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RARE EARTH METALS — THE OIL OF THE 21ST CENTURY

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EMPRESS CATHERINE II
ST. PETERSBURG MINING UNIVERSITY

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Abstract

The digest "Rare Earth Metals – the Oil of the 21st Century" brings together research published in the in Journal of Mining Institute between 1935 and 2026 on the topic of rare earth metals (REM). With the development of technology and industry, the problem of their extraction is becoming increasingly acute, as confirmed by the growing number of studies in this field. The collected works describe the mineralogy and geology of rare metals; the raw materials that can be used to obtain REM; and the methods of raw material processing that allow REM to be extracted.

Rare earth metals are a group consisting of 15 lanthanides, scandium, and yttrium. According to Order of the Government of the Russian Federation No. 2473-r dated 30.08.2022, REM are included in the list of strategic types of mineral raw materials. By Order of the Government of the Russian Federation No. 939-r dated 16.04.2024, they were included in the list of deficient types of solid mineral resources [State Report on the State and Use of Mineral and Raw Material Resources of the Russian Federation in 2023].

The main sphere of REM consumption in the world, according to the Argus agency, is the production of permanent magnets, widely used in electronics, electric vehicles, and wind power installations (26% of the global figure; Nd, Tb, Dy, Gd, Pr, Sm are used); polishing powders and glasses (25% – Ce, La); catalysts for the oil refining, chemical, and automotive industries (17% – Ce, La, Pr, Nd); nickel-metal hydride batteries (11% – La, Ce, Nd, Pr, Sm); mischmetals and special alloys (6% – Ce, La, Nd, Pr, Y); ceramics (6% – La, Ce, Nd, Y). REM are also involved in: the production of phosphors (Y, Yt, Tb, Gd, Eu, Ce, La, Ho), the nuclear industry (Gd, La), and others (9%). The consumption structure of individual countries depends on the technological mode of their economies. The share of magnets in the REM consumption structure is expected to grow to 42% by 2033 [State Report on the State and Use of Mineral and Raw Material Resources of the Russian Federation in 2023].

Libman E.P. On the issue of studying diperse rare elements // Journal of Mining Institute. 1935. Vol. 9. Part 2. P. 47-55. https://pmi.spmi.ru/pmi/article/view/15337

Abstract. In the numerous ore and mineral formations of the deposits of our country, even such rare elements dispersed in the earth's crust, such as thallium, germanium, cesium, cerium, indium, gallium, cadmium, hafnium, rhenium, etc., are undoubtedly concentrated. The listed elements usually do not form independent deposits, and their extraction is based on the fact that they are included in small quantities in the composition of some ores of ferrous and non-ferrous metals and other types of mineral raw materials. In creating a mobile raw material base for the elements under consideration, the primary task is a specific quantitative assessment of the values of certain contents in ores and large dumps of practically valuable components dispersed in all industrially interesting deposits, and primarily in deposits that will be put into operation in the coming years.

Monazite (Ce). From the collection of the Mining Museum

Panov E.N., Khokhlov V.V., Latikainen V.I. Mobility of element-impurities when mica is exposed to organic acid solution // Journal of Mining Institute. 1987. Vol. 111. P. 34-41. https://pmi.spmi.ru/pmi/article/view/10450

Abstract. The study of the degree of mobility of rare and disseminated elements, which are part of such rock-forming minerals-concentrators as biotite and muscovite, is of great importance in the knowledge of endo- and exogenous ore-forming processes.

Chirkst D.E., Litvinova T.E., Cheremisina O.V. Extraction of rare metals and radionuclides from lean raw materials and soils // Journal of Mining Institute. 2001. Vol. 147. P. 186-193. https://pmi.spmi.ru/pmi/article/view/9779

Abstract. The content of rare-earth metals (REM) in Kola apatite is about 1%. In the production of concentrates over 8 million tons per year, more than 80 thousand tons of REM are dumped into waste dumps annually, polluting the environment. The main

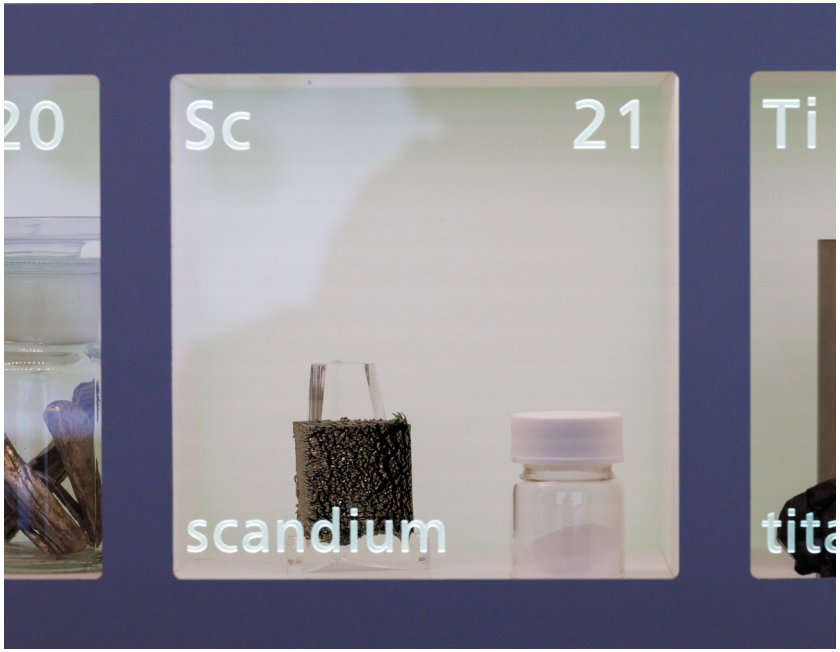
Apatite. From the collection of the Mining Museum

Rhabdophane. From the collection of the Mining Museum

bulk of apatite is processed according to the sulfuric acid scheme to produce extractive phosphoric acids. To extract rare-earth metals from phosphoric acid streams with a capacity of 45 t/h, it is necessary to develop a process lasting several minutes, which does not affect the basic technology and does not require expensive costs of reagents. Crystallization of lanthanide combinations on inoculum directly from production solutions of extractive phosphoric acids meets the requirements. Another pressing problem is the purification of soils contaminated with heavy metals and radionuclides. In laboratory and natural conditions, the purification of soils from ^{90}Sr contamination of the 5th quarter of Vasilievsky Island and Novozybkovsky district of the Bryansk region from ^{137}Cs contamination has been studied. Among different methods of soil decontamination, the most cost-effective and suitable for large soil masses and large territories is soil washing with diluted solutions of mixtures of ammonium and iron (3+) salts. This method can also be used to clean soils from heavy metal contamination in mining regions.

Kutsenko D.V. Disposal of intermediate products of scandium and its ligatures // Journal of Mining Institute. 2003. Vol. 155. Part 1. P. 189-192. https://pmi.spmi.ru/pmi/article/view/9104

Abstract. Metallic scandium and its ligatures are widely used in various products of science-intensive technologies. Scandium is one of the rare and expensive metals, which necessitates the complex use of its intermediate products. The main types of wastes produced during the metallothermal production of crystalline scandium and its ligatures are considered. The regularities of scandium transition into solid and liquid phases of intermediate products during recycling are determined. Based on the obtained scandium-containing materials, Al-Mg-Sc ligatures have been synthesized, which allows to carry out the technological process in a closed cycle with minimal losses of valuable components.



Scandium. Fragment of the display case "Periodic Table of Elements by D.I. Mendeleev". 2019

Chirkst D.E., Litvinova T.E., Cheremisina O.V., Ivanov M.V. Physico-chemical bases of deep processing of poor rare-earth raw materials // Journal of Mining Institute. 2004. Vol. 158. P. 36-38. https://pmi.spmi.ru/pmi/article/view/8778

Abstract. Extraction of cerium (3+) with tributyl phosphate was studied. The extraction constants were calculated from the dependences of the distribution coefficient on the concentration of salvent and extractant. According to their values, cerium salts are arranged in the series chloride < sulfate < nitrate corresponding to the Pearson reduction of the "hardness" of anions.

Roshchin G.S. Thermodynamic study of extraction of cerium nitrate by oleic acid // Journal of Mining Institute. 2006. Vol. 167. Part 1. P. 214-216. https://pmi.spmi.ru/pmi/article/view/8112

Abstract. The extraction of cerium nitrate from aqueous solutions by a solution of oleic acid in *o*-xylene was studied. The dependence of the distribution coefficient of cerium nitrate on the water-hydrogen index and on the volume of the organic phase was revealed, while the ratio between the concentrations of oleic acid and cerium remained constant. The solvation number at ex-traction of cerium nitrate by oleic acid was determined. The mechanism of the reaction was established. The equilibrium constant and Gibbs energy of extraction were calculated.

Chirkst D.E., Litvinova T.E., Starshinova V.S., Roshchin G.S., Lutskii D.S. Extraction of cerium(III) and yttrium(III) by carboxylic acids from nitrate media // Journal of Mining Institute. 2006. Vol. 169. P. 196-203. https://pmi.spmi.ru/pmi/article/view/7886

Abstract. Experimental data on the solvate extraction of cerium(III) and yttrium(III) by solutions of oleic and naphthenic acids in o-dimethylbenzene were obtained. After mathematical analysis of the dependences of the distribution coefficient on pH and the composition of the organic and aqueous phases, the structure and composition of the solvate complexes were determined, as well as the values of Gibbs free energies and equilibrium constants of the reaction.

Chirkst D.E., Litvinova T.E., Starshinova V.S., Lutskii D.S. Extraction of cerium(III) and yttrium(III) by naphthenic acid from chloride media // Journal of Mining Institute. 2006. Vol. 169. P. 204-208. https://pmi.spmi.ru/pmi/article/view/7887

Abstract. Data on the extraction of cerium(III) and yttrium(III) by naphthenic acid solution in *o*-xylene from chloride media were obtained. The experiment showed W-shaped dependence of the distribution coefficient of cerium(III) and yttrium(III) on the Cl content in the equilibrium aqueous phase. The minima of the dependence are explained by the formation of non-extractable complexes $MeCl^{2+}$ and $MeOH^{2+}$, the maxima – by the increase in the degree of dissociation of naphthenic acid and the increase in the ionic strength of the solution.

Chirkst D.E., Cheremisina O.V. Thermodynamic calculation of solubility of rare earth metal phosphates at different temperatures and concentrations of ortho-phosphoric acid // Journal of Mining Institute. 2006. Vol. 169. P. 219-226. https://pmi.spmi.ru/pmi/article/view/7890

Abstract. The thermodynamic calculation of oxygen solubility and ionic standing in solutions of cerium(III) phosphate acids allowed us to estimate the ionic composition of solutions and describe the course of crystallization and dilution processes of $CePO_4 \cdot 0.5H_2O$, as well as to determine the dependence of oxygen solubility on temperature and concentration of solutions.

Eudialyte in rock (fragment). From the collection of the Mining Museum

Chirkst D.E., Cheremisina O.V. Solubility of cerium(III) phosphate at different temperatures and concentrations of ortho-phosphoric acid // Journal of Mining Institute. 2006. Vol. 169. P. 227-230. https://pmi.spmi.ru/pmi/article/view/7891

Abstract. The thermodynamic calculation of solubility and ionic equilibria in phosphoric acid solutions of cerium(III) allowed us to estimate the ionic composition of solutions, describe the mechanism of crystallization and dissolution processes $CePO_4 \cdot 0.5H_2O$, determine the dependence of solubility on temperature and concentration of solutions.

Strashinova V.S. Thermodynamic description of extraction of rare earth metals by carboxylic acids from nitrate media // Journal of Mining Institute. 2007. Vol. 170. Part 1. P. 172-175. https://pmi.spmi.ru/pmi/article/view/7810

Abstract. Experimental data on the solvate extraction of cerium (III) and yttrium (III) by solutions of oleic and naphthenic acids in *o*-dimethylbenzene have been obtained. After mathematical analysis of the dependences of the distribution coefficient on pH and the composition of the organic and aqueous phases, the structure and composition of the solvate complexes, as well as the values of Gibbs free energies and equilibrium constants of the reaction were determined.

Луцкий Д.С. Влияние аниона на процесс жидкостной экстракции церия (III) олеиновой кислотой // Записки Горного института. 2009. Т. 182. С. 155-158. https://pmi.spmi.ru/pmi/article/view/6979

Abstract. Experimental data on solvent extraction of cerium (III) by solutions of oleinic acids in odimethylbenzene was obtained. After mathematical analysis of the dependences of the distribution coefficient from pH and composition of organic and aqueous phases was determined the structure and composition of solvate complexes and value of the Gibbs free energies and reaction equilibrium constant.

Lutskii D.S., Litvinova T.E., Chirkst D.E. Separation of cerium lanthanides by using oleic acid // Journal of Mining Institute. 2011. Vol. 189. P. 303-306. https://pmi.spmi.ru/pmi/article/view/6548

Abstract. Experimental data on solvent extraction of cerium (III), yttrium (III), lanthanum (III) by solutions of oleinic acid in o-dimethylbenzene was obtained. The possibility of extraction separation of cerium (III), yttrium (III), lanthanum (III) from nitrate media was shown.

Dzhevaga N.V., Chirkst D.E., Lobacheva O.L., Grigoreva L.V. Removal of samarium (3+) and cerium (3+) from nitrate and chloride solutions by ion flotation // Journal of Mining Institute. 2012. Vol. 196. P. 121-124. https://pmi.spmi.ru/pmi/article/view/6032

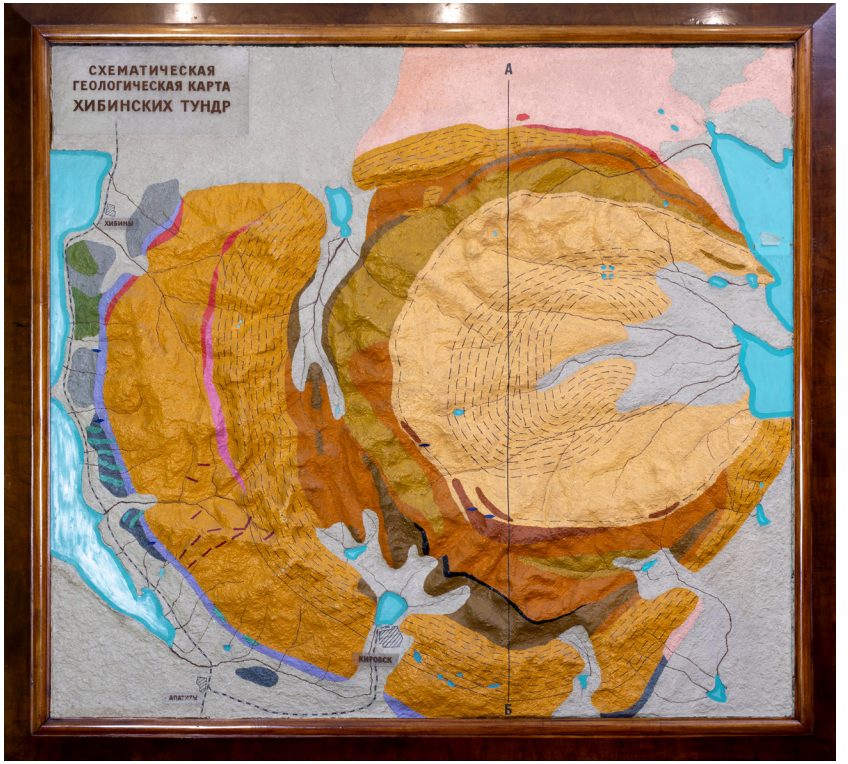
Abstract. The ion flotation of cerium (3+) and samarium (3+) from nitrate solutions by use of sodium dodecyl sulphate as a collector with addition of sodium chloride has been stated. The ratio of distribution coefficients and separation coefficient as function of the pH-aqueous phase with different concentration of chloride-ions has been analyzed. The separation coefficient has rise from 1,3 till 4,75 when chloride has been added.

Zhukov S.V., Litvinova T.E., Chirkst D.E. Extraction separation of aluminum, manganese and cerium group lanthanides by using oleic acid // Journal of Mining Institute. 2012. Vol. 197. p. 226-229. https://pmi.spmi.ru/pmi/article/view/5996

Abstract. The data on the extraction of aluminum and manganese by solution of oleic acid in o-xylene. The possibility of extraction separation of aluminum, manganese and cerium group lanthanides by solvent extraction from nitrate media.

Lutskii D.S., Litvinova T.E., Chirkst D.E., Lutskaya V.A., Zhukov S.V. Thermodynamic of cerium (III) and europium (III) extraction by using stoichiometric concentration solutions of naphtenic acid // Journal of Mining Institute. 2013. Vol. 202. P. 97-101. https://pmi.spmi.ru/pmi/article/view/5664

Abstract. Experimental data on solvent extraction of lanthanum (III) and samarium (III) by solutions of naphthenic acid from nitrate medium was obtained. Dependences of distribution coefficient of pH, concentration of organic and aqueous phase was obtained. thermodynamic characteristics of extraction equilibrium was calculated.



Schematic geological map of the Khibiny Tundras. Hall 17 of the Mining Museum

Lutskii D.S., Litvinova T.E., Chirkst D.E., Lutskaya V.A., Khruskin S.V. Extraction of cerium lanthanides by using stoichiometric concentration solution of naphtenic acid // Journal of Mining Institute. 2013. Vol. 202. P. 102-106. https://pmi.spmi.ru/pmi/article/view/5665

Abstract. Technology of solvent extraction and separation of cerium lanthanides by solutions of naphthenic acid in o-dimethylbenzene was obtained. The sequence of extraction Eu > Sm > Ce > La from nitrate media was calculated.

Eudialyte. From the collection of the Mining Museum

Danilov A.S., Dzhevaga N.V., Grigorjeva L.V., Lobacheva O.L. SM (III) extraction from aqueous solutions by sodium dodecylsulfate // Journal of Mining Institute. 2013. Vol. 206. P. 129-134. https://pmi.spmi.ru/pmi/article/view/5453

Abstract. Extraction process in Sm^{3+} aqueous solutions from nitrate media by sodium dodecylsulfate as collector is investigated. Distribution coefficients on depending of the pH aqueous phase in different concentration of Sm^{3+} is obtained.

Apatite-nepheline ore. From the collection of the Mining Museum

Cheremisina O.V., Schenk J., Cheremisina E.A., Ponomareva M.A. Thermodynamic model of ion-exchange process as exemplified by cerium sorption from multisalt solutions // Journal of Mining Institute. 2019. Vol. 237. P. 307-316. DOI: 10.31897/PMI.2019.3.307. https://pmi.spmi.ru/pmi/article/view/13199

Abstract. A complex heterogeneous process of ion exchange can be defined with an isotherm-isobar equation of the chemical reaction, which describes differential affinity between the process and its effect – the law of mass action. Ion exchange includes processes accompanied by changes in the charge of ions and functional groups caused by the passing of ionic bond into covalent one. Hence isotherm equations of ion exchange for such processes must differ from conventional stoichiometric equations, but they can be obtained by classical study approaches to ion exchange equilibrium. The paper describes a new thermodynamic model, based on linearization of mass action law, modified for the ion exchange equation. The application of this model allows to define stoichiometry of ion exchange and the shape of ions adsorbed by the solid phase of ion-exchange resins, as well as to estimate equilibrium constant and Gibbs free energy of the process. Comparative analysis has been carried out for the thermodynamic model of cerium sorption in the form of anionic complex with Trilon B from a multisalt solution with ionic strength of 1 mol/kg ($NaNO_3$) under pH = 3 and temperature 298 K on a test sample of weak-base anion-exchange resin Cybber EV009. Experimental isotherm of the sorption has been obtained. Calculations of thermodynamic parameters have been performed using Langmuir, Freundlich, Dubinin – Radushkevich, Temkin and Flory – Huggins models, as well as thermodynamic model of linearized mass action law, proposed by the authors. Calculated values of the equilibrium constant and Gibbs energy – K = 9.0±0.5 and ΔrG^0_{298} = –5.54±0.27 kJ/mol – characterize the sorption of EDTA cerate ions by ion-exchange resin. The shape of adsorbed ions has been defined in Stern-Helmholtz layer of CeTr, and total capacity of anion resin EV009 for EDTA cerate ions has been estimated as q_∞ = 2.0±0.1 mol/kg.

Alekseev V.I., Marin Y.B., Baksheev I.A. Association of greisens (zwitters) and tourmalinites in the granites of the Severny pluton (Chukotka, Russia) // Journal of Mining Institute. 2025. Vol. 276. Part 2. P. 170-183. https://pmi.spmi.ru/pmi/article/view/16496

Abstract. In the Severny pluton in Chukotka, an association of rare-metal, tin-bearing topaz-zinnwaldite greisens (zwitters) and tourmaline metasomatites has been identified through geological mapping and mineralogical-petrographic studies. These formations are genetically linked to magmatism producing Li-F granite intrusions. The distribution and composition of zwitters and muscovite-quartz-tourmaline metasomatites forming halos around quartz-tourmaline veins were investigated. A wide spectrum of tourmaline mineral species was established, occurring in pegmatoid pockets of leucogranites (tourmaline I), pre-ore quartz-tourmaline metasomatite veins with fluorite (tourmaline II), early ore quartz-tourmaline metasomatite veins (tourmaline III), and ore tourmaline and quartz veins (tourmaline IV). An evolution of tourmaline from Sc-bearing fluor-schorl in pre-ore metasomatites to oxy-schorl and tin-bearing ferro-bosiite in tin-ore metasomatites was revealed, with a gradual increase in lithium content and variable iron oxidation state. In zwitters, muscovite-quartz-tourmaline metasomatites, and tourmalinite veins, a combination of tin and rare-metal mineralization is noted. The research results can be used to assess the metallogenic potential and develop criteria for forecasting rare-metal (Nb, Ce, Y, W, Bi) mineralization in the Severny pluton.

Ayupova N.R., Maslennikov V.V., Tseluyko A.S., Yatimov U.A., Lebedeva S.M. Minerals of the crichtonite group in ooids of mineralized volcaniclastic rocks from the Rudnogorskoe iron deposit (Eastern Siberia) // Journal of Mining Institute. 2025. Vol. 276. Part 1. P. 157-171. https://pmi.spmi.ru/pmi/article/view/16525

Abstract. The article reports on the presence of minerals of the crichtonite group (MCG) in ooids of mineralized volcaniclastic rocks of the Rudnogorskoe iron deposit (Eastern Siberia). The ooids are characterized by a concentric-zoned structure of detrital component, expressed in a sequential change of hematite-smectite core → smectite-chlorite → chlorite-garnet → apatite-chlorite zones, which are rimmed by thin-layered magnetite. Rare crystalline MCG aggregates in ooids are found in the peripheral apatite-chlorite zone. Based on the chemical composition and Raman spectra, the MCG are identified as crichtonite and davidite-Ce. The following components are determined in the composition of crichtonite, wt.%: TiO_2 63.73-70.69, FeO 18.03-23.58, SrO 2.24-4.03, CaO 2.22-4.10, MgO 0.33-1.02, Al_2O_3 up to 2.01, MnO up to 0.54 and Ce_2O_3 up to 1.88. Davidite-Ce typically occurs along the edges of crichtonite and contains, wt.%: TiO_2 60.54-62.28, FeO 22.67-25.77, Ce_2O_3 3.18-5.0, La_2O_3 2.47-2.74 and SrO 0.58-0.64. The MCG also contain up to 4.69 wt.% UO_2. Complex processes of breakdown of MCG and their replacement by anatase are accompanied by the formation of REE (anzaite-Ce) and U (uraninite) minerals and subsequent transformation of anatase to rutile. A sequence of mineral formation of the ooids indicates that the formation and growth of the MCG crystals is a result of lithification of accumulated Ti and trace elements during smectitization of basaltic clasts. Further processes of mineral transformation are associated with the transformation of crichtonite to simple Ti oxides and the precipitation of REE and U minerals. Titanite is a product of the final skarn stages of ore formation.

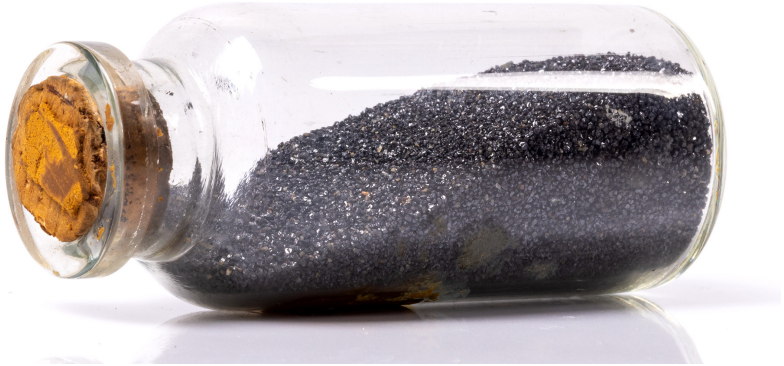
Litvinova T.E., Gerasev S.A. Behaviour of cerium (III) phosphate in a carbonate-alkaline medium // Journal of Mining Institute. 2025. Vol. 271. P. 181-188. https://pmi.spmi.ru/pmi/article/view/16416

Abstract. The article investigates the behaviour of rare earth metals in carbonate-alkaline systems. The results of experimental studies on rare earth element extraction from phosphogypsum, a large-tonnage industrial waste forming in production of phosphoric acid are presented. Using the liquid phase leaching method, it was possible to extract more than 53 % of rare earth elements from old phosphogypsum and more than 69 % from fresh phosphogypsum due to solid phase treatment with a 4 mol/l potassium carbonate solution at temperature 90 °C. The behaviour of model cerium (III) phosphate in a carbonate-alkaline medium is characterized: a solubility isotherm is obtained as well as the dependences of the degree of cerium extraction into solution on temperature, carbonate ion concentration, interphase ratio, stirring intensity, and pH. The ability of soluble rare earth element complexes to precipitate over time was established, which was confirmed using cerium and neodymium as an example. Within 240 h after the end of the experiment, approximately 25 % of cerium and 17 % of neodymium were precipitated from the liquid phase. A similar property was recorded in representatives of the light group and was not noted in elements of the heavy group. The ability to self-precipitate in future can serve as a basis for developing an alternative approach to separating rare earth metals into groups after extraction in a carbonate ion medium. Also, based on the analysis of experimental data, the mechanism of cerium (III) phosphate dissolution in a carbonate-alkaline medium was characterized. An assumption was made that rare earth metal phosphates dissolve sequentially passing into an insoluble carbonate and then into a soluble carbonate complex.

Cherepovitsyn A.E., Dorozhkina I.P., Jingna K. Sino-Russian cooperation in the Arctic: options for joint development of rare earth metals // Journal of Mining Institute. 2026. Vol. 277. P. 119-135. https://pmi.spmi.ru/pmi/article/view/16814

Abstract. The rare earth metals (REM) industry plays an important role in the modern global economy due to the extensive use of these elements in high-technology sectors. Russia possesses substantial REM reserves, giving the country a major competitive advantage: a strong mineral resource base capable of meeting growing demand in both domestic and global markets, where China remains the dominant player. China accounts for more than 70 % of global REM production, while Russia's share does not exceed 1 %. In recent years, countries worldwide have paid increasing attention to the REM supply chain, intensifying international competition in this sector. In this context, the development of Sino-Russian cooperation represents a key factor in strengthening the two countries' positions in the global market and should be based on collaboration in strategically significant areas for both sides. The purpose of this study is to explore options for implementing a Sino-Russian partnership in strategic sectors, using the REM industry as a case study. The Russian Arctic, where REM deposits unique in terms of reserves and concentrations of valuable components are concentrated, is considered a potential site for the implementation of technological cooperation. The study is based on a critical analysis of Russia's key REM deposits, with particular attention to Arctic sites, as well as a comparative analysis of the Russian and Chinese consumer markets and forecasts of their development. These analyses form the basis for proposed options for technological cooperation between the two countries. The findings indicate that the most promising form of Sino-Russian partnership is a consortium model, similar to joint projects such as Yamal LNG and Power of Siberia. This format enables Russia to attract investment and technologies, while allowing China to secure access to new sources of raw materials and strengthen its presence in the Arctic.

Loparite in rock. From the collection of the Mining Museum



Loparite concentrate. From the collection of the Mining Museum

Scientific edition

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