Radiation changes in serpentinite concretes of "dry" radiation shield in nuclear power plants

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Abstract. The article presents the results of computational studies of the radiation changes in serpentinite concretes of "dry" radiation shield of the Water-Water Energetic Reactor (WWER/ VVER) type of nuclear power plants built in the Russian Federation and other countries. The research was carried out in connection with the increase in radiation loads on the concrete of the "dry" protection of modern nuclear power plants, and also in connection with the possible use in "dry" protection of the modern nuclear power plants of concretes with serpentinite aggregates which mineral composition and structure differ from the composition and structure of the previously used serpentinites. The calculation studies were performed using the developed and experimentally tested methods for the analytical determination of radiation and thermal changes in concretes and their components. It was found out that the relative number of displaced by irradiation atoms from 0.026 to 0.1, degree of perfection of the crystal structure of serpentinite minerals, availability of impurities in serpentinite minerals (magnetite, chlorite, olivine, pyroxenes, hornblende, brucite, magnesite, calcite, dolomite, ankerite, mica, feldspar) in quantity from 0 to 40%, medium mineral grain size in the range of 0.0001 cm up to 0.02 cm influence on the radiation changes in the volume and strength of serpentinite concretes. There was also performed comparison of radiation and thermal changes. The research has showed that the lowest radiation changes will occur in the serpentinite concrete with aggregates consisting only of serpentine, especially with imperfect structure. The availability and quantity of magnetite, chlorite, calcite, brucite, feldspars and mica show insignificant influence on the radiation changes. The presence of dolomite, magnesite, ankerite and especially olivine, hornblende, pyroxenes with an increase in their volume content, as well as growth in the size of grains of minerals, the radiation changes in serpentinite concretes may grow up to 2-4 times. By increasing the duration of exploitation and power capacity of the reactor, as well as by extending the service life of a nuclear power plant, the radiation changes in the serpentinite concretes of "dry" radiation shield may grow up to 6-12 times.

Keywords: "dry" radiation shield in nuclear power plants, serpentinite concretes, radiation changes in volume and strength, influence mineral composition and structure

1. Introduction

In Russian Federation, the Water-Water Energetic Reactors (WWER/ VVER) have got radiation-heat "dry" protection of serpentinite concrete around the nuclear reactors. [1, 2]. The "dry" protection gets the impact of sufficiently high neutron fluxes [1, 3, 4], so when using concrete in "dry" radiation shield we should take into account the possible radiological changes.

The "dry" protection requires the concretes of serpentinite from Bazhenovskoe mineral deposit in the Russian Federation; the rationale for their use is based on the results of research carried out in 60-
ies of XX century. [1, 5 - 8]. However, the mining from this mineral deposit may cause to changes in the composition and structure of serpentinites. Besides, the Russian Federation may construct the nuclear power plants in other countries, so it can increase the probability of use of serpentinite from the foreign deposits with mineral composition and structure which may significantly differ from these characteristics of the serpentinites from Bazhenovskoe mineral deposit. In addition to that, the growth in power capacity of VVER reactors from 1000 MW to 1200-1500 MW, the extension of the lifespan of nuclear power plants from 30 years to 50 years, as well as the possible continuation of nuclear power plant operation after this period increase of the radiation load on the serpentinite concrete "dry" protection.

For the reasons mentioned above, the existing data of the radiation changes in serpentinite concrete and their components [6, 7], as well as generalized in the biggest major reviews information about radiation changes in various concretes [9-17], do not contain detailed information how the radiation changes in the serpentinite concretes can change. In this regard, the purpose of the present work was computational and analytical research of the influence of mineral composition and structure of serpentinite aggregates, as well as the magnitude of the radiation load on radiation-induced changes in serpentinite concrete.

2. Research Methodology
The main attention was paid to the study of the radiation changes in serpentinite concretes (caused by the action of neutrons). However, we also considered the thermal changes under the influence of maximum temperatures of exploitation.

The radiation and thermal changes in the volume and compressive strength of serpentinite concretes were calculated using theoretically developed and experimentally proven methods of analytical determination of the radiation and thermal changes in concretes and their components, which were summarized and described in the work. [13]. The thermal deformations of minerals were taken according to the data of the research [18].

We investigated the influence of magnetite, chlorite, olivine, pyroxene, hornblende, brucite, magnesite, calcite, dolomite, ankerite, mica, feldspar on the radiative changes of mineral impurities in serpentinite concretes, based on the analysis of the numerous literature and Internet sources describing the variations in the mineral composition and the structure of serpentinites. When carrying out the calculations, the serpentine content in serpentinizes was considered in the range from 100 to 60%, the content of impurity minerals - from 0 to 40% with an average grain size of 0.02 cm, the average grain size of minerals from 0.0001 cm to 0.02 cm. The average modulus of deformation of serpentinites was assumed to be 1x10^7 MPa.

The radiative changes of serpentinite concretes were calculated according to the data [1, 3, 4] on the flux density and the neutron spectrum, the temperatures acting on the "dry" radiation shield and on the basis of calculations of the relative number of displaced atoms. The changes were calculated on the basis of methods of work [13], under the following radiation loads and temperatures:

- the influence of damaging neutrons (with an energy of more than 10 keV) \( F = 1.9 \times 10^{19} \text{ neutron / cm}^2 \), the relative number of displaced atoms \( N_{dpa} = 0.026 \), the average temperature of 60°C - at the initial lifetime of the nuclear power plant \( t = 30 \text{ years} = 0.95 \times 10^9 \) s;
- \( F = 3.2 \times 10^{19} \text{ neutron / cm}^2 \), \( N_{dpa} = 0.044 \), average temperature is 60°C - with the increase in the lifetime of modern nuclear power plant to \( t = 50 \text{ years} = 1.6 \times 10^9 \) s;
- \( F = 4.8 \times 10^{19} \text{ neutron / cm}^2 \), \( N_{dpa} = 0.066 \), average temperature of 60°C - with the power increase of nuclear power plants from 1000 MW to 1200-1500 MW due to the increase in reactor power;
- \( N_{dpa} = 0.1 \), average temperature of 60°C when extending the operation period.

The calculation of thermal changes was based on the results of exposure to a temperature of 160°C.

In accordance with the data [19], the volume content of crushed stone and sand in the concrete was assumed to be \( V_{cs} = 0.44 \) and \( V_s = 0.26 \), respectively. Water-cement ratio - \( W/C = 0.7 \). We considered matured concrete (more than 10 month-old).
As a base concrete of the "dry" radiation shield we excepted the concrete with serpentinite of the Bazhenovskoye mineral deposit. According to the data [20, 21], it had an average level of mineral composition: serpentine - 80%, olivine - 5%, pyroxene - 5%, brucite - 5%, magnetite - 5%.

3. The results of the research and their discussion

As the example of dependence of the radiative changes of serpentinite concretes on the number of atoms displaced during irradiation and their comparison with thermal changes under the effect of temperature of 160 °C, you can see the concretes with serpentinites of Bazhenovskoye mineral deposit shown on Figure 1. It can be seen that the radiation changes in the volume of such concretes with increasing number of displaced atoms in the interval from 0.026 to 0.1 grows to 5 times (from 0.22% to 1.01%) with a thermal growth in volume at a temperature of 160 °C by a value of 0.35%.

\[ N_{dpa} = 0.026 \]

\[ N_{dpa} = 0.1 \]

\[ -2\% \text{ at } N_{dpa} = 0.026 \]

\[ -6\% \text{ at } N_{dpa} = 0.1 \]

\[ -18\% \text{ at } 160 °C \]

For comparison, we give the calculated changes a caused by the operation temperature of 160 °C.

The compressive strength of these concretes due to the action of neutron radiation does not become low not significantly for this characteristic. Radiation reduction in strength is from -2% at The compressive strength of these concretes due to the action of neutron radiation does not become low not significantly for this characteristic. Radiation reduction in strength is from -2% at \( N_{dpa} = 0.026 \) to -6% at \( N_{dpa} = 0.1 \). The thermal changes caused by heating to 160 °C are somehow more significant and amount to -18%.

The results of calculations of the radiation deformations of serpentinite and impurity minerals at the number of displaced atoms \( N_{dpa} = 0.026 \) and 0.1 are shown in Figures 2 and 3.
Figure 2. Comparison of the calculated radiation growth in volume (a) and size (b) in the most expanding direction of various serpentinite minerals after irradiation to the relative number of displaced atoms $N_{\text{dpa}} = 0.026$ at 60 °C

The radiation changes of serpentines with perfect structure are shown as they are the most common minerals. Serpentines with imperfect structure have no radiative changes in volume and size.

Figure 3. Comparison of the calculated radiation growth in volume (a) and size (b) in the most expanding direction of various serpentinite minerals after irradiation to the relative number of displaced atoms $N_{\text{dpa}} = 0.1$ at 60 °C

The radiation changes of serpentinites with perfect structure are shown as they are the most common minerals. Serpentinites with imperfect structure have no radiative changes in volume and size.
It can be seen that the radiation deformation of chlorite, calcite, magnetite, brucite, feldspar, mica is commensurable with the radiation deformations of the serpentine minerals with perfect structure or is less than theirs. The presence of these minerals in serpentine aggregates will not increase the radiative changes of serpentinite concretes with these aggregates and may even somehow reduce the changes in them. In this connection, the influence of these minerals on the radiation changes of serpentinite concretes was not considered further.

The radiation deformations of hornblende, pyroxenes, olivines, ankerite, dolomite and magnesite for all or even low radiation loads exceed the radiative deformations of serpentinites. The presence of these minerals in serpentine aggregates can increase the radiation changes in serpentinite concretes. Therefore, the effect of these minerals on the radiative changes of serpentinite concretes requires more detailed investigation.

As a result of computational studies, it has been found out that the smallest radiative changes are observed in concretes with serpentine aggregates that do not contain impurity minerals (Figures 4-7).

**Figure 4.** Dependence of the calculated increase in volume (a) and strength decrease (b) of concretes with serpentine aggregates from the aggregate volume content of ankerite, dolomite and magnesite in different relative numbers of $N_{dpa}$ atoms displaced during irradiation in conditions of "dry radiation shield when heated up to 160 °C.

Here are given the average values of the influence of the considered minerals and the boundaries of the differences in their influence.

In the presence of ankerite, dolomite, magnesite, especially olivine, hornblende, pyroxenes and serum contents in the composition of serpentine aggregates, the radiative changes of serpentine concretes mainly grow (Figures 4-7). The most significant effect of the mineral content of impurity minerals is observed in the presence of olivines, especially hornblende and pyroxenes in serpentine aggregates. With an increase in the content of these minerals, the radiation changes grow to 2-5 times. Thus, while the content of hornblende and pyroxenes is 40%, the radiative increase in the volume of serpentinite concrete reaches 1.82% and 3.2%, while the decrease in strength is -16.5% and -30%, respectively. By increasing the number of displaced atoms from 0.026 to 0.1, the radiation changes grow to 6-12 times.
Figure 5. Dependence of the calculated growth in volume (a) and strength reduction (b) of concretes with serpentine aggregates from volumetric content of olivine aggregate at different relative numbers of \( N_{dpa} \) atoms displaced during irradiation in conditions of "dry radiation shield" when heated up to 160 °C.

Figure 6. Dependence of the calculated growth in volume (a) and decrease in strength (b) of concretes with serpentine aggregates from the volume content of hornblende aggregate at different relative numbers of \( N_{dpa} \) atoms displaced during irradiation in conditions of "dry" radiation shield when heated up to 160 °C.
Figure 7. Dependence of the calculated growth in volume (a) and decrease in strength (b) of concretes with serpentinite aggregates from volume content of pyroxene-enstatite aggregate at different relative numbers of $N_{dpa}$ atoms displaced by irradiation under conditions of "dry" radiation shield with heating up to 160 °C.

The radiative changes of serpentinite concretes are mostly reduced when serpentines with an imperfect structure present in the serpentinite aggregate, instead of serpentines with the perfect structure. Instead of the thermal growth in volume, the volume of concrete will become low (by up to -0.38% at 160 °C and down to -0.485% after 160 °C) due to the removal of chemically bound water from serpentinites.

The effect of serpentines minerals with an imperfect structure in the serpentinite aggregate on radiation and thermal changes is most significant in the absence and presence of impurity minerals (10% or less), but is decreased with a growth in the content of impurity minerals and the number of displaced atoms. This is shown in Figure 8 by the example of the relationship between the calculated radiative and thermal changes of serpentinite concretes with serpentine of imperfect structure (is index) to changes in serpentinite concretes with serpentine of perfect structure (ps index) for different contents of pyroxene-enstatite and a different number of displaced atoms. These relationships are shown as $K_V = (\Delta V/V)_{is}/(\Delta V/V)_{ps}$ - for volume changes and $\Delta V/V$ and $K_R = (\Delta R/R)_{is}/(\Delta R/R)_{ps}$ - for strength changes $\Delta R/R$.

Figure 8 shows that when the content of pyroxenes and the number of displaced atoms is increased, the $K_V$ and $K_R$ coefficients mainly become higher when the atoms are irradiated. At the same time in case of the most significant content of the impurity mineral and the number of displaced atoms, the radiative changes of serpentinite concretes with serpentines of a perfect and imperfect structure are approximately equal, since $K_V$ and $K_R$ coefficients are close to be equal to 1, though radiation changes in strength have some local maxima and deviations. Thermal volume reduction with a growth of impurity mineral content becomes low, since the negative value of $KV$ becomes less in absolute value. The perfection of the serpentine structure and the bulk content of the impurity mineral practically do not influence on the thermal change in strength, since $K_R \approx 1$. The thermal change in strength practically has no change with the increase in the impurity mineral content.
Figure 8. Dependence of the calculated radiative and thermal changes in serpentinite concretes with serpentine of imperfect structure (is index) and perfect structure (ps index) at different contents of pyroxene-enstatite and various numbers of $N_{dpa}$ atoms displaced under conditions of "dry" radiation shield with heating up to 160 °C.

a - volume change ratio $K_V = (\Delta V/V)_{is}/(\Delta V/V)_{ps}$
b - strength change ratio $K_R = (\Delta R/R)_{is}/(\Delta R/R)_{ps}$

Figure 9. Dependence of the calculated growth in volume of concretes with serpentine aggregates of Bazhenovskoe mineral deposit (a) and serpentine aggregates with 40% of pyroxene-enstatite (b) at different relative numbers of $N_{dpa}$ atoms displaced during irradiation in conditions of "dry" radiation shield from the average grain size of minerals.
According to the results of calculations, the radiative changes of serpentinite concretes grow, under the conditions considered, with the growth of the grain size of minerals. In Figure 9, this is shown for the radiative changes in the volume of concretes on the serpentinite aggregate of the composition, similar to the serpentinite composition of the Bazhenovskoe mineral deposit, and serpentinite with 40% pyroxene content. Figure 9 shows that when the average grain size of minerals grows from 0.0001 cm to 0.02 cm, the radiative change in volume grow to 2.5 times.

4. Conclusion

1. The lowest radiation changes in "dry" radiation shield will occur in the serpentinite concrete consisting only of serpentine, especially with imperfect structure. However, if serpentines have imperfect structure, the volume of concrete will become low instead of a thermal growth in volume (by up to -0.38% at 160°C and down to -0.485% after 160 °C). Since this because chemically bound water is removed, it will be accompanied by a decrease in the protective properties of the serpentinite.

2. The influence of presence of serpentine minerals with imperfect structure in the serpentinite aggregate on the radiation and thermal changes is most pronounced in the absence or presence of small content of impurity minerals (10% or less) and becomes low with a growth in the content of impurity minerals and the number of displaced atoms.

3. The availability and quantity of magnetite, chlorite, calcite, brucite, feldspars and mica show insignificant influence on the radiation changes.

4. The presence of dolomite, magnesite, ankerite and especially olivine, hornblende, pyroxenes with a growth in their volume content, as well as increase in the size of grains of minerals, the radiation changes in serpentinite concretes may grow up to 2-5 times.

5. By increasing the duration of exploitation and power capacity of the reactor, as well as by extending the service life of a nuclear power plant, the radiation changes in the serpentinite concretes of "dry" protection may grow up to 6-12 times.

6. The obtained results are to be considered when choosing serpentinite for concrete "dry" protection of the modern nuclear power plants.

References

[1] Zholdak G I 1977 Dry radiation shield of power reactors Proceedings of MISI named after V.V. Kuibyshev No. 146 Moscow pp 16-22
[2] Zholdak G I, Lavdansky P A, Esenov A V, Pergamenschik B K 2011 Dry protection shield of the VVER-1000 reactor Vestnik MGSU [Proceedings of Moscow State University of Civil Engineering] issue 8 pp 316-319
[3] Calculation-experimental characteristics of the field of fast neutrons in the near-shell space / Brodkin E B, Borodin A V, Vikhrlov V I et al. 1987 Radiation safety and protection of nuclear power plants Moscow, Energoatomizdat issue 12 pp 19-22
[4] Borodkin G I, Lomakin S S, Eremin A N et al. 1987 Measurement of the neutron flux density in the near-shell space of the VVER-1000 serial reactor Radiation Safety and Protection of Nuclear Power Plants Moscow: Energoatomizdat issue 12 pp 10-12
[5] Arshinov I A, Veselkin A P, Egorov Yu A et al. 1966 Serpentinite concrete in the biological protection of nuclear power plants / Moscow, Atomizdat p 54
[6] Dubrovsky V B, Ibragimov Sh, Kulakovskiy M Ya, Ladygin A Ya, Pergamenschik B K 1968 Radiation resistance of serpentinite concrete Atomic Energy, No. 6, Vol 25, issue 6, p 515 (deposited article)
[7] Elleuch L, Dubois F, Rappeneau J 1972 Effects of neutron radiation on special concretes and their components. Special Publication of The American Concrete Institute 43, pp 1071–1108
[8] Arshinov I A, Vasilyev G A, Egorov Yu A et al. Serpentinite in the protection of nuclear reactors Ed. Yu.A.Egorov Moscow, Atomizdat 1972 p 238
[9] Dubrovsky V B, Lavdansky P A, Pergamenschik B K, Soloviev V N 1973 Radiation resistance of materials Reference book Ed. V.B. Dubrovsky Moscow, Atomizdat p 264
[10] Dubrovsky V B 1977 *Radiation resistance of building materials*. Moscow, Stroyizdat  p 278

[11] Hilsdorf H K, Kropp J, Koch H J 1978 The effects of nuclear radiation on the mechanical properties of concrete *Proc. of the Douglas McHenry International Symposium on Concrete and Concrete Structures*, ACI SP 55-10, American Concrete Institute, Mexico City, Mexico pp 223–251

[12] Kaplan M F 1989 *Concrete Radiation Shielding: Nuclear Physics, Concrete Properties, Design, and Construction*. John Wiley & Sons, New York, NY, USA

[13] Denisov A V, Dubrovsky V B, Soloviev V N 2012 *Radiation resistance of mineral and polymer building materials*. Moscow, MPEI Publishing House  p 284

[14] William K, Xi Y, Naus D 2013 *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

[15] Field K G, Remec I, Pape Y Le 2015 Radiation effects in concrete for nuclear power plants – Part I: Quantification of radiation exposure and radiation effects // *Nuclear Engineering and Design* Vol 282 pp 126–143.

[16] Pape Y Le, Field K G, Remec I 2015 Radiation effects in concrete for nuclear power plants, Part II: Perspective from micromechanical modeling // *Nuclear Engineering and Design* Vol 282 pp 144–157

[17] Beatrice Pomaro 2016 A Review on Radiation Damage in Concrete for Nuclear Facilities // *Experiments to Modeling. Modelling and Simulation in Engineering*. Vol 2016, Article ID 4165746, p 10 URL: https://www.hindawi.com/journals/mse/2016/4165746/

[18] *Handbook of physical constants of rocks*. Ed. S Clark. Trans. from English Moscow, Mir 1969  p 543

[19] Pergamenschik B K, Telichenko V I, Temishev R R 2011 Construction of special protective structures for nuclear power plants Moscow, MPEI Publishing house  p 240

[20] Zholdak G I 1979 About the thermal stability of serpentine concrete for the protection of a nuclear power plant reactor. *Construction of power plants with nuclear and organic fuel*. Digest No 165 (MISI named after V. V. Kuibyshev) Ed. V B Dubrovsky and N Turchin Moscow  pp 58-74

[21] Bakhterev V V, 2011 High-Temperature Electrical Conductivity of Serpentinised Hyperbasites and the Forecast of Mineralization *Mining information-analytical bulletin* (scientific-technical journal). No. 10 pp 69-73.