# MODERN SORPTION MATERIALS FOR CESIUM AND STRONTIUM RADIONUCLIDE EXTRACTION FROM LIQUID RADIOACTIVE WASTE

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*The paper describes the main types of sorption materials used to remove cesium and strontium radionuclides from low-level and intermediate-level liquid radioactive waste (LRW). It mainly focuses on sorbents produced at industrial or pilot scale in Russia. Based on the developed standardized technique, it presents the experimental values for $^{137}$Cs and $^{90}$Sr distribution coefficients ($K_d$) accounting for various types of sorbents. The study demonstrates that based on the developed technique, sorption characteristics of various types of materials can be unbiasedly compared and most effective sorbents can be reasonably selected to treat liquid radioactive waste of various salt and radionuclide composition.*

**Keywords:** *radioactive waste, liquid radioactive waste, treatment, cesium and strontium radionuclides, sorbents, characteristics.*

## Introduction

Nuclear fuel cycle enterprises, as well as the use of radioactive substances in various branches of science and technology generates significant amounts of liquid radioactive waste (LRW) of various chemical and radionuclide composition. Low- and intermediate-level LRW presents great environmental hazard due to its significant volume, high total activity and potential uncontrolled release in emergency situations.

At present time, methods implying the use of sorption materials of various types are widely used to treat low- and intermediate-level LRW. Most often, these methods are used to remove cesium and strontium, which in many cases make a decisive contribution to the total activity of the considered LRW type.

This paper overviews the main types of sorption materials that are most commonly used for low- and intermediate-level LRW treatment purposes nowadays, as well as quantitative sorption characteristics of various types of sorbents as regards cesium and strontium extraction that were identified experimentally in accordance with a developed standardized method. The main focus is placed on sorbents that are produced in Russia at industrial or pilot facilities.

## Main types of sorbents applied to extract cesium and strontium

Organic *ion-exchange resins* and *inorganic sorbents* of various types are used to extract cesium and strontium radionuclides.

Among *organic ion-exchange resins,* strongly acidic *sulfonic cation* exchangers are most commonly

used for LRW treatment purposes given the following selectivity range:

$$H^+ < Na^+ < K^+ < Rb^+ < Cs^+ < Mg^{2+} < Ca^{2+} < Sr^{2+} < Ba^{2+} < Al^{3+} < Fe^{3+} < Th^{4+}.$$
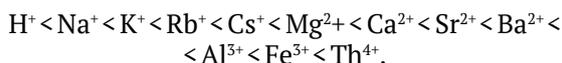
It can be noticed that the affinity of sulfonic cation exchangers increases along with the size and the charge of the absorbed ions. In general, sulfonic cation exchangers are not characterized with any noticeable specificity as it comes to the absorption of cesium and strontium radionuclides in the presence of inactive competing cations of sodium, potassium, calcium, magnesium, etc. After being saturated, organic ion exchange resins are regenerated using inorganic acid or salt solution and are recycled which is due to their limited selectivity and high cost. The operating experience of ion-exchange plants has shown that the use of organic cation-exchange resins appears to be feasible in case of LRW treatment with no more than 1 g/dm$^3$ of dissolved salts. Higher salt concentrations require frequent recycling of ion exchangers significantly increasing the amounts of active regeneration solutions [1—3].

In addition to sulfonic cation exchangers, weak *acid resorcinol-formaldehyde cation exchangers* are used for LRW treatment purposes: these are characterized with high selectivity to heavy alkali metal ions, especially cesium. Sorption on this type of sorbents appears to be most effective in strongly alkaline media (pH > 12). Absorbed metals can be easily desorbed with diluted acid solutions [4].

As compared to organic ion exchangers, *inorganic sorbents* have increased chemical, thermal and radiation resistance, as well as high selectivity to a particular ion or group of ions [1, 5]. The following types of inorganic sorbents are most commonly used to remove cesium and strontium from LRW:
• natural and synthetic aluminosilicates;
• titanium, zirconium, manganese oxyhydrates;
• titanium and zirconium phosphates;
• titanosilicates of alkali metals;
• ferrocyanides of transition metals.

Naturally-occurring and produced *aluminosilicate sorbents* are compounds the general formula of which can be described as follows:

$$Me_{2/n}O \cdot Al_2O_3 \cdot xSiO_2 \cdot yH_2O,$$
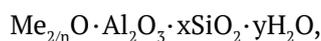
where Me is a cation of an alkali or alkaline earth metal with *n* valence. Sorption takes place by when mobile $Na^+$, $K^+$, $Ca^{2+}$, $Mg^{2+}$ cations present in the sorbent are replaced by cations from the solution.

By structure, aluminosilicates can be divided into layered and reticulated. Among layered aluminosilicate sorbents, bentonite clays are most commonly used for LRW treatment purposes [6—8]. Frame aluminosilicates (zeolites) have a rigid three-dimensional structure with a certain size of entrance pores in the lattice. Among natural zeolites, *clinoptilolite* being a high-silica zeolite $(Na,K)_4CaAl_6Si_{30}O_{12} \cdot 24H_2O$ is most commonly applied in practice [9—11]. Among *synthetic zeolites,* most commonly applied are zeolites of type A and X in the sodium form (NaA and NaX) with effective pore diameters of 0.4 and 0.9 nm, respectively [12, 13].

Synthetic and natural aluminosilicate sorbents are mainly used for LRW treatment from Cs and Sr radionuclides. The highest sorption efficiency is attained in a neutral and slightly alkaline medium with its pH ranging from 6.5 to 8.5. Sorbents of this type are used once and, after radionuclide saturation, are subject to disposal as solid radioactive waste.

Inorganic sorbents based on insoluble *oxyhydrates of multivalent metals* are compounds with the general formula that can be expressed as follows: $MeO_x(OH)_y \cdot zH_2O$, where Me is Fe(III), Cr(III), Mn(III, IV), Sn(IV), Ti(IV), Zr(IV), Sb(V), etc. [1, 5, 14]. Among the sorbents of this type, the most widely used are zirconium, titanium, manganese (III, IV) oxyhydrates. These sorbents are mainly used for strontium extraction purposes.

*Titanium* and *zirconium phosphate-based* sorbents are used to remove cesium, uranium, plutonium, cobalt, manganese and other radionuclides from solutions [5, 15].

*Crystalline* and *semi-crystalline titanosilicates of alkali metals* $(M_2Ti_2O_3SiO_4 \cdot nH_2O$, where M is Na, K, n = 2—6) are used to remove strontium and cesium radionuclides from alkaline solutions. Sodium titanosilicate under the brand name IONSIV IE-911 (UOP, USA) was successfully used to remove cesium and strontium from high-salt alkaline solutions in Hanford and Oak Ridge (USA) [16, 17]. In Russia, titanosilicates of alkali metals are not produced industrially. Small batches of TiSi sorbents of this type are manufactured at the Institute of Chemistry and Technology of Rare Elements and Mineral Raw Materials named after I. V Tananaev of the Kola Scientific Center of the Russian Academy of Sciences (IKhTREMS KSC RAS), Apatity [18].

Inorganic sorbents based on *transition metal ferrocyanides* have the following chemical composition: $M^I_{4-2x}M^{II}_x[Fe(CN)_6]$, where $M^I$ stands for $K^+$; $M^{II}$ stands for $Co^{2+}$, $Ni^{2+}$, $Cu^{2+}$, $Zn^{2+}$, etc. Selectivity range of transition metal ferrocyanides, namely, $Na^+ < K^+ < NH^{4+} << Rb^+ < Cs^+$ indicates their increased selectivity to $Cs^+$ ions [19, 20].

Ferrocyanide sorbents are produced in granular and finely dispersed forms. To produce granular sorbents, ferrocyanides of corresponding transition metals are applied to various carrier compounds

(silica gel, sawdust, carbon fibers) or granulated with various binders. Finely dispersed sorbents are generated by precipitation of transition metal ferrocyanides on the surface of a powdered mineral carrier.

Currently, Russia produces a wide range of sorbents based on transition metal ferrocyanides. Table 1 presents the brands of some industrially produced ferrocyanide sorbents.

*Table 1. Brands of Russian ferrocyanide sorbents (FOC - ferrocyanide)*

| Sorbent brand | Base | Carrier compound: binding substance | Content of the ferrocyanide component, wt. % |
|---|---|---|---|
| Thermoxide-35 | FOC Ni-K | zirconium hydroxide | 30−35 |
| NZhS; Phoenix; Selex CFN; FNS; FSS; SFTS | FOC Ni-K | silica gel | 5−10 |
| FS-1 | FOC Ni-K | silicic acid sol | 40−50 |
| FS-2, FS-10 | FOC Cu-K | silicic acid sol | 40−50 |
| Niket | FOC Ni-K | aluminosilicate | up to 10 |
| Fezhel; Anfezh; Uniket | FOC Fe-K | wood sawdust | up to 10 |
| ZF-N | FOC Ni-K | natural zeolite | 5−10 |
| FN | FOC Ni-K | carbon fiber | 20−30 |
| FND; SFNM | FOC Ni-K | chalk; diatomite | 15−25 |

So-called sorption-reagent materials (SRM) represent a special group of inorganic sorbents since sorption-active phase is formed due to sorbent-solution interaction. Such materials include CPM-Sr sorbent based on barium silicate synthesized at the Institute of Chemistry (Far East Branch, Russian Academy of Sciences, Vladivostok). This sorbent has increased selectivity when it comes to the extraction of radiostrontium from high-salt LRW such as sea water. Sorption of strontium is considered effective if the concentration of sulfate ions in the solution is no less than 1 g/dm³ [21, 22].

### Russian manufacturers of ion exchange resins and inorganic sorbents

*Production Association TOKEM (OOO PA TOKEM),* Kemerovo is the only large-capacity manufacturer of ion-exchange resins in Russia. It produces a wide range of cation and anion exchangers of various types under the Tokem trademark.

*JSC Axion — Rare and Precious Metals (JSC ARDM),* Perm, is involved in pilot-scale production of various ion-exchange resins designed for specific purposes: phosphate, aminocarboxyl, resorcinol-formaldehyde cation exchangers, vinyl pyridine anion exchangers, TVEKS, etc. The products are produced under the Axionit trademark.

*Research and production company Termoksid,* Zarechny, Sverdlovsk region is the largest producer of inorganic sorbents in Russia (Termoksid trademark). Selective inorganic sorbents of the Termoksid brand are produced in the form of spherical mechanically strong granules with high chemical, thermal and radiation resistance. Heat-resistant sorbents retain their physical, chemical and sorption properties upon extended exposure to water under pressure at temperatures of up to 350 °C [23, 24]. The main brands are Termoksid-3A, Termoksid-3K, Termoksid-5, Termoksid-35.

*OOO Research and Production Enterprise Eksorb,* Yekaterinburg produces a number of different ferrocyanide (Niket, Unicet, Anfezh) and oxyhydrate (Ratsir, Modix) sorbents.

*Ishimbay Specialized Chemical Catalyst Plant,* Ishimbay, Bashkiria produces synthetic zeolites of various types, in particular NaA and NaX.

*Institute of Chemistry FEB RAS,* Vladivostok produces ferrocyanide sorbents of the following grades: ZF-N ZF-F, ZF-F, as well as sorption-reagent material CPM-Sr.

*Institute of Chemistry and Technology of Rare Elements and Mineral Raw Materials named after I. V. Tananaev of the Kola Scientific Center of the Russian Academy of Sciences (IKhTREMS KSC RAS),* Apatity, Murmansk region produces sorbents such as TiP (titanium phosphate), TiSi (sodium titanosilicate), etc.

*Institute of Physical Chemistry and Electrochemistry named after A. N. Frumkin of the Russian Academy of Sciences (IPCE RAS),* Moscow produces the following types of inorganic sorbents on a pilot scale: FnS, FSS, SFNS, SFNM, FND, FS-1, FS-2, FS-10, MDM and other.

### Sorption-selective characteristics of various sorbents as regards cesium and strontium extraction

Since low- and intermediate-level LRW contains only trace amounts of cesium and strontium radionuclides, these are sorbed at a constant distribution coefficient value ($K_d$) in the linear section of the isotherm. In the region of micro-concentrations, $K_d$ values do not depend on the initial radionuclide activity in the solution and on the ratio of the sorbent mass and the solution volume. $K_d$ depends exclusively on the sorption capacity of the sorbent and the solution composition. Thus, distribution coefficient of the corresponding radionuclide is viewed as a most important sorption characteristic of the sorbent.

Scientific literature sources contain a large number of papers devoted to the identification of sorption characteristics for various sorbent types allowing the extraction of cesium and strontium. However, the characteristics of sorbents given in the literature were derived under different experimental conditions, providing no opportunities for an objective comparison of their sorption properties. Therefore, a standardized method was developed to identify $K_d$ values for various sorption materials as regards cesium and strontium extraction under static conditions. The method is based on over 35 years of research at the radioactive chromatography laboratory run by the Institute of Physical Chemistry and Electrochemistry of the Russian Academy of Sciences [25—32]. Table 2 presents standard conditions allowing to specify the $K_d$ values for $^{137}$Cs and $^{90}$Sr.

*Table 2. Standard conditions allowing to identify the $K_d$ values for $^{137}$Cs and $^{90}$Sr under static conditions*

| Parameter | Value |
|---|---|
| Particle size:<br>• for granular sorbents;<br>• for finely dispersed sorbents | 0.25−0.50<br>less than 0.25 |
| Sorbent weight, g | 0.05−0.20* |
| Solution volume, cm³ | 20.0 |
| Ratio between the sorbent mass and the solution volume (S:L), g/cm³ | 1:(100−400)* |
| Exposure time, h | 48 |
| Solution temperature, °C | 20−25 |
| Composition of model solutions during $^{137}$Cs sorption, mol/dm³, units pH | $NaNO_3$ − 0.1, pH=5−6;<br>$NaNO_3$ − 1.0, pH=5−6 |
| Composition of model solutions during $^{90}$Sr sorption, mol/dm³, units pH | $NaNO_3$ − 0.1, pH=5−6;<br>$Ca(NO_3)_2$ −0.01, pH=5−6 |
| Specific activity of $^{137}$Cs and $^{90}$Sr in the initial solution, Bq/dm³ | $10^5−10^6$ |

\* Depending on the sorption characteristics of the sorbent

Sorption material has to be pre-treated before its testing starts, which includes sample averaging, its drying followed by the fabrication of sorbent granules of a particular size. Wet, hygroscopic thermally stable sorbents are subject to air-drying to a constant weight at a temperature of 105 °C. Samples of organic ion-exchange resins are dried at a temperature of less than 60 °C. Thermally unstable sorbents are kept at a room temperature (20—25 °C) until constant weight is attained. After drying, the sorbents are subjected to sieving on standard sieves to obtain a fraction with a particle size of 0.25—0.50 mm for granular sorbents and less than 0.25 mm for fine sorbents.

$K_d$ is calculated under static conditions by mixing the sorbent sample with a solution aliquot of a known composition until sorption equilibrium is attained. Thereafter, solid and liquid phases are separated and the specific activity of the sorbed radionuclide in the initial and equilibrium solution is identified. $K_d$ is calculated using the following formula:

$$K_d = V_p \cdot (A_0 - A_p)/(A_p \cdot m_c),$$

where $A_0$, $A_p$ stand for the initial and equilibrium specific activity of the sorbed radionuclide respectively, Bq/dm³;
$V_p$ is the volume of the liquid phase, cm³;
$m_c$ is the sorbent mass, g.

Depending on sorption characteristics of the sorbent, the ratio between the sorbent mass and solution volume (S:L) amounts to 1:(100—400) g/cm³. For testing purposes, the use of 20 cm³ standard plastic containers (vials) with sealed screw caps is considered quite feasible. For sorbents with low sorption activity, it is recommended to use weighed amounts of 0.1—0.2 g, S:L=1:(200—100) g/cm³, whereas for sorbents with high sorption capacity, the weighed amount of sorbent should not exceed 0.05 g per 20 cm³ of solution (S:L=1:400 g/cm³). Sorbent samples are weighed on an analytical balance with a weighing accuracy of 0.0001 g.

To calculate the time needed to attain sorption equilibrium, preliminary kinetic experiments have been implemented. According to our experience, in most cases, 48 hours of continuous stirring is sufficient to complete the sorption process. To ensure constant contact of the phases, the use of shakers fitted with a horizontal platform has proved to be most effective.

After the mixing is completed, the sorbent particles are separated from the solution by filtration through a fine-pored "blue ribbon" paper filter. If it is impossible to separate the sorbent particles on a paper filter, centrifugation or filtration through a membrane filter with a rating of 0.45 or 0.2 microns is used.

During $^{137}$Cs sorbtion, model solutions with $NaNO_3$ concentration of 0.1 and 1.0 mol/dm³, pH=5—6 are used as liquid phase. Specific choice of solution composition is due to the fact that sodium salts account for the main salt component for most types of low- and intermediate-level LRW. Comparison of $K_d$ obtained for $^{137}$Cs in 0.1 and 1.0 mol/dm³ $NaNO_3$ solutions clearly demonstrates the selectivity of studied sorbents with respect to cesium in low- and high-salt LRW.

During $^{90}$Sr sorption, model solutions containing 0.1 mol/dm³ $NaNO_3$ having a pH of 5—6, and 0.01 mol/dm³ $Ca(NO_3)_2$ and a pH level of 5—6 are used as a liquid phase. Specific choice of solution

composition is due to the fact that in most cases cationic composition of low- and intermediate-level LRW depends on sodium and calcium compounds. Due to the similarity of chemical properties and sizes of $Ca^{2+}$ ions, these can most negatively affect the strontium sorption process. Comparison of $K_d$ values for $^{90}Sr$ in model solutions of a given composition allows to identify the selectivity of the studied sorbents with respect to strontium against the background of prevailing amounts of competing sodium and calcium ions.

$^{137}Cs$ and $^{90}Sr$ specific activity in the initial model solutions accounts for $\sim 10^5 - 10^6$ Bq/dm³, which corresponds to low- (intermediate-) level LRW and provides the accuracy considered sufficient to measure the activity of solutions after sorption.

$^{137}Cs$ specific activity in solutions is measured based on direct gamma-spectrometric method using an energy peak of 661 keV. The specific activity of $^{90}Sr$ in solutions is identified based on the total beta activity using beta or liquid scintillation spectrometers. Sample activity is measured according to relevant measurement procedures specified for particular analytical equipment.

Based on $K_d$ value, calculated is the purification factor ($K_{pur}$) of the solution at a given sorbent dosage ($D$) being viewed as an important parameter given its further practical application. It also allows to solve an inverse problem: to calculate the sorbent dosage ($D$) required to achieve the desired $K_{pur}$:

$$K_{pur} = 1 + K_d \cdot D/1000,$$

$$D = 1000 \cdot (K_{pur} - 1)/K_d,$$

where $K_d$ is the distribution coefficient, cm³/g; $D$ is the sorbent dosage, g/dm³.

As mentioned above, the developed unified method can be used to identify sorption-selective characteristics with respect to $^{137}Cs$ and $^{90}Sr$. During testing, these radionuclides are available in the only possible ionic state, which allows to reproduce these experiments in various laboratories. Radionuclides of other chemical elements (cobalt, manganese, iron, antimony, europium, uranium, americium, plutonium, etc.), that can be also found in neutral aqueous LRW solutions, may be available in different phase-dispersed states (ionic, colloidal, pseudo-colloidal). In this regard, sorption behavior of these radionuclides seems to be uncertain and poorly reproducible.

Tables 3 and 4 present the distribution coefficients of trace $^{137}Cs$ and $^{90}Sr$ amounts on various types of sorption materials that were identified based on the developed standardized method. The tables show the average of two parallel experiments. The relative error for the calculated $K_d$ values does not exceed 30 %.

*Table 3. $^{137}Cs$ distribution coefficients ($K_d$) for various sorbents*

| Sorbent type (brand) | Distribution coefficients ($K_d$) for $^{137}Cs$ in a solution, cm³/g | |
|---|---|---|
| | 0.1 mol/dm³ NaNO$_3$ | 1.0 mol/dm³ NaNO$_3$ |
| *Organic ion exchange resins* | | |
| Sulfonic cation resin KU-2-8 | 390 | 10 |
| Resorcinol formaldehyde cation exchanger Axionit RCs | 1,100 (pH=6) 8700 (pH=12) | 1,800 (pH=6) 1.1·10⁴ (pH=12) |
| *Natural and synthetic aluminosilicates and zeolites* | | |
| Bentonite clay[1] | 1.9·10⁴ | 2,400 |
| Bentonite clay[2] | 7,700 | 590 |
| Glauconite[3] | 1.6·10⁴ | 3,400 |
| Diatomite[4] | 2,700 | 880 |
| Tripoli[5] | 3,000 | 580 |
| Clinoptilolite[6] | 1,800 | 64 |
| Clinoptilolite[7] | 1,600 | 80 |
| Synthetic zeolite NaA[8] | 8,900 | 720 |
| Synthetic zeolite NaX[9] | 1,800 | 190 |
| *Oxyhydrates, phosphates, titanosilicates* | | |
| Silica gel ASKG | 305 | 20 |
| MDM[10] | 290 | 5 |
| Termoksid-3K[11] | 150 | 10 |
| Thermal oxide-5[12] | 44 | <1 |
| Termoksid-3A[13] | 1,800 | 150 |
| PTi[14] | 7,300 | 820 |
| TiSi (sodium titanosilicate)[15] | 1.9·10⁵ | 1.2·10⁵ |
| *Ferrocyanide sorbents* | | |
| Termoksid-35[16] | 1.2·10⁵ | 8.1·10⁴ |
| FNS; SFNS[17] | 8.4·10⁴ | 7.3·10⁴ |
| FND; SFNM[18] | 8.1·10⁴ | 7.9·10⁴ |
| Anfezh[19] | 2.0·10⁴ | 4.1·10³ |
| Niket[20] | 1.3·10⁴ | 5.5·10⁴ |
| FN[21] | 3.0·10⁶ | 1.5·10⁶ |
| *Carbon sorbents* | | |
| Activated carbon bicyclic | 43 | <2 |
| Natural schungite[22] | 910 | 135 |

1 — Nelidovsk field (Belgorod region); 2 — 10th Khutor deposit (Republic of Khakassia); 3 — Karinsk field (Chelyabinsk region); 4 — Inzensk field (Ulyanovsk region); 5 — Zikeevsk field (Kaluga region); 6 — Kholinsk deposit (Chita region); 7 — Shivyrtuiskoe deposit (Chita region); 8, 9 — synthetic zeolites without a binder (Ishimbay Specialized Chemical Catalyst Plant, Bashkiria); 10 — manganese (III, IV) oxides (IPCE RAS); 11 — hydrated zirconium oxide (Research and Production Company Termoksid); 12 — hydrated titanium oxide (Research and Production Company Termoksid); 13 — zirconium phosphate (Research and Production Company Termoksid); 14 — titanium phosphate (Tananaev Institute of Chemistry — Subdivision of the Federal Research Centre Kola Science Centre of the Russian Academy of Sciences, Science Centre of Russian Academy of Sciences, ICT KSC RAS); 15 — sodium titanosilicate, prototype (ICT KSC RAS); 16 — sorbent based on ferrocyanide (FOC) of nickel and zirconium hydroxide (Research and Production Company Termoksid); 17 — sorbent based on FOC of nickel and silica gel (IPCE RAS); 18 — finely dispersed sorbents based on FOC of nickel and diatomite (IPCE RAS); 19 — composite sorbent based on FOC of iron and cellulose (Research and Production Company Eksorb); 20 — composite sorbent based on FOC of nickel and natural aluminosilicate (Research and Production Company Eksorb); 21 — fibrous composite sorbent based on FOC of nickel and carbon fiber (Chemistry Institute of FEB RAS); 22 — Zazhoginsk deposit, Karelia.

**Table 4.** $^{90}$Sr distribution coefficients ($K_d$) for various sorbents

| Sorbent type (brand) | Distribution coefficients ($K_d$) for $^{90}$Sr in the solution, cm$^3$/g | |
|---|---|---|
| | 0.1 mol/dm$^3$ NaNO$_3$ | 1.0 mol/dm$^3$ Ca(NO$_3$)$_2$ |
| Sulfonic cation resin KU-2-88 | 2,000 | 310 |
| Bentonite clay[1] | 110 | 40 |
| Clinoptilolite[2] | 310 | 70 |
| Synthetic zeolite NaA[3] | 8.5·10$^4$ | 4,400 |
| Synthetic zeolite NaX[4] | 7,900 | 1,680 |
| MDM[5] | 4.0·10$^4$ | 8,600 |
| Termoksid-3K[6] | 3.5·10$^4$ | 217 |
| Termoksid-3A[7] | 326 | 440 |
| PTi[8] | 5.1·10$^4$ | 3.5·10$^4$ |
| TiSi[9] | 3.0·10$^4$ | 2.5·10$^4$ |
| Activated carbon bicyclic | 190 | < 2 |

1 — Nelidovsk field (Belgorod region); 2 — Shivyrtuisk deposit (Chita region); 3, 4 — synthetic zeolites without a binder (Ishimbay specialized chemical plant of catalysts, Bashkiria); 5 — manganese oxides (IPCE RAS); 6 — hydrated zirconium oxide (Research and Production Company Termoksid); 7 — zirconium phosphate (Research and Production Company Termoksid); 8 — titanium phosphate (ICT KSC RAS); 9 — sodium titanosilicate, prototype (ICT KSC RAS)

Presented results show that bentonite clays, natural and synthetic zeolites, titanium and zirconium phosphates, titanosilicates and ferrocyanide sorbents exhibit high selectivity to $^{137}$Cs ($K_d$ $^{137}$Cs > 10$^3$ cm$^3$/g) in low-salt solutions (0.1 mol/dm$^3$ NaNO$_3$). In high-salt solutions (1.0 mol/dm$^3$ NaNO$_3$), high selectivity to $^{137}$Cs is found only in case of titanosilicates and ferrocyanide sorbents.

According to the data from Table 4, during $^{90}$Sr sorption, synthetic zeolites, manganese oxide based (III, IV) sorbents — MDM, titanium phosphate, and sodium titanosilicate exhibit increased selectivity to strontium in the presence of sodium ions. In the presence of calcium ions, strontium sorption capacity decreases dramatically for most types of the studied sorbents. Maximum strontium sorption capacity in the presence of calcium ions is observed in case of MDM sorbent, titanium phosphate, and sodium titanosilicate.

Thus, the standardized method developed to identify sorption-selective characteristics for various types of sorption materials with respect to $^{137}$Cs and $^{90}$Sr radionuclides may provide opportunities for an objective comparison of their sorption properties and a targeted selection of most effective sorbents allowing to treat LRW with complex salt and radionuclide composition.

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