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Radiation-resistant composite for biological shield of personnel

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Abstract. This article presents the results of theoretical and practical justification for the use of polymer concrete based on nonisocyanate polyurethanes in biological shield structures. We have identified the impact of ratio: polymer – radiation-resistant filling compound on the durability and protection properties of polymer concrete. The article expounds regression dependence of the change of basic properties of the aforementioned polymer concrete on the absorbed radiation dose rate. Synergy effect in attenuation of radioactivity release in case of conjoint use of hydrogenous polymer base and radiation-resistant powder is also addressed herein.

1. Introduction
Development of nuclear power industry is undoubtedly an evidence of progress. Nuclear power is relatively cheap, and its generation is quite safe, given the adequate organization of the process. However, many years of operating experience of nuclear installations worldwide revealed that along with improvement of reliability of the reactors, measures should be taken to make biological shield of the plant personnel more effective. This article addresses the development of a composite in support of the a.m. task.

2. General problem statement and correlation with significant theoretical and practical problems
Conventionally, biological shields for the personnel of nuclear facilities are made of various metals and concrete with maximum density of 4500 kg/m³ with radiation-resistant filling compounds [1].

Apart from this, combinations of the a.m. materials are widely used, depending on the gamma-radiation dose rate. At the same time, the commonly recognized protection methods are at times not efficient enough. This is caused by variable penetration power of the particles generated in the course of nuclear reactions. Thus, for example, electrically charged electrons, protons, alpha particles and fission fragments, slowdown very fast in comparatively thin layers of substance. The path of the most penetrating of the listed particles – electron – with energy 5…6 MeV in aluminum is maximum 1 cm. The major danger is posed by the neutral particles – neutrons and gammas. Decay of elementary particles generates gammas with energy coming to 70 MeV. When fast neutrons penetrating the substance slow-down, photons with energy up to several tens of GeV may emerge in Coulomb field of nuclei.
As is well known, the most intensive moderators of high-energy fast neutrons to medium-energy neutrons are the elements possessing the capability of inelastic scattering of neutrons – for example, barium and iron [1]. Apart from this, hydrogen which is not only slowing-down, but also captures the slow neutrons, shall be included in the material composition.

Due to the fact that the fast neutrons slowing-down is accompanied by the heat release, provisions shall be made for additional heat resistance of material which is attained through inclusion of radiation-resistant filling compound.

Given all the apparent merits of the high-density concrete used in the “dry” reactor shield, significant disadvantages yet exist, such as penetrability for the neutron flux, considerable water absorption, susceptibility to cracking in tensioned locations [2].

Operating experience with fast-neutron reactors showed that the list of additional requirements to the materials being developed should include the ability of slowing-down and absorption of neutrons with various energies [2]. Such materials include the majority of polymers, which may be the basis for all sorts of composites with a complex of properties that to the maximum extent possible meet the requested operating requirements [3].

In this connection, when constructing radiological protection facilities, all the engineering and economic advantages and disadvantages of various materials should be carefully considered. Preference should be given to the materials with the properties that are critical for the given structure and construction conditions. Owing to the material science development, such materials appear to be polymer-based composites. Experience gained in the use of polymer-concrete for protective structures showed their advantages as compared to the concrete based on the mineral binding materials [3, 4].

This is caused by high durability, fracture strength and chemical stability of hardened composites and reduced construction and commissioning periods. The currently required characteristics of constructional materials ensuring the adequate level of protection cause the need for management of the structure formation process, to promote the quality control.

Apart from this, the design of formulation for the composites intended for biological shield, an integrated approach is required, since besides the maximum possible linear attenuation coefficient, the material under development shall be sufficiently radiation-resistant to ensure the design lifetime of protection structure. In all, the research mentioned above provide for the resolution of scientific task to create effective composite materials owing to the use of polymer raw material and advance technologies changing the mechanism of radiological protection and improving performance characteristics of products made from such materials. Actually, the practical goals are to increase the lifetime of civil structures, improve their reliability in operation and ensure specified level of personnel protection.

3. Review of research and publications addressing the problem and serving as guidance to the author

The current scientific approaches to the development of radiation-resistant composites are based on the efficient use of chemical composition and structure of polymeric and non-polymeric materials.

Radiation resistance of polymeric materials depends on their chemical structure. Polymers with double bonds and aromatic cycles boast of higher resistance as compared to polymers with saturated bonds. This is explained by energy dissipation in the structural elements of macromolecules. Such a phenomenon is particularly characteristic of polymers with aromatic groups with a big set of energy levels, due to which ionizing radiation is dispersed by bonds. Apart from this, due to free electrons, redistribution of energy takes place in macromolecules. Polymers with bonds C-F, C-Si, C-O [3, 5] are characterized by a lower radiation resistance.

Experience has been gained in radiation protection of glass, [6], sulphur [7, 8] and liquid rubber [9]. It is stated that in those cases when it is desirable for the materials to have insulation properties, polymer compounds are used with introduction of metal powders of high density, such as tungsten, lead, boron, cadmium and iron [1].
Also, there is a sufficient number of examples of using epoxy resins and vulcanized rubber as polymeric base to solve the problems caused by corrosion, ultraviolet radiation, radiation and other adverse effects of environmental and technogenic factors [4,10].

Despite the fact that nowadays a wide range of materials capable of long-term resistance to radiation exposure are available, the most promising of these is polymer-concrete with a set of operating characteristics of which high and actually universal chemical and radiation resistance, technological effectiveness and small shrinkage are outstanding.

Based on the results of polymer-concrete development activities, we may regard them as radiation-resistant materials [11].

4. Identification of pending items of the general problem
Since all the kinds of radiation cause chemical transformations in polymers, resulted in destruction of the existing bonds and generation of the new ones, the radiation protection composite should be based on a polymer characterized by increase of hardness and thermal resistance at the initial radiation phase while protection against neutron flux is provided for.

We cannot attain attenuation of neutron flux by increasing the density and atomic number of the substance, while this is conventionally used for gamma attenuation – the a.m. change will result in the increase of linear absorption factor. Such dependence does not exist for the neutron flux attenuation.

Technology of slowing-down and absorption of neutrons with various energies involves several phases. Firstly, fast neutrons need to be slow down to thermal neutrons, as the nuclei are not good at absorption of fast neutrons, while the light elements slow down the neutron of average to low energies more intensively. Thereafter, the slow neutrons need to be captured. It is common knowledge that hydrogen does not only slows the neutrons down, but also captures them [5].

Boron, cadmium and lithium are also effective for capture and absorption of slow neutrons [5].

Apart from the aforementioned requirements, the materials used for radiation protection facilities should provide for minimum generation and minimal energy of the secondary radiation, in particular, the minimal release of gammas with minimal energy generated at photon capture; low induced radioactivity in the shield; mechanical strength of material, primarily compressive strength; relatively low modulus of elasticity promoting decrease of tensioning stress caused heating of the inner layers of the shield; minimal thermal expansion, ensuring the structure integrity and reducing the stresses; water and gas resistance, corrosion resistance; technological effectiveness (simple to erect and dismantle) and low cost [9].

The majority of such requirements are to a great extent mutually antithetical, which complicates optimization of composite composition by a single target function. In this connection, we conducted research to specify formulations focused on assurance of long-term maintenance of the original properties of polymer concrete used for biological shields in radiation exposure conditions at specified strength.

5. Problem statement
Effective radiological protection requires a composite combining a polymeric basis and sufficient number of hydrogen bonds attenuating and absorbing the neutron radiation, along with radiation-resistant filling compound to ensure the specified values of physical and mechanical properties.

Special attention should be paid to compatibility of the filling compound and polymeric base to prevent blowout and disintegration of the prefabricated composite.

Besides, the experience of the predecessors revealed that introduction of exclusively micro-grain filling compounds into polymer-concrete composition is the most effective, since biological shield structures are fabricated to casting technology and the appropriate accessories are not fit for supply of compound with macro-grain filling compound.

6. Materials, research techniques and principal research data
According to our suggested scientific hypothesis, production of radiation-resistant composite is
feasible, given that we combine hydrogenous basic polymeric base with sufficient radiation resistance properties and high-density radiation-resistant filling compound ground to the required condition. For that, polymeric base with high content of hydrogen should be combined with radiation-resistant filling compound.

Rational correlation of the aforementioned components will ensure protection against neutron, as well as gamma-radiation at specified strength. Apart from this, provisions shall be made for adequate environmental safety in production of biological shield as well as in its long-term lifetime.

The bases for selection of formulation of polymer-based composite for fabrication of biological shield structures are well-known theses of polystructural theory of V.I. Solomatov and the concept of systematic and structural approach to the material quality management, assuming transition from fragmentariness principle to integration when the structure of material, technology and structure of products are presented as interrelated systems.

Research activities carried out for selection of polymeric base, revealed a class of compounds with the integrity of properties meeting the aforementioned requirements – polyurethanes, produced by cold solidification of oligocyclocarbonates (Laprolat 803, Laprolat 301, Laproxid 503M brands). Laprolats are the products of carbonization of epoxy derivatives of polyoxide propylenes (laprols) with the end cyclocarbonate groups. Laprolats are solidified by reaction urethane generation: cyclocarbonate - amine with primary aliphatic or cycloaliphatic amines, generating hydroxyurethane structure [5, 13].

The properties of non-isocyanate polyurethanes are caused by interactions of specific nature (hydrogen bonds, ion-type bonds) and nonspecific (dipole-dipole, Van der Waals interactions and crystallization), the total input of which into generation of polyurethane properties’ complex is decisive. In generation of hydrogen bonds the donors of protons are atoms of H- urethane groups, in case of polyurethane-carbamides and polyamideurethanes – atoms H of the appropriate urethane groups. Proton acceptors are carbonyls of the listed groups [13].

Availability of a large quantity of hydrogen in polymer composition promotes effective capture of fast neutrons and reduction of fluence density of the particles mentioned above. At the same time, the process is accompanied by radiation self-heating, which has a negative impact on the strength characteristics of material. It is evident that effective biological shield and resistance to thermal effects should be provided concurrently. Such problems are resolved conjointly, since introduction of a filling compound with high linear attenuation coefficient promotes decrease of heat generation in polymer-concrete body. Preliminary investigations revealed that the most promising filling compounds are fine-dispersed radiation-resistant powders [14, 15].

The key characteristic of the material under development is linear radiation attenuation coefficient:

\[ \mu = n \sigma, \]

where \( n \) – number of atoms of absorbing material in the unit of volume, \( \sigma \) – cross-section of radiation interaction with one atom of substance, depends not only on material properties, but also on radiation energy.

Value \( \sigma(Z,E) \) depends on \( Z \) – atom number of substance and radiation energy – \( E \). For complex substances the linear attenuation coefficient (LAC) may be expressed by expression:

\[ \mu = \mu_1 a_1 + \mu_2 a_2 + \ldots + \mu_i a_i, \]

where \( a_1, a_2, a_i \) – mass fractions of each of the components.

Magnitudes \( \sigma \) may be calculated by well-known formulas consistent with experimental data within three percent. The main input to calculated LAC inaccuracy ЛКО comes from вносят uncertainty of \( \sigma_i \) values and variation of absorber material density. Apparently, this factor is particularly significant in case of composite materials under review.

In this connection, it is important that LAC is obtained and measured specifically for the radiation energy range in question. In this investigation the range of values was 0.1...1.5 MeV, since the main radioactive isotopes determining the radiation dose, have radiation energies within this interval.
The design of radiation-resistant composites should account for the fact that on the one hand, introduction of filling compounds ensures the composite strength, while on the other hand, it reduces the consumption of polymeric component containing hydrogen bonds.

Apparently, we need balanced combination of the a.m. components providing for the maximum possible linear attenuation coefficient as per (2) at specified strength.

We conducted comparative analysis of physical and chemical characteristics of ground serpentine, barite, limonite, magnetite and powdered glass of sodium-boron-silicate composition, and evaluated their compatibility with polymeric binding material. The a.m. powders were selected on the account of their conventional use in radiological protection.

Table 1 presents the ranking of filling materials based on the values of specific surface $S_{sp}$, oil absorption and $pH$ of water extraction.

In selection of the fineness of grinding of the filling material particles, we bore in mind the following: the particles are prone to agglomeration, which increases when specific surface of filling material increases; sedimentation of particles, which accelerates while specific surface of filling material decreases, the filling material density increases and the binding material viscosity decreases.

### Table 1. Physical and chemical characteristics of filling materials

| Name             | Mean density, kg/m³ | $S_{sp}$, m²/g | Chemical composition                     | Oil absorption, g/100 g | $pH$ of water extraction |
|------------------|---------------------|----------------|------------------------------------------|-------------------------|--------------------------|
| serpentine       | 2300…3200           | 300…350        | $Mg_2(OH)_2Si_2O_5$ or $3MgO.2SiO_2.2H_2O$ | 28…60                  | 9.1…10.3                 |
| barite           | 2900…3600           | 280…310        | $BaSO_4$                                 | 30…50                  | 6…8                      |
| limonite         | 2400…3700           | 310…340        | $Fe_2O_3.H_2O + Fe_2O_3.2H_2O$          | 40…56                  | 5…5.5                    |
| magnetite        | 3250…4100           | 290…340        | $Fe_3O_4$                                | 35…50                  | 5.5…6.2                  |
| powdered glass   | 600…900             | 15…200         | $Na_2O \approx 7.5\%$                    | 9…11                   | 6.6…7.4                  |
| apparent density |                     |                | $B_2O_3 \approx 12\%$                    |                        |                          |
| density          |                     |                | $SiO_2 \approx 80.5\%$                   |                        |                          |

Rational correlation of polymeric base and the filling material was established with account of the following three indices: specified viscosity providing for the cast technique, compressive strength (not lower than reinforced concrete strength), radiation resistance.

Double-component polymeric binding material was used in investigations [16].

Component A - epoxy resin - ED-20 (ED-22) as per GOST 10587 with EDOS diluent – plasticizer as per Technical Specifications TU 2493-003/3004794-93, density 1.16…1.25 kg/m³. Component B - inclusion complex of Laprolat -803 (TU 6-05-221-995-88 with mass fraction of cyclocarbonate groups – 21…31, epoxy group – 2.5%, density 0.971 kg/l, $pH$ 3.5…5.5) with amines (isophorondiamine, diethylenetriamine, triethylenetetramin).

Radiation resistance tests of the samples were conducted at installation GURKh-1000 with gamma-energy of radioactive source $Co^{60}$ 1.25 MeV.

The controlled parameter determining radiation resistance was the change of sample compression strength depending on various absorbed gamma doses. The required total absorbed doses accumulated depending on exposure time in $\gamma$-bundle. The temperature of samples in the course of dose accumulation owing to radiation heating did not exceed 45°C.

Experimental measurements of linear attenuation coefficient were carried out by linear 4096-train semi-conducting gamma-spectrometer with diffusive Ge-Li semi-conducting detector DGDK-160B.

The tests were conducted in accordance with the procedure set forth by O.E. Perekalsky in the relevant qualification thesis [9]. At first phase, investigations were carried out to identify the input of filling materials to alteration of composite viscosity. It was determined that introduction of fine filling materials significantly
increases viscosity of the composite, even under conditions of exothermal reaction between polymer and the hardening group components. As introduction of plasticizers of chemical nature into radiation-resistant materials is not practical, we considered the possibility of using plasticizer of physical type - powdered glass.

Selection of the a.m. plasticizer was caused by a number of reasons. Firstly, availability of microspheres in powder provides for considerable reduction of composite resistance to viscous shift. Secondly, chemical composition of powder meets the radiological protection requirements.

Analysis of experimental results enabled us to make a conclusion that in case of conjoint introduction of fine-dispersed filling materials viscosity \( \eta \) changes in accordance with the following relation:

\[
\eta = \eta_0 + A x_1 + B x_2,
\]

where \( \eta_0 \) – original viscosity of polymer, \( \text{Pa} \cdot \text{s} \); \( x_1, x_2 \) – a number of introduced components, mass%; \( A, B \) – coefficients characterizing the input of each filling component (thickening, dilution).

Based on (3), we calculated combinations of various filling materials with powdered glass. As a result of calculations of possible combinations, we determined the boundaries for variation of volume content of filling materials in specified quantity of binder.

Given the complex composition of the composite polymeric base, it is quite difficult to judge about the chemistry of processes taking place when the a.m. powders interact with polymer. However, comparative analysis of obtained data enabled us to identify the most acceptable filling material – limonite.

In connection with the above-stated, we suggested the assumption of composite viscosity decrease at complex introduction of limonite and powdered glass, even at high concentrations, owing to spherical shape of the particles and small oil absorption plays a role of a sliding layer between the main filling material and a binder.

As a result of experiments, it was revealed that when fillers are combined with a binder under conditions of significant difference in pH (for example, when serpentine is introduced) composite blow-out may occur due to release of gaseous products of side reactions at the interface. It was established that the fillers should satisfy condition \( 8 > pH > 5 \).

At the second phase we carried out investigations to establish rational relation “binder-filler”. It should be noted that reference books lack the data about the rate of radiation absorption by powdered glass. In this connection, we did not evaluate LAC of the powder itself, but of the composite in general. As target functions, we assigned gamma attenuation factor (LAC, compressive strength \( R_{\text{compr}} \) ) and composite viscosity (\( \eta \)).

To establish the rational combination of components (RCC), we applied two-factor and two-level experiment. The following factors affecting the key RCC properties were assigned: the quantity of powdery filler of the corresponding dispersibility \( (X_1) \), the quantity of glass spheres \( (X_2) \), in mass fractions from mass of polymeric binder.

Considering the fact that combination of hardening group components and polymeric base is an exothermic reaction, when powders were introduced, the composite temperature registered was 30°C. The temperature reduction was monitored with alcohol thermometers. Viscosity measurements were conducted at two values of temperature: 30 and 20°C. The rational relation “binder-filler” was established by means of two-factor three-level experiment. The data of preceding experiments enable us establish the maximum and minimum filling degrees consistent with the viscosity threshold value. The plan of experiment with obtained values of target functions is presented on figure 2. Notations provided in the plan, such as “+”, “−” and “0” correspond to the upper, lower and medium level of factors as appropriate.

As a result of experimental data processing, we obtained regression equations for variations of viscosity, linear attenuation coefficient and compressive strength:

\[
\eta = 28,66 + 11,8x_1 + 4,5x_2;
\]

\[
LAC = 1,03 + 0,27x_1 - 0,15x_2;
\]

\[
R_{\text{compr}} = 24,74 - 6,8x_1 + 3,1x_2;
\]
at temperature 20°C:

$$\eta = -3.633 + 40.18 x_1 + 17.35 x_2$$

(5)

$$LAC = -0.276 + 0.264 x_1 + 0.135 x_2$$

(6)

$$R_{es} = 24.87 + 5.72 x_1 + 5.58 x_2$$

(7)

Verification of the equations by Fisher and Student criteria showed their adequacy and validity. Considering that regressive equations are linear, it is quite difficult to optimize the composition by any of the selected parameter. Due to this, optimization was combined by LAC and viscosity.

According to Equation 6, the input if fillers into LAC value is ambiguous. Degree of gamma attenuation by limonite powder is a bit higher, than for powdered glass. At the same time, LAC values obtained for the composite are in general considerably higher than the total LAC values of the stated fillers. Apparently, conjoint use of limonite and glass powders in polymer-concrete results in synergic effect, thus reciprocally reinforcing gamma attenuation effect. In our opinion, this circumstance may be explained by presence in composite of components that are different by nature and component composition ensuring, in the aggregate, effective radiation protection. Comparative analysis of the impact of powder concentration on the strength of consolidate composite demonstrated that in general the input of the a.m. powders in the strength is identical. Coefficients of equation 5 are practically equal: 5.72 and 5.58 as appropriate. It is apparent that mechanical strengthening is basically implemented through ordering of composite structures, i.e. by generation of clusters around active centers.

**Table 2.** Plan of two-factor three-level experiment with obtained values of target functions

| Line No. | $X_1$ | $X_2$ | $R_{compr.}$, MPa | LAC, cm$^{-1}$ | $\eta^*$ (Pa·s) at temperature: |
|----------|-------|-------|-------------------|----------------|-------------------------------|
|          |       |       |                   |                | $20^\circ C$ | $30^\circ C$ |
| 1        | +/3   | -/1   | 47.2/47.61        | 0.665/0.651    | 141/140         | 70/72 |
| 2        | +/3   | +/3   | 58.5/58.77        | 0.890/0.921    | 177/171         | 78/77 |
| 3        | -/1   | +/3   | 47.5/47.33        | 0.335/0.393    | 88/92           | 55/58 |
| 4        | 0/2   | +/3   | 53.6/53.05        | 0.689/0.657    | 131/128         | 64/68 |
| 5        | 0/2   | -/1   | 41.3/41.89        | 0.369/0.387    | 97/98           | 55/59 |
| 6        | +/3   | 0/2   | 53.4/53.19        | 0.775/0.786    | 135/133         | 74/73 |
| 7        | -/1   | 0/2   | 42.5/41.75        | 0.265/0.258    | 70/68           | 51/57 |
| 8        | 0/2   | 0/2   | 46.8/47.47        | 0.538/0.522    | 110/108         | 60/66 |

* above the line – experimental data, behind the line – regressions obtained by equations

In general, we observe the trend of strength enhancement by increasing the filling degree. Concurrently with the strength enhancement, LAC value also increases, i.e. the “range law” is implemented. Theoretically, we may come to the filling degree up to 90% by volume; however, to introduce such amount of filler, we need to increase the binder temperature to the values at which consolidation rate will increase by hundred times, that would make the composite viability impossible.

As the process of mixing the ground filler and polymeric base is carried out at the temperature up to 30°C, the amount of introduced filler is considerably less than maximum possible. However, as mentioned earlier, increase of temperature of reaction mixture will inevitably result in acceleration of consolidation. In this connection, we carried out investigations of temperature effect of viability of mixture. This parameter was evaluated by the change of mixture viscosity in time at fixed temperature.

Thus, at temperature 50°C consolidation reaction commenced in 17 minutes following the termination of mixing, and at temperature 40°C consolidation started at the 34th minute. As a result of investigations, we established the rational range of the mixture temperature – from 30 to 35°C.

With account of specified viscosity, the amount of introduced sodium-boron-silicate composition – 30 mass. %. Based on the test data of three series of nine samples of material composition under conditions of short-term load, the design and normative values of strength characteristics for radiation-
resistant composite were established, as presented in Table 3.

**Table 3.** Normative and design characteristics of radiation-resistant composite

| Characteristic                               | Value, MPa |
|---------------------------------------------|------------|
| Cubic compressive strength with provision 0.95 | 58         |
| Tensile flexural strength with provision 0.95 | 5.7        |
| Normative prism compressive strength        | 46.4       |
| Normative modulus of elasticity             | 18720      |
| Design compression resistance               | 52.7       |
| Design modulus of elasticity                | 15730      |

The mean density of tested samples came to 1280 kg/m³.

For the designed composite we determined the values of basic characteristics under conditions of radiation exposure. In the first run, we determined gamma attenuation coefficient as quality characteristic.

Radiation resistance was determined by holding-up the samples 2.5 cm thick to the specified radiation dose with subsequent control of changes of basic characteristics values: compressive strength \( R_{\text{compr.}} \), modulus of elasticity under compression \( E \), linear attenuation coefficient \( \mu \).

Changes of the a.m. characteristics under radiation exposure conditions expressed by the appropriate coefficients \( K_{\text{rd}} \) and \( K_E \) implicitly testify to attenuation of the bond between the filler and organic binder due to degradation of properties of the latter. Outputs of conducted investigations are given in Table 4.

**Table 4.** Radiation-induced change of \( \mu \), ultimate strength and modulus of elasticity under compression

| Dose of \( \gamma \)-radiation, \( R \) | \( K_{\text{rd}} = \frac{R_{\text{compr.}}}{R_{\text{compr.init.}}} \) | \( K_E = \frac{E}{E_{\text{initial}}} \) | \( \mu \), cm\(^{-1} \) |
|--------------------------------------|-----------------|-----------------|-----------------|
| 10\( \cdot \)10\(^6 \)              | 1.0             | 1.0             | 0.26±0.02       |
| 50\( \cdot \)10\(^6 \)              | 1.0             | 1.0             | 0.14±0.01       |
| 250\( \cdot \)10\(^6 \)             | 0.94            | 1.0             | 0.12±0.01       |
| 500\( \cdot \)10\(^6 \)             | 0.91            | 0.98            | 0.11±0.01       |

7. **Conclusions and prospects of further investigations**

Gamma and neutron radiation in the first place affects the organic part of polymer-concrete, which is confirmed by the bands on IC-spectrum at 1730 cm\(^{-1} \), testifying to the destruction of double bond and oxidation of unsaturated hydrocarbon with formation of \( C=O \) – bond. Hence, we may assume that structural modification of the binder takes place providing for additional linkage of molecular chains and strengthening of the composite in general.

At the same time, material is considered radiation-resistant, given that its indices do not degrade by more than 25% of its initial value. Specified exposure of the samples of nonisocyanate polymer-concrete corresponded approximately to seven-eight years of operation under severe radiation exposure conditions. Considering the fact that the values of strength characteristics over the first two-three years have been improved, we may anticipate reliable biological shield of the personnel against radiation exposure for at least 10…12 years. Our further investigations will be focused on detailed analysis of thermo physical characteristics of the composite to ensure effective design of the civil structures.

**References**

[1] Ma B 1987 *Materials for nuclear power installations* (Moscow: Energoatomizdat) 408 p
[2] 1990 *Radiation protection of nuclear installations* (Moscow: Atomizdat) 352p
[3] Milinchuk V, Klinshpont E and Tupikov V 1994 *Foundations of radiation resistance of organic materials* (Moscow: Energoatomizdat) 256 p

[4] Bhattacharya A 2000 *Progress in Polymer Science* 25(3) p 371

[5] 1992 *Encyclopedia of polymers* Ed. by Kargin V A-K (Moscow, Soviet Encyclopedia) 1224 p.

[6] Brekhovskikh S, Victorova Yu and Grinshtein Yu 1971 *Foundations of radiological material science of glass and ceramics* (Moscow: Stroyizdat) 256 p

[7] Korolyov E, Bazhenov Yu and Alkabasov A 2010 *Radiation-protective and chemically resistant sulphur constructional materials* (Penza-Orenburg: OSU) 364 p

[8] Korolyov E 2005 *MS thesis* (Moscow) 491 p

[9] Perekalsky O 2006 *MS thesis* (Voronezh) 174 p

[10] Khudiakov V 1994 *MS thesis* (Penza) 160 p

[11] Paturoyev V 1987 *Polymer concrete* (Moscow: Stroyizdat) 285 p

[12] Figovsky O and Shapovalov L 2006 *Encyclopedia of surface and colloid science* Ed. by Somasundaran P 3 pp 1633

[13] Shapovalov L, Figovsky O and Kudryvtsev B 2004 *Issues of chemistry and chemical technologies* 1 p 232

[14] Barabahs D, Borisov Yu and Anisimov A 2013 *Constructional materials* 5 p 20

[15] Barabahs D, Borisov Yu, Panfilov D and Anisimov A 2013 *Scientific Israel – Technological Advantages* 15 p 103

[16] Kudryvtsev B, Eselev A, Kulkov A and Gurova N 2003 *RF Patent* 2263126