Extraction of Eu(III), Gd(III), and Tb(III) in aqueous two-phase systems based on polyethylene glycol 1500-NaNO3-H2O with the addition of extractants (D2EHPA, TBP, TOMAN)

A Ya Fedorov*, A V Levina, M I Fedorova

1 Kurnakov Institute of General and Inorganic Chemistry of the Russian Academy of Sciences, Leninsky prospect, 31, 119991, Moscow, Russia

*Corresponding author: alfedwork@gmail.com

Abstract. Luminophores that used, for example, in fluorescent lamps, contain a large number of rare earth elements. Therefore, the processing of waste equipment containing luminophores is a rational approach to the obtaining of rare-earth metals, firstly, from the economics point of view, since they have a high cost, and secondly, from the ecological point of view, since environmental pollution will not occur. The cheapest way to extract rare earth elements from waste products is to dissolve them in strong acids and the following reprocessing by liquid extraction methods. In this case, neutral or ion exchange extractants (tributyl phosphate, di(2-ethylhexyl)phosphoric acid and quaternary ammonium salts) are used, which show high extraction ability and, in some cases, selectivity. Their applying is associated with the use of non-polar organic solvents, which contradicts the principles of «green» chemistry. A good and promising alternative to organic solvents can be aqueous two-phase systems, which have already proved themselves as low-toxic, but highly effective systems for the separation of a number of metals. Thus, in this work, we performed an experimental study of the interphase distribution of Eu(III), Gd(III), and Tb(III) in two-phase systems based on water-soluble polymers with or without the introduction of traditional organic extractants as an additive. The possibility of using such ATPS as a «green» solvent for traditional extractants for Eu(III), Gd(III), and Tb(III) extraction has been shown.

Key words: luminophores, liquid-liquid extraction, «green» chemistry, aqueous two-phase systems, waste, rare earth elements.

1. Introduction
Rare earth elements (REEs) are widely used, they can be found in smartphones and PCs, in energy-saving lamps and displays, in permanent magnets and electric motors, in radars and lasers [1]. Since the demand for REE is growing, their production is also growing, as a result, prices for this already expensive raw material are growing. Consequently, the demand for alternative sources of these elements is increasing. This is e-waste, the increase in which is directly proportional to the growth in demand for electronic equipment. However, at the moment, only about 1% of the used REE is returned from secondary raw materials, which is explained by the difficulties associated with waste collection [2].

Waste fluorescent lamps, which contain luminophores, are considered the most economical light sources and are promising for processing in order to extract REE. Luminophores that include rare-earth elements in their composition can be divided into five main types: red luminophores - Y2O3:Eu3+, green...
luminophores - LaPO₄: Ce³⁺, Tb³⁺, blue luminophores BaMgAl₁₂O₁₉: Eu²⁺, GdMgB₂O₄: Ce³⁺, TbMgAl₁₂O₁₉ [3]. Of interest is the fact that the listed luminophores often contain more REE than ores.

The traditional method based on the leaching of phosphor scrap using mineral acids (sulfuric, nitric, hydrochloric and their mixtures) with subsequent extraction and separation of REEs [4]. Researchers Tunsu and others [5] leached Y and Eu with a mixture of hydrochloric and nitric acids (within 24 hours), De Carolis and others [6] leached them with HCl (6 mol·L⁻¹) for a day, Takahashi and others [7] succeeded in doing this using 1.5 mol·L⁻¹ H₂SO₄ at 70°C per one hour.

Organophosphate acids are effective extractants of REE, among which D2EHPA is of the greatest practical application [8]. The extraction proceeds according to the cation-exchange mechanism and is characterized by high distribution coefficients. The work [9] studied the extraction of Y, Dy, and Nd.

Salts of quaternary ammonium bases (QAB) are extracted with REE by an anion exchange mechanism [10]. They have the highest selectivity among primary, secondary, tertiary amines, and Nd.

The listed methods imply the use of strong acids, which entails strong economic losses due to the need for neutralization of reagents and disposal of waste water [13]. In addition, organic solvents are often used, which are not only toxic and environmentally unsafe, but also flammable and explosive [14]. Also, often, traditional extraction systems have low selectivity, which reduces the efficiency of the entire process [15].

These problems can be avoided by following the principles of "green" chemistry and making a partial or full transition to "green" solvents and reagents [16]. In addition, many modern approaches allow using and combining existing ineffective methods, increasing their effectiveness. A striking example is the hybrid method of liquid-liquid chromatography - this is one of the most promising methods for separating organic and inorganic substances, combining the ideology of liquid extraction and high efficiency of chromatography [17]. At present, using this method, the processes of separation of rare-earth metals and a number of other metals [18] have been implemented, both with the use of column equipment and industrial extractors [19]. Another promising approach to replacing organic solvents with "green" reagents is the use of deep eutectic solvents (DES) [20]. Being a eutectic mixture of solids (Lewis and Bronsted acids and bases) linked by hydrogen bonds, DES are most often liquid at room temperature and show high efficiency for the extraction of rare earth metals and their compounds from various media [21]. Another approach is the use of aqueous two-phase systems, including those based on water-soluble polymers [22]. These heterogeneous systems are already used for the separation and extraction of organic [23, 24] and inorganic compounds, including metals [25, 26]. Replacing the organic solvent with non-toxic polymers will have a positive effect in the environmental aspect, as well as change the selectivity of the processes. In addition, in studies [27, 28] it was found that the use of salts of quaternary ammonium bases has a positive effect on the extraction efficiency, and in some cases contributes to the selective extraction of certain metals [29]. On the contrary, the use of aqueous two-phase systems is not a complete solution to the problem of extraction metals, since the system can have low selectivity and simultaneously extract a number of metals [30]. The initial solution medium is also important, for example, sulfate [31] or chloride. In addition, attention is paid to liquid-liquid equilibria of aqueous two-phase systems, which can subsequently be used for extraction processes [32].

In this regard, the aim of this study was the replacement of organic solvents with aqueous two-phase systems, in the processes of extraction processing of acidic solutions of leaching of phosphors. Promising luminophores containing Eu, Gd, and Tb were chosen as model solutions.

2. Experimental
The tools were used in this work: 50 ml measuring beakers, measuring pipettes (from 10µ to 5ml), 20 ml separation funnels, 15 ml graduated plastic tubes, drop tube, analytical Balance (AND HR-100AZ), Magnetic stirrer (IKA C-MAG HS4) with stirrer bar, centrifuge (ELMI CM-6MT), desalinated filter paper, Enviro-Genie thermostatically controlled shaker (Scientific Industries, Inc.).
Reagents were used in this research: sodium nitrate (NaNO$_3$), distilled water, poly(ethylene glycol) 1500 (PEG-1500), Trioctylmethylammonium chloride (Aliquat 336), bis(2-Ethylhexyl)hydrogen phosphate (D2EHPA), Tributyl phosphate (TBP), Ethylenediamine tetraacetate sodium (EDTA-Na$_2$), Europium nitrate hexahydrate (Eu(NO$_3$)$_3$·6H$_2$O), Gadolinium nitrate hexahydrate (Gd(NO$_3$)$_3$·6H$_2$O), Terbium nitrate hexahydrate (Tb(NO$_3$)$_3$·6H$_2$O), xylene orange, nitric acid (HNO$_3$).

The initial solutions of metal nitrates were obtained by dissolving the sample weights of Eu(NO$_3$)$_3$·6H$_2$O, Gd(NO$_3$)$_3$·6H$_2$O and Tb(NO$_3$)$_3$·6H$_2$O of the qualification “chemical grade” suspended on an analytical balance (AND HR-100AZ) in distilled water. Trioctylmethylammonium nitrate (TOMAN) was prepared as follows: 1.6 mol·L$^{-1}$ sodium nitrate solution was mixed with Aliquat 336 in a 1:1 ratio [33] Stirring was performed until the chloride ions were completely replaced by nitrate ions. The mixing time was 20 minutes.

The metal ions extraction was carried out using nitrate two-phase aqueous systems, based on polyethylene glycol 1500 and with an initial metal concentration of 0.01 mol·L$^{-1}$. Phase composition were chosen based on phase diagrams, PEG-1500 - NaNO$_3$ [34]. The acid concentration in the salt phase was equal 0.01 mol·L$^{-1}$ (for the hydrolyze avoiding).

The metal ions Eu(III), Gd(III) and Tb(III) extraction was carried out at a temperature of 25°C in graduated plastic tubes in an Enviro-Genie thermostatically controlled shaker (Scientific Industries, Inc.) at a rotation speed of 30 rpm for it was chosen as optimal time for the effective extraction of both metals.

The complexometric titration using EDTA and xylene orange at pH=6 was used to determine the metal ions concentration in the initial solutions and in the aqueous phases after extraction.

The presented experimental data are the result of a series of experiments and processed by methods of mathematical statistics.

3. Results and discussion

We carried out a series of experiments aimed at studying the interphase distribution of metal ions Eu(III), Gd(III), Tb(III) in various systems PEG-1500 (16.3 wt.%) - NaNO$_3$ (36 wt.%) - H$_2$O, PEG -1500 (16.3 wt.%) - NaNO$_3$ (36 wt.%) - H$_2$O with the addition of TOMAN, PEG-1500 (16.3 wt.%) - NaNO$_3$ (36 wt.%) - H$_2$O with the addition of TBP, PEG-1500 (16.3 wt.%) - NaNO$_3$ (36 wt.%) - H$_2$O with the addition of TBP and D2EHPA in the ratios of 1:4, 2:3, and 4:1. The addition of TOMAN, TBP, and D2EHPA was motivated by the fact that the introduction of traditional extractants into the system intensifies the extraction process in the internal combustion engine. As a result, quantitative characteristics of extraction were obtained, such as distribution coefficients (Fig.1), degrees of extraction (Fig.2) and the number of theoretical stages (Fig.3) of extraction for metal ions Eu(III), Gd(III) and Tb(III). The number of theoretical stages of extraction was calculated by the formula (1):

$$n = \frac{\ln q (1 - \frac{X_n}{X_0})}{\ln \left(\frac{X_n}{X_0}\right)},$$

where $n$ is the number of theoretical extraction steps; $q$ is the ratio $X_0 / X_n$; $X_0$ is the initial concentration of the metal introduced into the system, mol·L$^{-1}$; $X_n$ is the final specified metal concentration, mol·L$^{-1}$; $\lambda$ is the ratio $V_n / V_w$; $V_n$ - volume of the lower vase, ml; $V_w$ - volume of the upper phase, ml; $D$ - distribution coefficient. When using this formula, the following assumptions were made:

- distribution coefficient $D = const$;
- the volumes of the phases $V_n$ and $V_w$ are constant, therefore, their ratio ($\lambda = const$);
- the original extractant does not contain the substance to be distributed.

With the initial metal concentration $X_0 = 0.01$ mol·L$^{-1}$, the final metal concentration $X_n = 1·10^{-6}$ mol·L$^{-1}$, therefore, $q = 10000$, thus, the extraction of metal ions will occur with a degree of 99.99%.

As can be seen in Figures 1-3, with the addition of TOMAN (Fig. 1-3, b), in comparison with the first experiment (Fig. 1-3, a), the distribution coefficients increased: for Eu(III) by 1.78, Gd(III) by 1.15 and Tb(III) by 1.65. The number of theoretical stages of extraction has noticeably decreased (by about
2 times). Consequently, such an extraction system with the addition of TOMAN can be used in the extraction of Eu(III), Gd(III), and Tb(III), but is impractical due to low distribution coefficients.

With the addition of TBP (Fig. 1-3, c) to the upper phase, in comparison with the first experiment (Fig. 1-3, a), the distribution coefficients increased: for Eu(III) by 1.12, Gd(III) by 2.74 and Tb(III) at 1.96. The number of theoretical stages of extraction, as well as in the system with the addition of TOMAN, decreased by about 2 times. This extraction system can be used in the extraction of Eu(III), Gd(III) and Tb(III), however, it is impractical due to low distribution coefficients.

It is known from the literature [35] that the combined use of TBP and D2EHPA gives rise to a synergistic effect, and the extraction of Nd(III) from acidic media, the distribution coefficients increased several times. It was decided to conduct a series of experiments to find the most effective ratio of TBP and D2EHPA for extraction (Fig. 1-3, d, f, e). The synergistic effect was calculated by the formula (2):

$$S_k = \frac{D}{D_1 + D_2}, \tag{2}$$

where are $D$ the distribution coefficient for extraction with a mixture of extractants; $D_1$, $D_2$ - distribution coefficients for extraction with each extractant separately.

From the data obtained (Figs. 1-3, d, e, f), a synergistic effect is observed only in the case of an extraction system with the addition of TBP and D2EHPA in a ratio of 1: 4 and only in the case of Eu(III): $S_k(Eu) = 1.99$, that is, this system can improve the extraction by almost two times. The distribution coefficients are high in all cases, which makes it possible to solve the problem of element extraction. Accordingly, such extraction systems with the addition of TBP and D2EHPA are excellent for use in the extraction of Eu(III), Gd(III) and Tb(III).

The system PEG-1500 (16.3 wt.% - NaNO$_3$ (36 wt.% - H$_2$O + TBP:D2EHPA (1:4) is the most effective for separating Eu(III) from its mixture with Gd (III) and Tb (III). We have calculated the separation coefficients based on experimental data by the formula (3):

$$\beta_{Eu/M} = \frac{D_{Eu}}{D_{Me}}, \tag{3}$$

where $\beta_{Eu/M}$ is the separation coefficient of Eu(III) in relation to another metal; $D_{Eu}$ – is the distribution coefficient of Eu(III); $D_{Me}$ – is the distribution coefficient of Eu(III).

Thus, $\beta_{Eu/Gd}=2.97$ and $\beta_{Eu/Tb}=3.36$ are high values for the separation coefficients for metal [36], which suggests that this system is excellent for solving the problem of selective extraction of Eu(III) from this mixture of metals.

![Distribution coefficients of metal ions](image-url)

Fig. 1. Partition coefficient for extraction of Eu(III), Gd(III), Tb(III) in various systems a) PEG-1500 (16.3 wt.% - NaNO$_3$ (36 wt.% - H$_2$O; b) PEG-1500 (16.3 wt.% - NaNO$_3$ (36 wt.% - H$_2$O + TOMAN; c) PEG-1500 (16.3 wt.% - NaNO$_3$ (36 wt.% - H$_2$O + TBP; d) PEG-1500 (16.3 wt.% - H$_2$O + TBP; e) PEG-1500 (16.3 wt.% - H$_2$O + TBP; f)
NaNO$_3$ (36 wt.%) - H$_2$O + TBP:D2EHPA (1:4); f) PEG-1500 (16.3 wt.%) - NaNO$_3$ (36 wt.%) - H$_2$O + TBP:D2EHPA (2:3); e) PEG-1500 (16.3 wt.%) - NaNO$_3$ (36 wt.%) - H$_2$O + TBP:D2EHPA (4:1).

**Fig. 2.** Extraction degree of Eu (III), Gd (III), Tb (III) in different systems a) PEG-1500 (16.3 wt.%) - NaNO$_3$ (36 wt.%) - H$_2$O; b) PEG-1500 (16.3 wt.%) - NaNO$_3$ (36 wt.%) - H$_2$O + TMAN; c) PEG-1500 (16.3 wt.%) - NaNO$_3$ (36 wt.%) - H$_2$O + TBP; d) PEG-1500 (16.3 wt.%) - NaNO$_3$ (36 wt.%) - H$_2$O + TBP:D2EHPA (1:4); f) PEG-1500 (16.3 wt.%) - NaNO$_3$ (36 wt.%) - H$_2$O + TBP:D2EHPA (2:3); e) PEG-1500 (16.3 wt.%) - NaNO$_3$ (36 wt.%) - H$_2$O + TBP:D2EHPA (4:1).

**Fig. 3.** The number of theoretical stages of extraction of Eu (III), Gd (III), Tb (III) in various systems a) PEG-1500 (16.3 wt.%) - NaNO$_3$ (36 wt.%) - H$_2$O; b) PEG-1500 (16.3 wt.%) - NaNO$_3$ (36 wt.%) - H$_2$O + TMAN; c) PEG-1500 (16.3 wt.%) - NaNO$_3$ (36 wt.%) - H$_2$O + TBP; d) PEG-1500 (16.3 wt.%) - NaNO$_3$ (36 wt.%) - H$_2$O + TBP:D2EHPA (1:4); f) PEG-1500 (16.3 wt.%) - NaNO$_3$ (36 wt.%) - H$_2$O + TBP:D2EHPA (2:3); e) PEG-1500 (16.3 wt.%) - NaNO$_3$ (36 wt.%) - H$_2$O + TBP:D2EHPA (4:1).
4. Conclusions
The extraction system based on PEG-1500 (16.3 wt.%) - NaNO₃ (36 wt.%) - H₂O with the addition of TBP and D2EHPA in ratios of 1:4, 2:3, and 4:1 is more efficient for the extraction of Eu(III), Gd(III) and Tb(III) compared to systems without the addition of this mixture of extractants or with the addition of TOMAN or TBP. It was found that in the system with the addition of TBP and D2EHPA in a ratio of 1:4, Eu(III) is extracted with high efficiency.

Acknowledgments
This work was supported by IGIC RAS state assignment.

References
[1] Gupta C K and Krishnamurthy N 2016 Extractive metallurgy of rare earths CRC Press 522
[2] Omodara L, Pitkaaho S, Turpeinen E M, Saavalainen P, Oravijärvi K and Keiski R L 2019 Recycling and substitution of light rare earth elements, cerium, lanthanum, neodymium, and praseodymium from end-of-life applications - A review J. Clean. Prod. 236 1 117573
[3] Belova V V, Voshkin A A, Egorova N S and Khokhin A I 2012 Solvent extraction of rare earth metals from nitrate solutions with di(2,4,4-trimethylpentyl)phosphinate of methyltrioctylammonium J. Mol. Liq. 172 144-6
[4] Binnemans K and Jones PT 2014 Perspectives for the recovery of rare earths from end-of-life fluorescent lamps J. Rare Earths 32 3 195-200.
[5] Tunsu C, Ekberg C and Retegan T 2014 Effect of solution composition on the optimum redox potential for chalcopyrite leaching in sulfuric acid solutions Hydrometallurgy 91 144-9
[6] De Carolis R, Fontana D, Pietrantonio M, Puccinellati S and Torelli G N 2015 A hydrometallurgical process for recovering rare earths and metals from spent fluorescent lamps Environ. Eng. Manag. J. 14 1603-10
[7] Takahashi T, Takano A, Saitoh T, Nagano N, Hirai S and Shimakage K 2001 Separation and recovery of rare earth elements from phosphor sludge in processing plant of waste fluorescent lamp by pneumatic classification and sulfuric acid leaching Shigen to Sozai 117 579-85
[8] Поляков Е Г 2018 Металлургия редкоземельных металлов ред. Нечаев А В и Смирнов А В (Москва: Металлургиздат ЗАО)
[9] Mohammad M, Forsberg K, Kloo L, De La Cruz J M and Rasmussen A 2015 Separation of Nd(III), Dy(III) and Y(III) by solvent extraction using D2EHPA and ЕЕЕHPA Hydrometallurgy 156 215-24
[10] Zakhodyaeva Y A, Voshkin A A, Belova V V and Khokhin A I 2012 Extraction of monocarboxylic acids by trioctylmethylammonium di(2-ethylhexyl)phosphate Theor. Found. Chem. Eng. 46 413-8
[11] Степанов С И 2004 Экстракция редких металлов солями четвертичных аммониевых оснований ред. Степанов СН и Чемарев АМ (Москва: ИздАТ)
[12] Пятрин А К, Кондрин А А, Пузиков Е А и Богатов К Б 1996 Экстракция нитратов редкоземельных металлов смесями три-н-бутилфосфата и нитрата триметилалкиламмония из водно-солевых растворов ЖНХ 41 2 347-51
[13] Belova V V, Voshkin A A, Egorova N S and Khokhin A I 2010 Extraction of rare earth metals from nitrate solutions with a binary extractant based on Cyanex 272 Russ. J. Inorg. Chem. 5 629–33
[14] Fedorova M I, Zinov’eva I V, Zakhodyaeva Y A and Voshkin A A 2020 Extraction of Fe(III), Zn(II), and Mn(II) Using a System with a Green Solvent for Trioctylmethylammonium Thiocyanate Theor. Found. Chem. Eng. 54 313-8
[15] Zakhodyaeva Y A, Izyumova K V, Solov’eva M S and Voshkin A A 2017 Extraction separation of the components of leach liquors of batteries Theor. Found. Chem. Eng. 51 5 883-7
[16] Anastas P and Warner J 1998 Green Chemistry: Theory and Practice (Oxford: Oxford University Press)
[17] Kostanyan A E, Voshkin A A and Kodin N V 2011 Pulsed cyclic device for liquid countercurrent chromatography Theor. Found. Chem. Eng. 45 779
[18] Kostanian A E and Voshkin A A 2007 Analysis of new counter-current chromatography operating modes J. Chromatogr. A 1151 126-30
[19] Kostanyan A E and Voshkin A A 2009 Pulsation cyclic liquid-liquid chromatography Theor. Found. Chem. Eng. 43 729-33
[20] Abbott A, Capper G, Davies D, Rasheed R and Tambahrajah V 2003 Novel solvent properties of choline chloride/urea mixtures Chem. Commun. 70-1
[21] Liu F, Porvali A, Wang J L, Wang H, Peng C, Wilson B P and Lundstrom M 2020 Recovery and separation of rare earths and boron from spent Nd-Fe-B magnets Miner. Eng. 145 106097
[22] Voshkin A A, Zakhodyaeva Y A, Zinov’eva I V and Shkinev V M 2018 Interphase Distribution of Aromatic Acids in the Polyethylene Glycol–Sodium Sulfate–Water System Theor. Found. Chem. Eng. 52 890-3
[23] Shkinev V M, Zakhodyaeva Y A, Dzhenloda R Kh, Mokhodoeva O B and Voshkin A A 2017 Synthesis of magnetic iron oxide nanoparticles at the interface of the polyethylene glycol–ammonium sulfate–water extraction system Mendeleev Commun. 27 485-6
[24] Zakhodyaeva Y A, Solov’ev V O, Zinov’eva I V, Rudakov D G, Timoshenko A V and Voshkin A A 2019 Interphase Distribution of Thiophene, Toluene, and o-Xylene in the Hexane–Polymer–Water Extraction System Theor. Found. Chem. Eng. 53 4 550-5
[25] Belova V V, Voshkin A A, Khol’kin A I and Payrtman A K 2009 Solvent extraction of some lanthanides from chloride and nitrate solutions by binary extractants Hydrometallurgy 97 198–203
[26] Voshkin A A, Shkinev V M and Zakhodyaeva Y A 2017 A new extraction method for the preparation of zinc oxide nanoparticles in aqueous two-phase systems Russ. J. Phys. Chem. A 91 226–8
[27] Belova V V, Voshkin A A and Khol’kin A I 2011 Liquid-liquid distribution of metals in systems with trioctylmethylammonium dimonyl naphthalenesulfonate Theor. Found. Chem. Eng. 45 764
[28] Fedoroava M I, Zakhodyaeva Y A and Voshkin A A 2020 Interphase Distribution of Fe(III) and Zn(II) in Chloride Systems with Aliquat 336 in Polypropylene Glycol 425 Theor. Found. Chem. Eng. 54 425-30
[29] Voshkin A A, Belova V V and Khol’kin A I 2003 Extraction of iron(III) by binary extractants based on quaternary ammonium bases and organic acids Russ. J. Inorg. Chem. 48 4 608-13
[30] Zakhodyaeva Y A, Zinov’eva I V, Tokar E S and Voshkin A A 2019 Complex extraction of metals in an aqueous two-phase system based on poly(ethylene oxide) 1500 and sodium nitrate Molecules 24 4078
[31] Zinov’eva I V, Zakhodyaeva Y A and Voshkin A A 2020 Data on the extraction of benzoic, salicylic and sulfosalicylic acids from dilute solutions using PEG-based aqueous two-phase systems Data in Brief 28 105033
[32] Zakhodyaeva Y A, Rudakov D G, Solov’ev V O, Voshkin A A and Timoshenko A V 2019 Liquid–Liquid Equilibrium in an Extraction System Based on Polyvinylpyrrolidone-3500 and Sodium Nitrate Theor. Found. Chem. En. 53 2 159-65
[33] Nayl A 2010 Extraction and separation of Co(II) and Ni(II) from acidic sulfate solutions using Aliquat 336 J. Hazard. Mater. 173 223-30
[34] Zakhodyaeva Y A, Rudakov D G, Solov’ev V O, Voshkin A A and Timoshenko A V 2019 Liquid-liquid Equilibrium of Aqueous Two-Phase System Composed of Poly(Ethylene Oxide) 1500 and Sodium Nitrate J. Chem. Eng. Data. 64 3 1250-5
[35] Дошарова Д Т и Сальникова Е В 2016 Влияние смеси экстрагентов трибутилфосфата и ди-(2-этилгексил)фосфорной кислоты на извлечение неодима из кислых сред Изв. вузов. Прикладная химия и биотехнология. 6 4 86-91

[36] Valadares A, Valadares C F, Rodrigues de Lemos L, Mageste A B and Rodrigues G D 2018 Separation of cobalt and nickel in leach solutions of spent nickel-metal hydride batteries using aqueous two-phase systems (ATPS) Hydrometallurgy 181 180-8