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CONTENTS

Chemistry

МАЗМҰНЫ

ХИМИЯ

СОДЕРЖАНИЕ

ХИМИЯ

ACADEMIC SCIENTIFIC JOURNAL OF CHEMISTRY
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D.V. Sokolsky Institute of Fuel, Catalysis and Electrochemistry, Almaty, Kazakhstan.
E-mail: n.ivanov@ifce.kz

SEQUENTIAL ELECTROCHEMICAL PROCESSES FOR THE TREATMENT OF MAGNESIUM LEACHING SOLUTIONS

Ivanov Nikolay — Candidate of Chemical Sciences, D.V. Sokolsky Institute of Fuel, Catalysis and Electrochemistry, Almaty, Kazakhstan,
E-mail: n.ivanov@ifce.kz, https://orcid.org/0000-0002-2153-2802;
Abilmagzhanov Arlan — Candidate of Chemical Sciences, D.V. Sokolsky Institute of Fuel, Catalysis and Electrochemistry, Almaty, Kazakhstan,
E-mail: a.abilmagzhanov@ifce.kz, https://orcid.org/0000-0003-2931-9640;
Nurtazina Aizhan — PhD, D.V. Sokolsky Institute of Fuel, Catalysis and Electrochemistry, Almaty, Kazakhstan,
E-mail: nurtazina.aizhan@bk.ru, https://orcid.org/0000-0001-7202-5344;
Adelbayev Iskander — Master's Degree, D.V. Sokolsky Institute of Fuel, Catalysis and Electrochemistry, Almaty, Kazakhstan,
E-mail: clerikc88@mail.ru, https://orcid.org/0000-0003-1435-8583;
Kholkin Oleg — PhD, D.V. Sokolsky Institute of Fuel, Catalysis and Electrochemistry, Almaty, Kazakhstan,
E-mail: g.freeman-17@mail.ru, https://orcid.org/0000-0002-4797-3374.

Abstract. Processing anthropogenic wastes from the asbestos industry to recover magnesium oxide is a relevant task that simultaneously addresses environmental and economic challenges. Nitric-acid leaching is a promising approach; however, its industrial implementation is constrained by the complexity of purifying the resulting solutions. In this study, an integrated hydrometallurgical flowsheet was developed and investigated, sequentially combining electrochemical oxidation of Fe(II), electrochemical precipitation of impurities, and electrodialytic concentration of the target magnesium nitrate solution. Electrochemical oxidation enabled Fe(II) to Fe(III) conversion exceeding 98%. Kinetic analysis revealed a shift in the rate-controlling step: at T < 40°C, the process is kinetically controlled (E_a = 94.8 kJ/mol, reaction order n = 1.34), whereas at T > 40°C it transitions to the diffusion-controlled regime (E_a = 17.9 kJ/mol, n = 0.40). The combined neutralization method mitigated precipitant passivation and removed >99% of impurities at a specific energy consumption of 38.1 kWh/m³. Analysis of variance showed that process time is the dominant factor. Electrodialytic

concentration of the purified magnesium nitrate solution demonstrated an almost sixfold reduction in energy demand compared with thermal evaporation (52.6 kWh/m³ vs 313.8 kWh/m³), achieving a current efficiency of 95.6%. The proposed reagent-free scheme is a technically feasible and energy-efficient technology for processing serpentinite wastes within the circular economy concept. The implementation of the developed process in industrial practice will significantly reduce the environmental burden associated with the accumulation of asbestos-containing waste, while simultaneously enabling the production of a high-value, in-demand chemical product. The obtained results can serve as a basis for process scale-up and further optimization of technological parameters, taking into account the specifics of the raw material base and the requirements of industrial operation.

Keywords: asbestos, magnesium oxide, electrolysis, oxidation, electrodialysis

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Д.В. Сокольский атындағы жанармай, катализ және электрохимия институты, Алматы, Қазақстан.

E-mail: n.ivanov@ifce.kz

МАГНИЙДІ ШАЙМАЛАУ ЕРІТІНДІЛЕРІН ҚАЙТА ӨҢДЕУ ТЕХНОЛОГИЯСЫНДАҒЫ ДӘЙЕКТІ ЭЛЕКТРОХИМИЯЛЫҚ ПРОЦЕСТЕР

Иванов Николай — химия ғылымдарының кандидаты, Д.В. Сокольский атындағы жанармай, катализ және электрохимия институты, Алматы, Қазақстан,
E-mail: n.ivanov@ifce.kz, https://orcid.org/0000-0002-2153-2802;
Абильмагжанов Арлан — химия ғылымдарының кандидаты, Д.В. Сокольский атындағы жанармай, катализ және электрохимия институты, Алматы, Қазақстан,
E-mail: a.abilmagzhanov@ifce.kz, https://orcid.org/0000-0003-2931-9640;
Нұртазина Айжан — Ph.D, Д.В. Сокольский атындағы жанармай, катализ және электрохимия институты, Алматы, Қазақстан,
E-mail: nurtazina.aizhan@bk.ru, https://orcid.org/0000-0001-7202-5344;
Адельбаев Искандер — металлургиялық технологиясы және техника магистрі, Д.В. Сокольский атындағы жанармай, катализ және электрохимия институты, Алматы, Қазақстан,
E-mail: clerikc88@mail.ru, https://orcid.org/0000-0003-1435-8583;

Холкин Олег — Ph.D, Д.В. Сокольский атындағы жанармай, катализ және электрохимия институты, Алматы, Қазақстан,
E-mail: g.freeman-17@mail.ru, https://orcid.org/0000-0002-4797-3374.

Аннотация. Магний оксидін алу үшін асбест өнеркәсібінің техногендік қалдықтарын қайта өңдеу экологиялық және экономикалық мәселелерді қатар шешетін өзекті мәселе болып табылады. Азот қышқылымен шаймалау – перспективалы әдіс, алайда оны өнеркәсіптік енгізу алынған ерітінділерді тазартудың күрделілігіне байланысты тежелуде. Бұл жұмыста Fe(II) электрохимиялық тотығуын, қоспалардың электрохимиялық тұнбасын және мақсатты магний нитратының ерітіндісінің электродиализдік концентрациялауды дәйекті түрде біріктіретін кешенді гидрометаллургиялық схема әзірленіп, зерттелді. Электрохимиялық тотығу Fe(II)-нің Fe(III)-ке 98%-дан астам конверсиялануына қол жеткізуге мүмкіндік берді. Процестің кинетикалық талдауы шектеу сатысының өзгеруін анықтады: T<40°C кезінде процесс кинетикамен бақыланады (есептелген E_a = 94,8 кДж/моль, реакция реті n=1,34), ал T>40°C диффузиялық аймаққа ауысады (E_a = 17,9 кДж/моль, n=0,40). Біріктірілген бейтараптандыру әдісі тұнбаны пассивациялау мәселесін шешуге және меншікті энергия шығыны 38,1 кВт*сағ/м³ болатын қоспаларды 99%-дан астамын жоюға мүмкіндік берді. Дисперсиялық талдау процесс уақыты басым фактор екенін көрсетті. Тазартылған магний нитраты ерітіндісін электродиализдік концентрациялау термиялық буландырумен салыстырғанда энергия шығымының 6 есеге жуық төмендегенін көрсетті (313,8 кВт*сағ/м³-ке қарсы 52,6 кВт*сағ/м³), бұл ретте ток бойынша шығым 95,6%-ға жетті. Ұсынылып отырған реагентсіз схема айналмалы экономика тұжырымдамасы шеңберінде серпентинит қалдықтарын қайта өңдеуге арналған техникалық тиімді және энергияны үнемдейтін технология болып табылады. Әзірленген технологиялық схеманы өнеркәсіптік практикаға енгізу асбесткұрамды қалдықтардың жиналуымен байланысты экологиялық жүктемені едәуір төмендетуге, сонымен қатар жоғары қосылған құны бар, сұранысқа ие химиялық өнім алуға мүмкіндік береді. Алынған нәтижелер процесті ауқымдауға және шикізат базасының ерекшеліктері мен өнеркәсіптік пайдалану талаптарын ескере отырып, технологиялық параметрлерді одан әрі оңтайландыруға негіз бола алады.

Түйін сөздер: асбест, магний оксиді, электролиз, тотығу, электродиализ

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Институт топлива, катализа и электрохимии имени Д.В. Сокольского, Алматы, Казахстан.
E-mail: n.ivanov@ifce.kz

ПОСЛЕДОВАТЕЛЬНЫЕ ЭЛЕКТРОХИМИЧЕСКИЕ ПРОЦЕССЫ В ТЕХНОЛОГИИ ПЕРЕРАБОТКИ РАСТВОРОВ ВЫЩЕЛАЧИВАНИЯ МАГНИЯ

Иванов Николай — кандидат химических наук, Институт топлива, катализа и электрохимии имени Д.В. Сокольского, Алматы, Казахстан,
E-mail: n.ivanov@ifce.kz, https://orcid.org/0000-0002-2153-2802;
Абильмагжанов Арлан — кандидат химических наук, Институт топлива, катализа и электрохимии имени Д.В. Сокольского, Алматы, Казахстан,
E-mail: a.abilmagzhanov@ifce.kz, https://orcid.org/0000-0003-2931-9640;
Нуртазина Айжан — PhD, Институт топлива, катализа и электрохимии имени Д.В. Сокольского, Алматы, Казахстан,
E-mail: nurtazina.aizhan@bk.ru, https://orcid.org/0000-0001-7202-5344;
Адельбаев Искандер — магистр техники и технологии металлургии, Институт топлива, катализа и электрохимии имени Д.В. Сокольского, Алматы, Казахстан,
E-mail: clerikc88@mail.ru, https://orcid.org/0000-0003-1435-8583;
Холкин Олег — PhD, Институт топлива, катализа и электрохимии имени Д.В. Сокольского, Алматы, Казахстан,
E-mail: g.freeman-17@mail.ru, https://orcid.org/0000-0002-4797-3374.

Аннотация. Переработка техногенных отходов асбестовой промышленности для извлечения оксида магния является актуальной задачей, позволяющей одновременно решать экологические и экономические проблемы. Азотнокислотное выщелачивание является перспективным методом, однако его промышленное внедрение ограничено сложностью очистки получаемых растворов. В работе разработана комплексная гидрометаллургическая схема, включающая электрохимическое окисление Fe(II), электрохимическое осаждение примесей и электродиализное концентрирование раствора нитрата магния. Электрохимическое окисление обеспечило конверсию Fe(II) в Fe(III) свыше 98%. Кинетический анализ показал смену лимитирующей стадии: при $T < 40$ °C процесс контролируется кинетикой ($Ea = 94{,}8$ кДж/моль, $n = 1{,}34$), а при $T > 40$ °C — диффузией ($Ea = 17{,}9$ кДж/моль, $n = 0{,}40$). Комбинированный метод нейтрализации позволил устранить проблему пассивации осадителя и обеспечить удаление более 99% примесей при удельных энергозатратах 38,1 кВт·ч/м³. Электродиализное концентрирование показало почти шестикратное снижение энергопотребления по сравнению с термическим выпариванием (52,6 кВт·ч/м³ против 313,8 кВт·ч/м³) при выходе по току 95,6%. Предложенная безреагентная схема является энергоэффективной и технологически жизнеспособной для переработки серпентинитовых отходов в рамках циркулярной экономики.

Ключевые слова: асбест, оксид магния, электролиз, окисление, электродиализ

Introduction. The asbestos industry, historically a supplier of a unique mineral resource, is now facing a dual existential challenge. First, an overwhelming body of evidence has accumulated demonstrating the carcinogenic nature of all forms of asbestos. Leading international organizations, including the World Health Organization (WHO) and the International Agency for Research on Cancer (IARC), classify asbestos as a Group 1 carcinogen. This has resulted in increasing global regulatory pressure and complete bans on its use in more than 67 countries, steadily contracting world markets (Pira et al., 2018; Li et al., 2024; Petrović, 2017; Kratzke et al., 2018; Chen et al., 2022).

Second, decades of mining and beneficiation have led to the accumulation of vast man-made waste dumps and beneficiation tailings. While these wastes pose an environmental threat, they are paradoxically among the richest sources of valuable secondary raw materials. Chrysotile production residues, composed predominantly of serpentinite minerals, may contain up to 40 wt.% or more of magnesium oxide (Baigenzhenov et al., 2024). Against the backdrop of a declining asbestos market, the global magnesium oxide market shows steady growth, with a projected compound annual growth rate (CAGR) of 5.5-7.4%, and an expected increase in market size from USD 7.1-7.8 billion in 2023-2024 to USD 12.2-12.7 billion by 2030-2034 (Zhu et al., 2025). The refractory and agricultural sectors are the key end-users. This creates a strong economic incentive to diversify asbestos operations by converting wastes into a high-demand product.

Literary review. Various hydrometallurgical approaches have been proposed to extract magnesium from serpentinites. Sulfuric- and hydrochloric-acid leaching routes are the most extensively studied (Beglaryan et al., 2023; Sirota et al., 2018; Souza et al., 2020). However, both have major drawbacks that hinder the establishment of a closed-loop process. The sulfuric-acid route requires thermal decomposition of magnesium sulfate at temperatures around 1200°C to regenerate the acid, leading to extremely high energy consumption. The hydrochloric-acid technology, although it enables HCl regeneration, is associated with severe corrosivity and significant challenges in process equipment design.

In this context, nitric-acid leaching represents a promising alternative. Its key advantage is that thermal decomposition of magnesium nitrate to magnesium oxide proceeds at substantially lower temperatures (approximately 550°C). This makes it possible to implement a fully closed cycle with nitric acid regeneration, thereby markedly reducing energy barriers and environmental impacts (Zhao et al., 2022). During production of the main product, other valuable intermediate products can also be obtained, such as magnesium nitrate, which is compatible with other fertilizers and can stimulate photosynthesis (Mao et al., 2022). In addition, organic magnesium compounds for medical applications may be produced. This enables the synthesis of various bioactive magnesium forms, including magnesium aspartate (Grigoryan et al., 2005), magnesium citrate (Lu, 2011), magnesium malonate (Rixin et al., 2015), and magnesium glycinate (Wenkun, 2014). These compounds exhibit higher bioavailability than inorganic (mineral) magnesium salts (Blancquaert et al., 2019; Turck et al., 2018).

Despite its advantages in terms of reagent regeneration, the nitric-acid route faces a number of unresolved technological challenges at the leachate purification stage. The

leach solutions constitute a complex multicomponent system containing residual acid and impurity ions such as iron, aluminum, calcium, chromium, and others. Efficient purification therefore remains a key barrier to industrial implementation.

This study focuses on addressing three critical issues arising after the leaching step:

- Oxidation challenge. After nitric-acid leaching, the solution inevitably contains impurity ions in addition to the target component. The presence of Fe^{2+} causes the greatest difficulties because $Fe(OH)_2$ precipitates in a pH range close to that of $Mg(OH)_2$, whereas $Fe(OH)_3$ begins to precipitate at pH values above approximately 3.5. Oxidation of ferrous to ferric iron enables more complete purification of the leach solutions and reduces precipitant consumption.

- Neutralization challenge. The use of conventional precipitants (e.g., MgO slurry) to neutralize residual acid and precipitate impurities leads to passivation of the precipitant particles due to the formation of a hydroxide shell on their surface. This inhibits further reaction and results in excessive reagent consumption.

- Concentration challenge. Purified magnesium nitrate solutions are typically highly diluted. Conventional concentration by thermal evaporation is extremely energy-intensive.

The aim of this work is to develop and experimentally substantiate an integrated, reagent-free, and energy-efficient process flowsheet for the treatment of magnesium-containing nitrate solutions. To achieve this goal, an innovative sequence is proposed that combines electrochemical oxidation of Fe^{2+} to Fe^{3+}, hybrid neutralization coupled with electrochemical precipitation of impurities, and electrodialytic concentration of the purified magnesium nitrate solution.

Materials and methods. Chrysotile-asbestos ore beneficiation tailings from the Zhetikary deposit were used as the feedstock; the material contained 39-42% MgO.

A stock leachate (mother solution) was prepared for the experiments. Leaching was carried out under the following conditions, previously identified as optimal: nitric acid concentration 300 g/L, solid-to-liquid ratio (S/L) = 1:7, temperature 95°C, and duration 3 h (Ivanov et al., 2025). Working solutions for subsequent experiments were prepared from the stock leachate by dilution and, when required, by adding ferrous nitrate.

Electrolyzer for Fe^{2+} oxidation. The experiments were performed in a laboratory electrolyzer with a working volume of 0.5 L. The anode and cathode compartments were separated by an ion-exchange membrane to prevent the back-reduction of Fe^{3+} at the cathode. The setup included a solution circulation loop through a heat exchanger connected to a thermostat to maintain the заданная temperature.

Neutralization and precipitation experiments were carried out in an electrolyzer with separated electrode compartments. In contrast to the oxidation step, the solution under study was placed in the cathode chamber. Upon current passage, hydrogen evolution occurred at the cathode, leading to local generation of hydroxide ions and an increase in pH, which induced precipitation of metal hydroxides.

Concentration of the purified magnesium nitrate solution was performed using a laboratory electrodialysis unit. A five-compartment configuration was employed, comprising an anode chamber, a concentrate chamber, two diluate chambers, and a

cathode chamber, separated by cation-exchange and anion-exchange membranes (29 × 17 cm). The diluate volume in each experiment was 400 mL.

Fe^{2+} ion concentrations in the solutions were monitored by permanganometric titration. Magnesium and other metal concentrations were determined using standard analytical methods.

The study was conducted using design-of-experiments (DoE) approaches.

For the oxidation step, a five-factor, five-level experimental design (25 runs) was implemented. The investigated factors were: X1 – treatment time (min), X2 – current (A), X3 – circulation flow rate (L/h), X4 – initial Fe^{2+} concentration (g/L), and X5 – temperature (°C).

For the neutralization and precipitation step, a Taguchi L16 orthogonal array was used. Two factors were studied time and current each at four levels (6, 8, 10, 12 min; and 2.0, 2.5, 3.0, 3.5 A, respectively).

Results and discussion. Based on the results of the five-factor experiment, partial response function plots were constructed (Figures 1.1–1.5). In all cases, a semi-automatic procedure was used to select the best-fitting approximation function by minimizing the mean squared error.

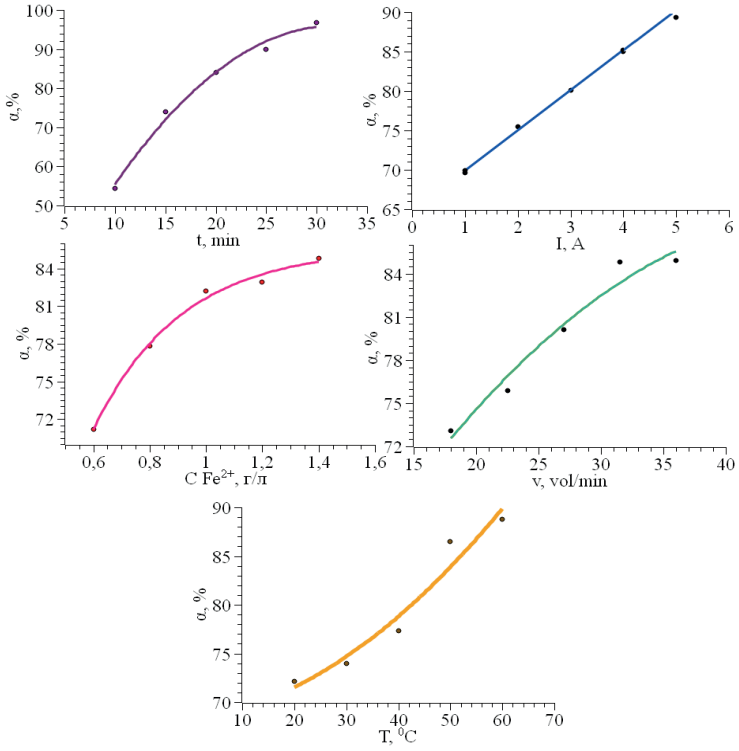

Figure 1. Dependence of iron oxidation degree on various parameters

The dependence of Fe^{2+} oxidation degree on time shows an increasing asymptotic trend (growth with gradual saturation). At the beginning, the oxidation degree increases

almost linearly as electric charge passes through the system; however, over time the rate of increase decreases and the curve approaches a plateau. This behavior is explained by Faraday's law: the amount of oxidized species is proportional to the charge passed. Therefore, at the start of the process the fraction of oxidized ions rises rapidly. As the process proceeds, the Fe^{2+} concentration in solution decreases, and the oxidation rate correspondingly declines. Consequently, the maximum oxidation degree can be achieved at sufficiently long electrolysis times, approaching complete conversion.

The dependence of oxidation degree on current is generally close to linear: as the current increases, the fraction of oxidized ions rises almost proportionally. This follows directly from Faraday's law for electrolysis: at a fixed time, the number of electrons transferred and thus the amount of Fe^{2+} oxidized is proportional to the current. The higher the current, the more equivalents of iron are oxidized per unit time. At very high currents, the curve may become slightly less steep or deviate from ideal linearity due to reactant depletion near the electrode surface, increased polarization, or competing side reactions such as oxygen evolution, which can limit further increases. Overall, increasing current enhances the Fe^{2+} oxidation degree up to the practical efficiency limit of the process. However, operation at higher currents typically reduces current efficiency and therefore lowers overall energy efficiency.

According to Figure 1.3, all else being equal, a higher initial Fe^{2+} concentration results in a lower fraction of the ion being oxidized. This is because, at a fixed time and current, the total number of moles oxidized is determined by the charge passed; when the initial amount of Fe^{2+} increases, the same charge corresponds to a smaller relative conversion. In other words, at higher Fe^{2+} loadings, the same current oxidizes a smaller portion of the available Fe^{2+}. As a result, the oxidation degree (expressed as a percentage of the initial amount) decreases with increasing initial concentration. To maximize the fraction of oxidized ions, it is therefore reasonable to use a moderate or low initial Fe^{2+} concentration (for a given charge input). However, it should be noted that to maximize the absolute amount of Fe oxidized, operating at higher concentrations can still be advantageous.

As shown in Figure 1.4, the circulation rate (or mixing intensity) affects the delivery of Fe^{2+} ions to the anode surface. The dependence of oxidation degree on circulation rate (expressed as the number of anode-chamber working volumes per hour) typically shows an increasing trend with saturation: as mixing becomes more intense, the oxidation degree increases markedly, but the effect gradually levels off at sufficiently high circulation rates. The main reason is the role of mass transport of ferrous ions. Under weak mixing, the oxidation rate is limited by diffusion of Fe^{2+} to the anode, and part of the applied current may be consumed by side reactions. More intense mixing reduces the diffusion-layer thickness and homogenizes ion concentrations throughout the electrolyte volume, thereby improving Fe^{2+} oxidation efficiency. At very high circulation rates, further improvements become marginal because mass transfer is no longer the rate-limiting step. Therefore, better electrolyte mixing (within practical limits) leads to a higher Fe^{2+} oxidation degree; an optimal condition is a sufficiently high circulation rate that ensures uniform supply of Fe^{2+} to the electrodes.

As shown in Figure 1.5, increasing the electrolyte temperature has a beneficial effect on the Fe^{2+} oxidation degree. The dependence is increasing and often becomes steeper with temperature (approaching an exponential-like rise). This can be attributed to accelerated electrochemical reaction kinetics at higher temperatures. As a result, Fe^{2+} oxidation proceeds more efficiently and reaches higher conversion within the same processing time. In addition, elevated temperature may increase the solubility of possible by-products and decrease electrolyte resistance, thereby improving charge transfer. The highest oxidation degree is achieved at the upper end of the investigated temperature range, provided that electrolyte stability is maintained and no adverse side effects occur. At temperatures above 40°C, the increased conversion may also be partly associated with a possible chemical reaction between Fe^{2+} and nitrate ions, yielding Fe^{3+} and nitrogen oxides.

The calculated reaction order decreases monotonically from 1.34 at 20°C to 0.40 at 60°C. This trend indicates a change in the rate-controlling step as the temperature increases.

Kinetic parameters derived using the differential van't Hoff method reveal two key features. The rate constant k increases exponentially with temperature, showing a pronounced jump (almost tenfold) between 40°C and 50°C. The apparent activation energy calculated in the 20-40°C range is 94.8 kJ/mol, a value typical of processes controlled by the intrinsic electrochemical reaction rate.

In contrast, the activation energy estimated for the 50-60°C range is much lower, 17.9 kJ/mol. Activation energies of 15-25 kJ/mol are characteristic of diffusion-controlled regimes, where the overall rate is limited by the transport of reactants to the electrode surface.

Current efficiency varied over a wide range. The lowest values were observed at higher current (or current density), and vice versa; moreover, current efficiency increased with temperature. The minimum current efficiency was recorded in experiment 20 and was 6.7%, whereas the maximum was observed in experiment 6 and reached 70.9%.

Statistical analysis confirmed the high significance of all partial response functions ($R > 0.99$), which enabled the derivation of an adequate generalized equation ($R = 0.90$; $t\_R = 20.33$) of the following form:

$$Y_{\Pi} = \frac{1}{79{,}8^4} * (\,9{,}5999 + 5{,}4311 * x - 0{,}0854 * x^2) * \\ *(4{,}77 * \mathrm{x} + 65{,}47)*(\,48{,}3599 + 1{,}6555 * \mathrm{x} - 0{,}0172 * x^2)* \\ *(86{,}0759 * (1 - e^{-2{,}938 * x}))*(\,68{,}0799 + 0{,}0761 * \mathrm{x} + 0{,}0047 * x^2) \quad (1)$$

Another important aspect that requires further development is the neutralization of unreacted acid followed by precipitation of accompanying impurities. Using non-regenerable reagents such as sodium hydroxide increases operating costs and generates additional waste streams. In this work, magnesium oxide in the form of a slurry is

proposed as the neutralizing agent. However, this approach has inherent limitations because the low solubility of MgO and $Mg(OH)_2$ makes neutralization a heterogeneous process, unlike neutralization with aqueous NaOH.

As the experiments showed, when the residual acid concentration is still high, the reaction between MgO particles and the acid proceeds without significant difficulties. However, as acidity decreases and the system approaches the pH at which iron ions hydrolyze, the local acidity at the MgO particle–solution interface becomes lower than in the bulk. As a result, iron hydroxide precipitates on the MgO surface, forming a blocking layer that passivates the particles and halts the process. Consequently, additional MgO is required for complete neutralization and impurity removal, and the unreacted fraction inevitably ends up in the solid residue. To overcome this limitation, a combined neutralization–precipitation strategy was investigated. Specifically, primary neutralization to pH 0.5-1 was performed using MgO, followed by electrochemical precipitation in an electrolyzer with separated electrode compartments.

Purification of the magnesium nitrate solution from Fe^{3+}, Al^{3+}, and Ca^{2+} ions by electrolysis in a divided-cell configuration was examined. Hydrogen evolution at the cathode leads to a local increase in pH in the catholyte. As pH rises, the corresponding hydroxides precipitate sequentially: first $Fe(OH)_3$, then $Al(OH)_3$, and only at substantially higher pH, $Ca(OH)_2$. The solubility products of these hydroxides are approximately 6.3×10^{-38}, 1.9×10^{-33}, and 7.9×10^{-6}, respectively; therefore, iron hydroxide precipitates first, whereas calcium hydroxide precipitates last.

Based on the Taguchi L16 design, a linear regression model was obtained to describe the purification degree (Y, %) as a function of time (t, min) and current (I, A):

$$Y = 30.02 + 4.054*t + 4.35*I \quad (2)$$

The model shows good predictive performance (adjusted R2 = 82.9%). The ANOVA results and regression coefficients are summarized in Table 1.

Table 1 – ANOVA results and regression coefficients for the precipitation model.

Factor	DF	Adj MS	F-Value	P-Value	Coef	T-Value	P-Value
Regression	2	704.72	37.41	0.000	-	-	-
Time (t)	1	1314.95	69.80	0.000	4.054	8.35	0.000
Current (I)	1	94.48	5.02	0.043	4.350	2.24	0.043
Error	13	18.84	-	-	-	-	-
Intercept	-	-	-	-	30.02	4.30	0.001

ANOVA indicates that both factors are statistically significant ($p < 0.05$). However, the F-value for time (69.80) is an order of magnitude higher than that for current (5.02). This clearly shows that electrolysis time is the dominant factor governing the purification degree, whereas the applied current has a smaller, although positive, effect.

The Taguchi analysis (Table 2) corroborated the conclusions drawn from ANOVA.

Table 2 – Response means (Y, %) at different factor levels.

Level	Time (min)	Current (A)
1 (6 min / 2.0 A)	68.05	76.02
2 (8 min / 2.5 A)	72.40	76.22
3 (10 min / 3.0 A)	81.26	79.40
4 (12 min / 3.5 A)	92.12	82.20
Difference (Delta)	24.07	6.19
Rank	1	2

The largest Delta was observed for the time factor (Rank 1), confirming its dominant influence. The optimal conditions for achieving maximum purification correspond to the highest levels of both factors: 12 min and 3.5 A.

The electrochemical approach demonstrated high purification efficiency for magnesium nitrate solutions. The regression model adequately describes the process (R^2 = 85.2%), enabling optimization of operating parameters to achieve complete purification at minimal energy consumption. Considering that 100 mL of solution was treated in the experiments and the average cell voltage was 5.4 V, achieving complete purification requires 37.8 kWh of electricity per 1 m^3 of solution.

Electrodialysis performance was evaluated at currents of 1, 2, and 3 A. The time-dependent decrease in Mg^{2+} concentration in the diluate is shown in Figure 2.

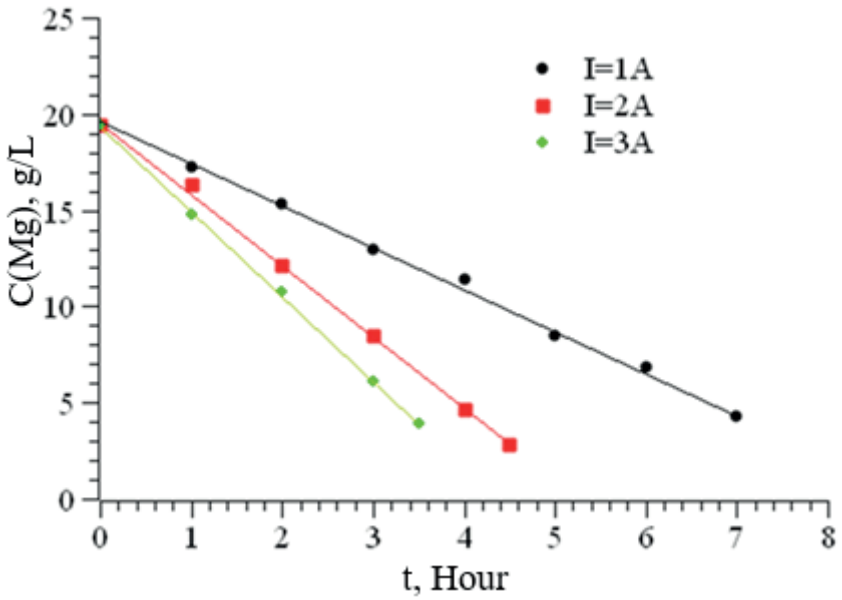

Figure 2 – Decrease in magnesium concentration in the diluate at different current values

The key techno-economic indicators (TEI) of the process, calculated on the basis of the experimental data, are presented in Table 3.

Table 3. Summary TEI for electrodialytic concentration.

Indicator	I = 1 A	I = 2 A	I = 3 A
Duration, h	7.0	4.5	3.5
Average voltage,, V	3.01	3.58	4.2
Demineralization rate, g/(L·h)	2.17	3.70	4.20
Current efficiency, %	95.6%	81.6%	61.8%
Energy consumption per 1 m3 of solution, kWh/m^3	52.6	80.6	110.3
Specific energy consumption per 1 kg of Mg, kWh/kg	3.46	4.84	7.50

The TEI analysis reveals a key technological trade-off between throughput and efficiency:

Mode at 1 A (efficient): delivers the highest current efficiency (95.6%) and the lowest specific energy consumption (3.46 kWh/kg Mg). However, it is the slowest operating mode.

Mode at 3 A (fast): provides the highest demineralization rate (4.20 g/(L·h)), but the current efficiency decreases to 61.8%, while the energy required to transfer 1 kg of Mg increases by more than twofold (7.50 kWh/kg).

The decrease in current efficiency at higher currents is attributed to an increase in cell voltage and intensification of side reactions, primarily water splitting, where H^+ and OH^- ions begin to compete with salt ions for charge transport.

To assess the economic feasibility of electrodialysis, its energy consumption was compared with conventional thermal evaporation. Task: concentrate 1 m^3 of solution by a factor of 2, i.e., remove 500 kg of water. The specific latent heat of water vaporization is 2260 kJ/kg, which corresponds to a theoretical minimum of 1.13×10^6 kJ (≈313.9 kWh) for removing 500 kg of water.

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$$E_{вып} = \frac{500kg*2260kJ/kg}{3600\frac{kJ}{kW}*h} = 313.8 \text{ kWh} \quad (3)$$

The comparison shows that the energy required for thermal evaporation is 5.96 times higher than that for electrodialysis in the optimal 1 A mode. This demonstrates the clear economic advantage of electrodialysis for this application.

Conclusion. In this study, an integrated hydrometallurgical flowsheet for processing nitrate solutions obtained from leaching asbestos-industry wastes was developed and experimentally validated.

Electrochemical oxidation of Fe(II) to Fe(III) was shown to achieve conversions above 98%. Kinetic analysis and activation-energy calculations indicated a shift in the rate-controlling step at temperatures above 40°C, from kinetic control to a diffusion-controlled regime.

A combined neutralization and impurity precipitation method was proposed to overcome precipitant passivation. The approach enables >99% purification of the solution at a specific energy consumption of 38.1 kWh/m^3, with process time identified as the dominant factor.

Electrodialytic concentration of the purified magnesium nitrate solution was demonstrated to be approximately six times more energy-efficient and economically justified than conventional evaporation, achieving a current efficiency of 95.6% under the optimal operating mode.

Overall, the proposed technology represents an environmentally friendly and economically promising alternative that transforms hazardous asbestos wastes into a valuable product within the circular economy framework.

References

Pira E., Donato F., Maida L., Discalzi G. (2018) Exposure to asbestos: past, present and future, J Thorac Dis., 10:237-245. DOI:10.21037/jtd.2017.10.126 (in Eng.).

Li X., Su X., Wei L., Zhang J., Shi D., Wang Z. (2024) Assessing trends and burden of occupational exposure to asbestos in the United States: a comprehensive analysis from 1990 to 2019, BMC Public Health, 24:1404. DOI:10.1186/s12889-024-18919-7 (in Eng.).

Petrović E.K. (2017) Materials for a Healthy, Ecological and Sustainable Built Environment, Woodhead Publishing: Sawston, UK, Persisting issues with the most recognized building material health risks: Lead and asbestos. — P. 155–174. DOI:10.1016/B978-0-08-100707-5.00006-X (in Eng.).

Kratzke P., Kratzke R.A. (2018) Asbestos-related disease, Journal of Radiology Nursing, 37(1):21–26. DOI:10.1016/j.jradnu. 2017.12.003 (in Eng.).

Chen J., Wang C., Zhang J., Zhang T., Liang H., Mao S., Li H., Wang Z. (2022) A comparative study of the disease burden attributable to asbestos in Brazil, China, Kazakhstan, and Russia between 1990 and 2019, BMC Public Health, 22:2012. DOI:10.1186/s12889-022-14437-6 (in Eng.).

Baigenzhenov O.S., Chepushtanova T.A., Altmyshbayeva A.Zh., Temirgali I.A., Maldybayev G., Sharipov R.H., Altaibayev B.T., Dagubayeva A.T. (2024) Investigation of thermodynamic and kinetic regularities of asbestos waste leaching processes, Results in Engineering, 21:102000. DOI:10.1016/j. rineng. 2024.102000 (in Eng.).

Zhu Z., Yu Z., Yi F., He J., Zhang H.D., Zhu Z., Zhao G., Tiwari S.K. (2025) Cleaner production techniques in magnesium alloy recycling: optimizing processes for environmental sustainability, Journal of Alloys and Compounds, 1026:180083. DOI:10.1016/j.jallcom.2025. —180083 p. (in Eng.).

Beglaryan H., Isahakyan A., Zulumyan N., Melikyan S., Terzyan A. (2023) A study of magnesium dissolution from serpentinites composed of different serpentine group minerals, Minerals Engineering, 201:108171. DOI:10.1016/j.mineng.2023.108171 (in Eng.).

Sirota V., Selemenev V., Kovaleva M., Pavlenko I., Mamunin K., Dokalov V., Yapryntsev M. (2018) Preparation of crystalline $Mg(OH)_2$ nanopowder from serpentinite mineral, International Journal of Mining Science and Technology, 28(3):499–503. DOI:10.1016/j.ijmst.2017.12.018 (in Eng.).

Souza B., Souza R., Santos I., Brocchi E. (2020) $MgSO_4$ carbothermic reductive decomposition to produce a highly reactive MgO powder, Journal of Materials Research and Technology, 9(2):1847–1855. DOI:10.1016/j.jmrt.2019.12.017 (in Eng.).

Zhao D., Ma B., Wang C., Zhang Y., Shi S., Chen Y. (2022) Investigation of the thermal behavior of $Mg(NO_3)_2 \cdot 6H_2O$ and its application for the regeneration of HNO_3 and MgO, Chemical Engineering Journal, 433:133804. DOI:10.1016/j.cej.2021.133804 (in Eng.).

Mao Y., Chai X., Zhong M., Zhang L., Zhao P., Kang Y., Guo J., Yang X. (2022) Effects of nitrogen and magnesium nutrient on the plant growth, quality, photosynthetic characteristics, antioxidant metabolism, and endogenous hormone of Chinese kale (Brassica albograbra Bailey), Scientia Horticulturae, 303:111243. DOI:10.1016/j.scienta.2022.111243 (in Eng.).

Grigoryan I.V., Kompantseva E.V. (2005) Developing methods of preparation and quantitative analysis of magnesium aspartate, Pharmaceutical Chemistry Journal, 39:548–550. DOI:10.1007/s11094-006-0018-6 (in Eng.).

Lu S. Method for producing magnesium citrate. CN Patent 102285877A, December 21, 2011. (in Eng.).

Rixin X. Tao L. Method for preparing magnesium malate. CN Patent 104355989A, February 18, 2015 (in Eng.).

Wenkun Z. Preparation method of magnesium glycinate chelate. CN Patent 103626669A, March 12, 2014 (in Eng.).

Blancquaert L., Vervaet C., Derave W., (2019) Predicting and testing bioavailability of magnesium supplements, Nutrients, 11:1663, 1–17. DOI:10.3390/nu11071663 (in Eng.).

Turck D., Castenmiller J., De Henauw S., Hirsch-Ernst K.I., Kearney J., Knutsen H.K., Maciuk A., Mangelsdorf I., McArdle H.J., Naska A., Pelaez C., Pentieva K., Siani A., Thies F., Tsabouri S., Vinceti M., Dean T., Engel K.H., Heinonen M., Marchelli R., Neuhauser-Berthold M., Poulsen M., Poting A., Sanz Y., Schlatter J.R., Germini A., van Loveren H. (2018) Magnesium citrate malate as a source of magnesium added for nutritional purposes to food supplements, EFSA Journal, 16(12):5484. DOI:10.2903/j.efsa.2018.5484 (in Eng.).

Ivanov N.S., Kholkin O.S., Abilmagzhanov A.Z., Adelbayev I.E., Oparin S.K., Ivanova N., Kudryashov V. (2025) Nitric acid leaching for magnesium extraction from asbestos ore waste: from DoE to predictive modeling and cost-efficient optimization, Molecules, 30:4396. DOI:10.3390/molecules30224396 (in Eng.).

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