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 ÷14):

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

- $\sigma_d(E_g)$ = (0.2 – 0.5)· 10^{-24} 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 $n_{см}$ when irradiated by gamma ray in the minerals should be determined by the formulas:

$$n_d = \sum_{i-1}^{m} \left[\sigma_d(E_{gi}) F_g(E_{gi}) \right] \tag{1}$$

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

$$n_d = \sigma_d(E_g) F_g(E_g) \tag{2}$$

– 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 , cm^2;

– $F_g(E_{gi})$ and $F_g(E_g)$ are fluence of γ-quantum with energy E_{gi} and E_g , γ-quantum/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)·10^{-12} Gy/(γ-quantum/cm^2) ≈5·10^{-12}Gy/(γ-quantum/cm^2) for gamma-rays with energy E_g = 1 MeV;

$k_{D_g/F_g}(E_g)$ = (7.5 – 9.2)·10^{-12} Gy/(γ-quantum/cm^2) ≈8·10^{-12} Gy/(γ-quantum/cm^2) for gamma rays with energy E_g = 2 MeV;

$k_{D_g/F_g}(E_g)$ = (1.39 – 1.6)·10^{-11} Gy/(γ-quantum/cm^2) ≈1.5·10^{-11}Gy/(γ-quantum/cm^2) for gamma rays with energy E_g = 5 MeV.

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

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

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:

$$a(T) = \alpha(T)/\beta(T) \tag{4}$$

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

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:

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

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:

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

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

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 10^{-2} % 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:

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

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:

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

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

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 ... 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]:

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

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:

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

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:

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

where $\frac{\Delta R_{AG}}{R_{AG0}}$ are the relative changes in strength, as the ratio of the absolute change in strength ΔR_{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	Dunite	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:

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

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

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.

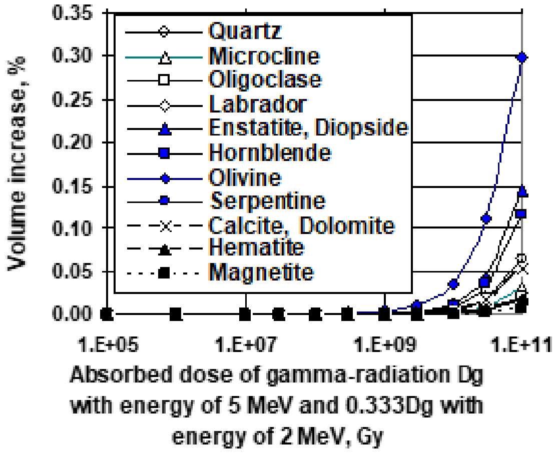


Figure 1. Dependence of the calculated radiation increase in the volume of various minerals on the absorbed dose of gamma ray with an average energy of 5 MeV and 2 MeV at an irradiation temperature of 30 °C.

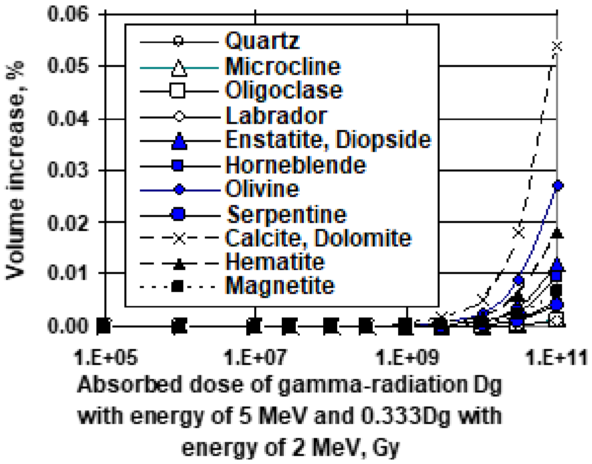


Figure 2. Dependence of the calculated radiation increase in the volume of various minerals on the absorbed dose of gamma ray with an average energy of 5 MeV and 2 MeV at an irradiation temperature of 100 °C.

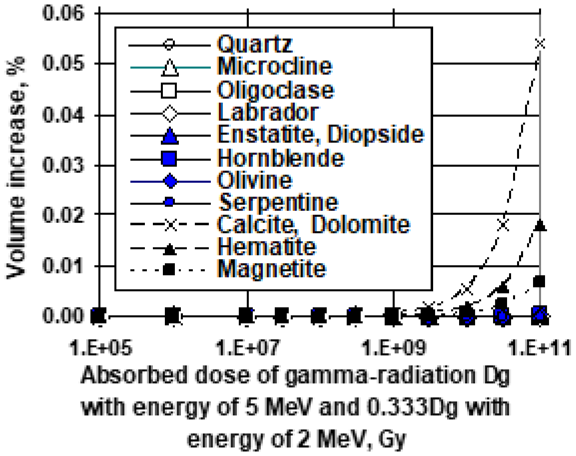


Figure 3. Dependence of the calculated radiation increase in the volume of various minerals on the absorbed dose of gamma ray with an average energy of 5 MeV and 2 MeV at an irradiation temperature of 300 °C.

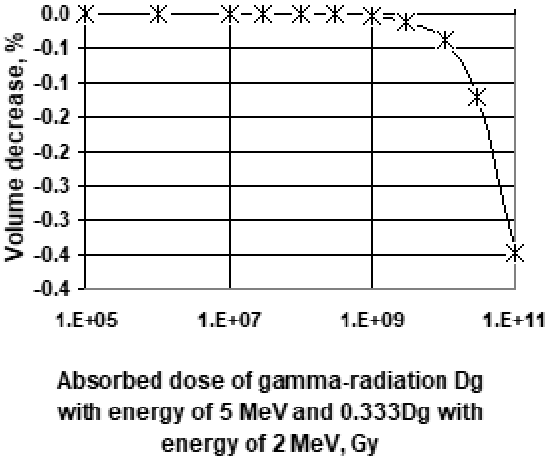


Figure 4. The dependence of the calculated radiation decrease in the volume of quartz glass on the absorbed dose of gamma ray with an average energy of 5 MeV and 2 MeV at irradiation temperatures from 30 to 300 °C.

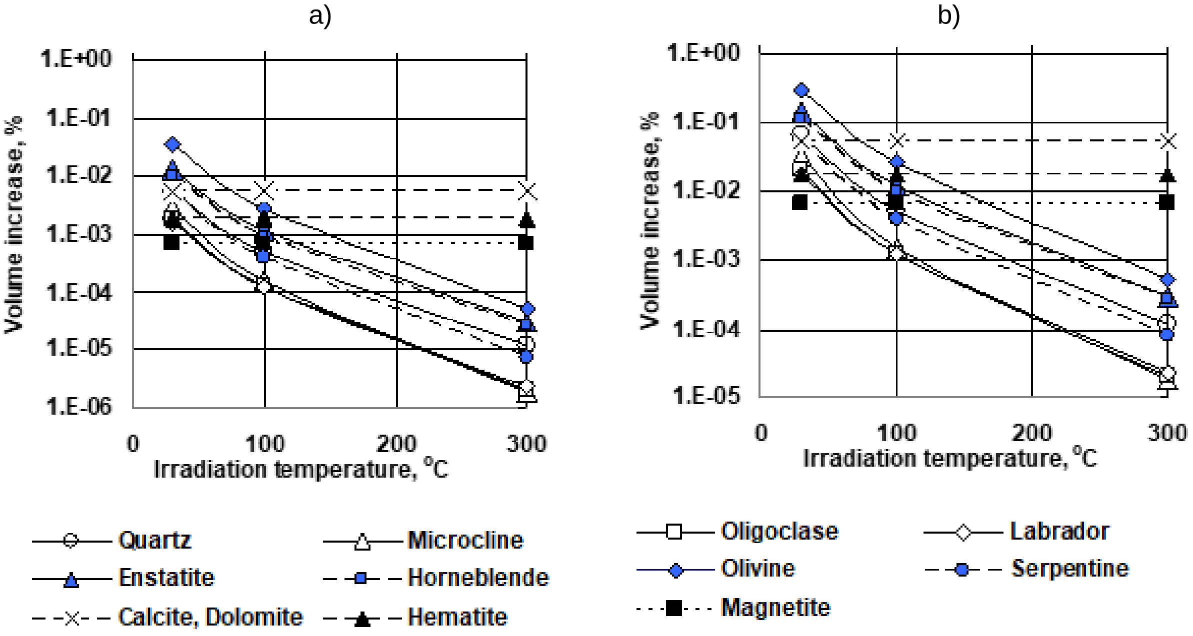


Figure 5. Dependence of the calculated radiation increase in the volume of various minerals on the irradiation temperature at an absorbed dose of gamma ray with an average energy of 5 MeV $1 \cdot 10^{10}$ Gy (a) and $1 \cdot 10^{11}$ Gy (b)

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.

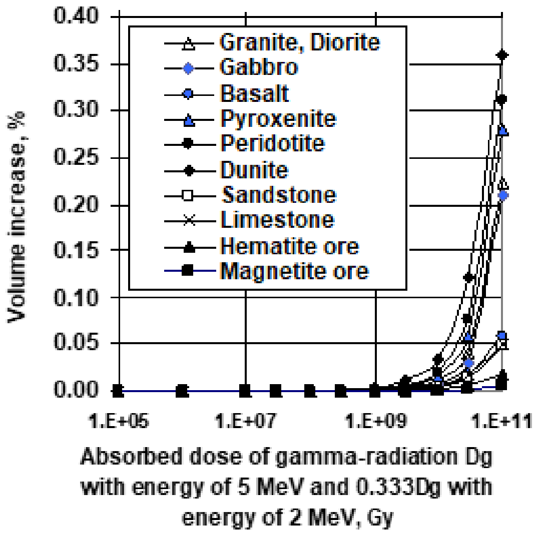


Figure 6. Dependence of the calculated radiation increase in the volume of various concrete aggregate rocks on the absorbed dose of gamma ray with an average energy of 5 MeV and 2 MeV at an irradiation temperature of 30 °C.

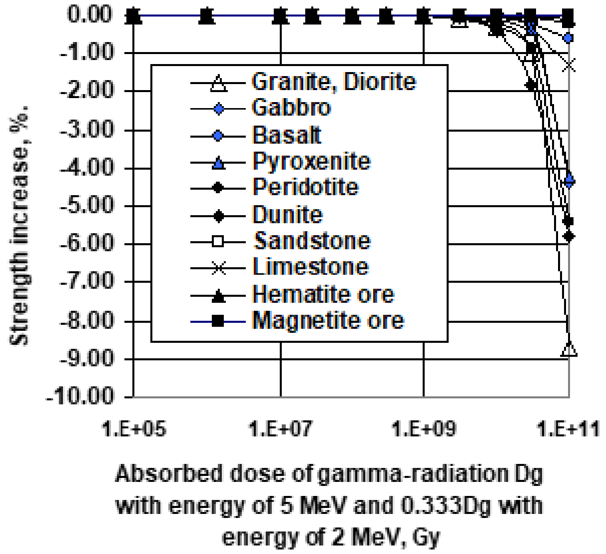


Figure 7. Dependence of the estimated residual strength of various concrete aggregate rocks on the absorbed dose of gamma ray with an average energy of 5 MeV and 2 MeV at an irradiation temperature of 30 °C.

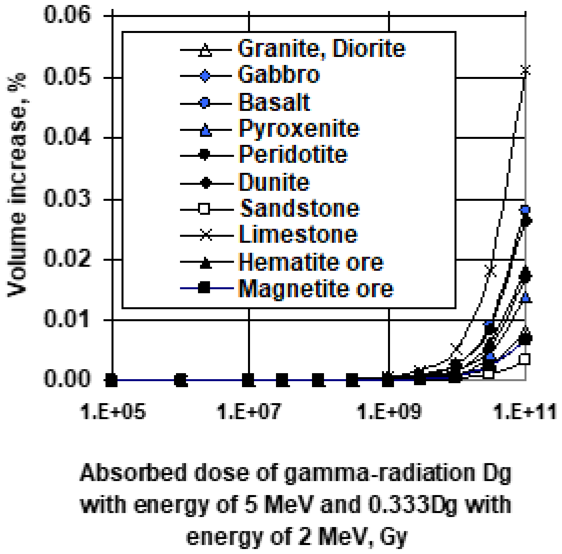


Figure 8. Dependence of the calculated radiation increase in the volume of various concrete aggregate rocks on the absorbed dose of gamma ray with an average energy of 5 MeV and 2 MeV at an irradiation temperature of 100 °C.

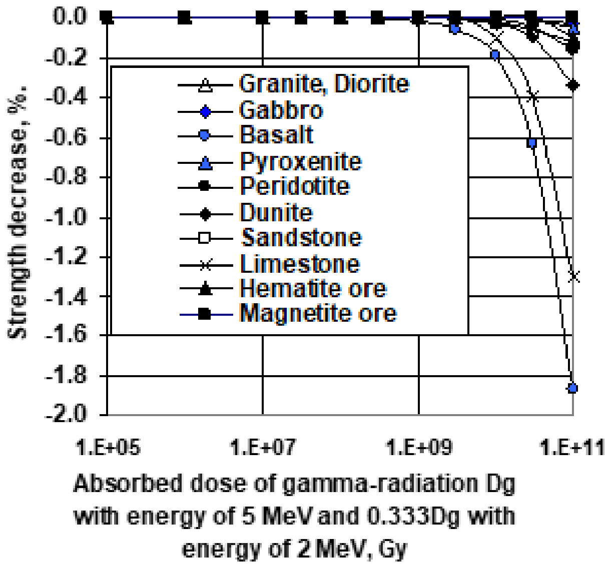


Figure 9. Dependence of the estimated residual strength of various concrete aggregate rocks on the absorbed dose of gamma ray with an average energy of 5 MeV and 2 MeV at an irradiation temperature of 100 °C.

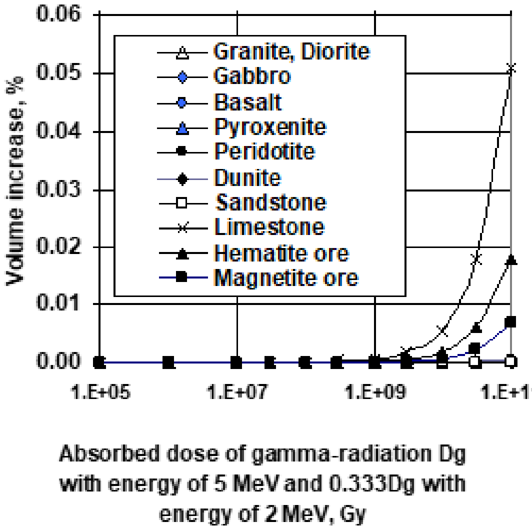


Figure 10. Dependence of the calculated radiation increase in the volume of various concrete aggregate rocks on the absorbed dose of gamma ray with an average energy of 5 MeV and 2MeV at an irradiation temperature of 300 °C.

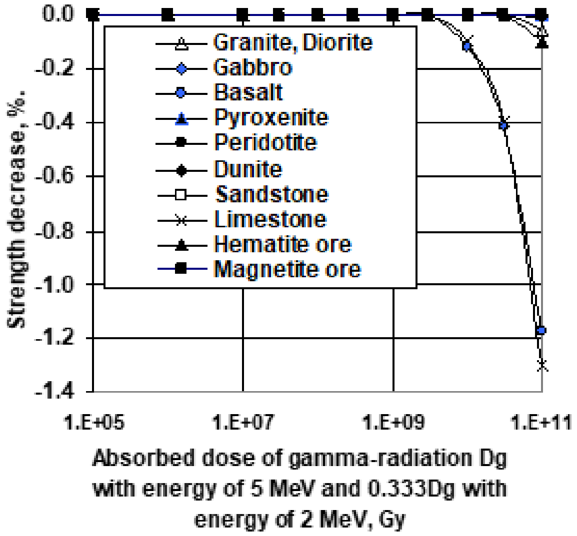
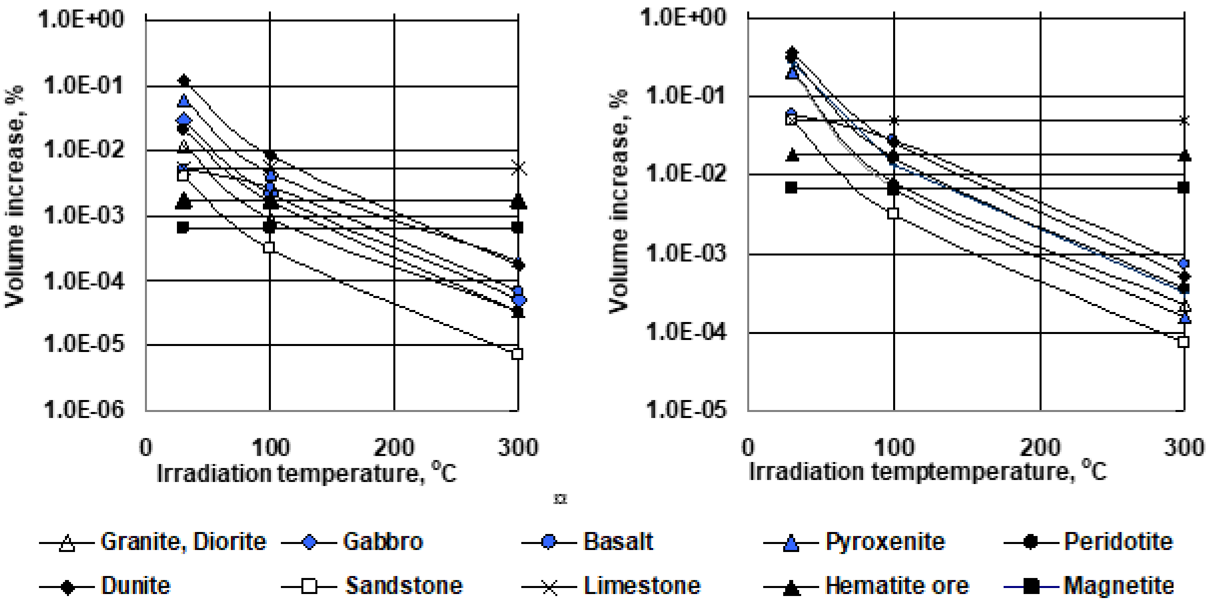


Figure 11. Dependence of the estimated residual strength of various concrete aggregate rocks on the absorbed dose of gamma ray with an average energy of 5 MeV and 2MeV at an irradiation temperature of 300 °C.


a)

b)

Figbre 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 ≈2 times at 100 °C and ≈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 pyroxenitis (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 %) → limestone (up to -1.3 %) → dunite (up to 0.3 %) → 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 ^{2} for silicate materials at 30 ^{o}C;
- $3{\cdot}10^{20}$ neutron/cm ^{2} for silicate materials at 100 ^{o}C;
- $10{\cdot}10^{20}$ neutron/cm ^{2} for silicate materials at 300 ^{o}C;
- $(1\text{-}10){\cdot}10^{20}$ neutron/cm^2 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^2 correspond to the fraction of displaced atoms $n_{см}$ = 0.14–1.4, since the average cross section for atomic displacement is $\sigma_{см}(E_n)$ = $1400{\cdot}10^{-24}$ cm^2. 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:

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

$D_g = n_{см} / 3.3{\cdot}10^{-14}$ = (0.14 – 1.4)/$3.3{\cdot}10^{-14}$ = $4.2{\cdot}10^{12}$ -$4.2{\cdot}10^{13}$ Gy – at gamma ray energy E_g = 5 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 φ_n / φ_g of the density of the damaging neutron flux (with an energy of more than 10 KeV) φ_n (neutron/(cm^2·s)) to the energy flux density of gamma ray φ_g (MeV/(cm^2·s)) behind the nuclear reactor vessel is:

- $\varphi_n / \varphi_g \approx 0.05$ MeV^{-1} – for uranium-graphite and water-cooled thermal neutron reactors;
- $\varphi_n / \varphi_g \approx 3$ 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 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 $\sigma_d(E_g)$ = 0.5·10^{-24} cm^2 and $\sigma_d(E_n)$ = 1400·10^{-24} cm^2 will be:

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

$$n_{d.g} / n_{d.n} = \varphi_n / \varphi_g \cdot \frac{\sigma_d(E_g)}{E_g \cdot \sigma_d(E_n)} = 3 \cdot \frac{0.5 \cdot 10^{-24}}{5 \cdot 1400} = 2.1 \cdot 10^{-4}$$ – 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 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 dunits. 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 $D_{g0} = 1\cdot10^9 - 1\cdot10^{10}$ Gy for gamma rays with an energy of 5 MeV and $D_{g0} = 3\cdot10^9 - 3\cdot10^{10}$ 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.

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