Structures. *Cement and Concrete Research*. 2005. 35. Pp. 1447–1451.
26. Lowinska-Kluge, A., Piszora, P. Effect of gamma irradiation on cement composites observed with XRD and SEM methods in the range of radiation dose 0-1409 MGy. *Acta Physica Polonica-Series A General Physic.*, 2008. 114. Pp. 399–411.
27. Kitsutaka, Y., Matsuzawa, K. The effect of gamma radiation on the fracture properties of concrete. Proceedings of FraMCoS-7, May 23-28, 2010. *Fracture Mechanics of Concrete and Concrete Structures - Recent Advances in Fracture Mechanics of Concrete*. Korea Concrete Institute, Seoul, ISBN 978-89-5708-180-8. Pp. 61–64.
28. Vodák, F., Vydra, V., Trtík, K., Kapičková, O. Effect of  $\gamma$ -irradiation on Properties of Hardened Cement Paste. *Materials and Structures*. 2011. 44. Pp. 101–107.
29. Kontani, O., Ichikawa, Y., Ishizawa, A. Irradiation Effects on Concrete Durability of Nuclear Power Plants. Proceedings of ICAPP 2011, Nice, France, May 2-5, Paper 11361.
30. Kontani, O., Sawada, S., Maruyama, I., Takizawa, M., Sato, O. Evaluation of irradiation effects on concrete structure: gamma-ray irradiation tests on cement paste. Proceedings ASME 2013 Power Conference, Boston, USA 29 July-1 August 2013. New York, USA: American Society of Mechanical Engineers, 2013-98099.
31. Ishikawa, S., Maruyama, I., Takizawa, M., Etoh, J., Kontani, O., Sawada, S. Hydrogen Production and the Stability of Hardened Cement Paste under Gamma Irradiation. *Journal of Advanced Concrete Technology*. December 2019.17. Pp. 673–685. DOI: 10.3151/jact.17.673.
32. Kircher, J. F., Bowman, R. E. Effects of Radiation on Material and Components. Eds. Reinhold, New York: Chapman and Hall, 1964. 690 p.
33. Pergamenschik, B.K., Samotayev, A. V. Raschet chisla smeshchennykh atomov v kvartse pri obluchenii v reaktore [Calculation of the number of displaced atoms in quartz during irradiation in the reactor]. *Materialy i konstruksii zashchit yadernykh ustanovok*. Sbornik trudov MISI. 1974. № 114 (kafedra Stroitelstva yadernykh ustanovok). Pp. 102–112. (rus)
34. Kovalchenko, M.S., Ogorodnikov, M.S., Rogovoy, Yu.I., Krayniy, A. G. Radiatsionnoye povrezhdeniye tugoplavkikh soyedineniy [Radiation damage to refractory compounds]. Moscow: Atomizdat, 1979. 160 p.
35. Kwon, J., Motta, A.T. Gamma displacement cross-sections in various materials. *Annals of Nuclear Energy*. 2000. No. 27. Pp. 1627–1642.
36. Denisov, A.V., Sprince, A. Analytical determination of thermal expansion of rocks and concrete aggregates. *Magazine of Civil Engineering*. 2018. No. 4. Pp.151–170. DOI: 10.18720/MCE.80.14
37. Kelly, B. Radiatsionnoye povrezhdeniye tverdykh tel [Irradiation Damage of Solids]. *Perevod s angl.* Moscow: Atomizdat, 1970. 240 p. (rus)
38. Mashkovich, V.P., Kudryavtseva, A.V. Zashchita ot ioniziruyushchih izlucheniy [Protection against ionizing radiation]. *Spravochnik [Handbook] – 4 –ye izd. pererab. i dlop.* Moscow: Energoatomzdat, 1995. 496 p. (rus)
39. *Spravochnik fizicheskikh konstant gornykh porod [Handbook of physical constants of rocks*. Edited by S. Clarke]. Pod red. S. Klarka ml. Moscow: MIR, 1969. 543 p.(rus)
40. Dubrovskiy, V.B., Pergamenschik, B.K. Dopuskayemye radiatsionnyye nagruzki na betonnyuyu zashchitu yadernykh reaktorov [Permissible radiation loads on concrete shielding of nuclear reactors]. *Energeticheskoye stroitelstvo*. 1969. No 9. Pp. 74-75. (rus)

### **Contacts:**

*Aleksandr Denisov, den-al-v@inbox.ru*