

<https://doi.org/10.51301/ejsu.2026.i1.01>

## A small-sized continuous reactor system for extracting nickel, cobalt and iron from stale tailings

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**Abstract.** The increasing accumulation of stale tailings from mining operations poses both environmental risks and opportunities for the recovery of valuable metals. This study focuses on the development, additive manufacturing, and experimental validation of a small-scale continuous reactor system for the extraction of nickel, cobalt, and iron from stale pyrite tailings at the Sokolovsko-Sarbaisky Mining and Processing Plant (Kazakhstan). The reactor system was fabricated using additive manufacturing (3D printing) with PET-G polymer, allowing for rapid prototyping, modular assembly, chemical resistance, and cost-effective production. The system comprises three sequentially connected reactors operating in continuous flow. Reagent and slurry feeding were conducted using peristaltic pumps, while a stepper-motor-driven mechanical stirrer ensured homogeneous mixing. Temperature was controlled by circulating a heat-transfer fluid through integrated heat-exchange channels, enabling stable operation over 20-120°C. Before leaching, stale tailings were subjected to oxidative roasting in a fluidized-bed furnace at 650-700°C for 1 hour, which facilitated the decomposition of sulfides into oxides. Subsequent leaching experiments were conducted with sulfuric acid concentrations ranging from 25 to 175 g/dm<sup>3</sup>, varying residence times, and controlled thermal conditions. Optimal parameters were established as 100 g/dm<sup>3</sup> H<sub>2</sub>SO<sub>4</sub>, 100°C, and 120 minutes, resulting in recoveries of 93.01% for Ni and 91.49% for Co, with moderate Fe dissolution of 64.4%. The results confirm that the designed continuous reactor system provides reproducible hydrometallurgical performance, stable process control, and scalability potential. This approach highlights the combined advantages of continuous-flow chemistry and additive manufacturing in processing low-grade, environmentally challenging raw materials.

**Keywords:** continuous reactor; additive manufacturing; nickel; cobalt; iron; leaching; stale tailings; hydrometallurgy.

Received: 17 September 2025

Accepted: 14 February 2026

Available online: 28 February 2026

### 1. Introduction

The global mining industry plays a pivotal role in supplying raw materials that underpin modern technologies, from energy storage devices and renewable energy infrastructure to advanced alloys and everyday consumer products. However, alongside the production of concentrates and metals, mining and mineral processing operations generate enormous amounts of waste, particularly tailings. These fine-grained residues are usually stored in impoundments or waste dumps, which pose long-term environmental and social challenges. Tailings storage facilities have been associated with catastrophic dam failures, leaching of toxic elements, dust emissions, and land occupation. At the same time, tailings frequently contain appreciable amounts of valuable metals that were not fully recovered during initial processing due to technological or economic limitations at the time [1].

Kazakhstan, as one of the major producers of iron ore, copper, and polymetallic ores, faces similar challenges. The Sokolovsko-Sarbaisky Mining and Processing Plant (SSGPO) is among the largest producers of iron ore in the

country. Over the course of its decades-long operation, it has generated substantial volumes of tailings that have become stale. These tailings contain residual concentrations of nickel (Ni), cobalt (Co), and iron (Fe), along with associated gangue minerals. Historically, the recovery of Ni and Co was not prioritized in such operations, leading to their accumulation in waste storage. As global demand for Ni and Co increases, particularly due to their role in lithium-ion batteries and clean energy technologies, the reprocessing of stale tailings becomes both a strategic and environmentally necessary initiative [2].

Hydrometallurgy has long been recognized as a viable method for extracting metals from low-grade ores, concentrates, and secondary raw materials. Compared to pyrometallurgical methods, hydrometallurgical processes generally operate at lower temperatures, produce fewer gaseous emissions, and allow for selective recovery of metals through leaching, solvent extraction, and ion exchange [3]. Sulfuric acid is the most widely used leaching reagent for Ni and Co, especially when combined with oxidative pretreatments.

Oraby et al. [1] demonstrated that flotation tailings rich in Ni and Co sulfides could be successfully processed using glycine–ammonia systems, achieving metal recoveries above 85–90%. Likewise, sulfuric acid leaching is effective for metallurgical slags, with hydrogen peroxide serving as an auxiliary oxidant to enhance dissolution of Ni and Co [2].

Pretreatment is often essential to improve the solubility of refractory minerals. Roasting transforms sulfides, silicates, and refractory oxides into more leachable forms. Reduction roasting, in particular, has been applied to oxidized nickel ores, with temperatures between 400 and 850°C resulting in nearly complete Ni recovery after sulfuric acid leaching [3]. In the case of cobalt-bearing pyrite, oxidative roasting reduced sulfur content and facilitated Co recovery by producing soluble oxide phases [4]. Such approaches demonstrate that a combination of thermal and hydrometallurgical processes is necessary to achieve efficient extraction from complex tailings.

Despite the maturity of hydrometallurgical techniques, most laboratory and pilot studies rely on batch systems, which present limitations in scalability, reproducibility, and process control. Continuous flow systems address these challenges by maintaining steady-state conditions, reducing reagent fluctuations, and enabling tighter control of temperature, pH, and residence time. Panda et al. [5] reviewed the hydrometallurgical recovery of valuable metals from industrial wastes, highlighting the advantages of continuous processes in terms of efficiency and energy consumption. Continuous stirred-tank reactors (CSTRs), plug-flow reactors, and tubular reactors have been successfully applied in copper heap leaching, rare earth element recovery, and nickel hydrometallurgy, yielding improved yields and reduced reagent use compared to batch operations.

Parallel to advances in process engineering, new approaches to equipment design are reshaping laboratory-scale experimentation. Additive manufacturing, commonly known as 3D printing, has emerged as a disruptive technology that enables the rapid fabrication of complex geometries, modular components, and chemically resistant reactors at a relatively low cost. Kitson et al. [6] introduced the concept of “reactionware”, demonstrating how 3D-printed reactors could be configured as modular flow systems for organic synthesis. Beauchamp et al. [7] extended these concepts to photochemical reactions, highlighting the ability of 3D-printed reactors to control reaction pathways and to enable scale-up. Moreover, the article's author designed and utilized a reactor system to produce metronidazole derivatives [8].

The advantages of 3D printing for reactor design are manifold. First, rapid prototyping enables researchers to test and refine designs quickly, eliminating the need for expensive machining. Second, features such as mixing chambers, heat exchangers, or sensor channels can be directly embedded into the printed structure, eliminating the need for post-processing. Third, new materials such as PET-G, polypropylene, and polymer–ceramic composites provide resistance to acidic and oxidative environments [9, 10]. Nordin et al. [9] fabricated corrosion-resistant 3D-printed microfluidic devices for electrochemical studies, demonstrating their durability under aggressive chemical conditions. Liravi and Toyserkani [10] reported on polymer–ceramic composites tailored for additive manufacturing of chemical reactors, enabling operation under harsher conditions than conventional polymer devices.

While applications of 3D-printed reactors in hydrometallurgy are still rare, examples from related fields illustrate their potential. Chisholm et al. [11] designed 3D-printed reactors for nanoparticle synthesis, achieving precise size control unattainable in conventional batch reactors. Chen et al. [12] developed 3D-printed flow reactors for polymer synthesis, demonstrating reproducibility and scalability. These studies suggest that additive manufacturing can bridge the gap between laboratory research and industrial applications by offering modular, adaptable reactor systems.

Integrating additive manufacturing with continuous hydrometallurgical processing creates a powerful synergy. Continuous operation provides process stability and scalability, while 3D printing ensures flexibility, cost reduction, and rapid design iteration. This integration is particularly promising for the treatment of low-grade ores and stale tailings, where conventional equipment may be too costly or inflexible. Furthermore, compact 3D-printed reactors are well-suited for decentralized operations, enabling in situ processing at mine sites and reducing transportation of hazardous wastes.

The present research seeks to explore this intersection by developing a small-scale, continuous reactor system fabricated via 3D printing and applying it to the recovery of Ni, Co, and Fe from stale tailings of the Sokolovsko-Sarbaisky Mining and Processing Plant. The study involves designing reactor modules with integrated mixing and heating, applying oxidative roasting as pretreatment, and optimizing sulfuric acid leaching conditions. The outcomes are expected to demonstrate not only the feasibility of additive manufacturing in hydrometallurgy but also its potential to provide scalable, sustainable solutions for tailings reprocessing.

## 2. Materials and methods

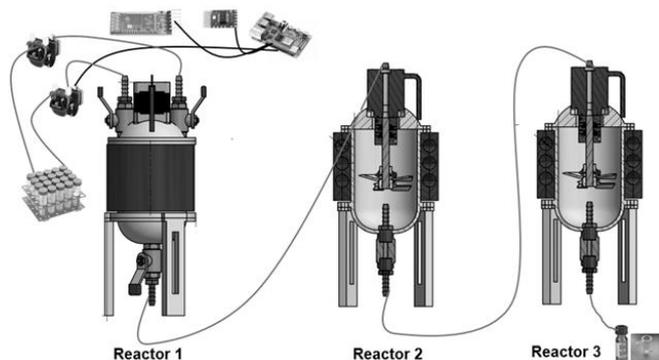
### 2.1. Raw materials and reagents

As the feedstock, a roasted pyrite concentrate was used, obtained from the stale tailings of the Sokolovsko-Sarbaisky Mining and Processing Plant (SSGPO, Kazakhstan). The material contained mainly iron oxides and sulfides with minor amounts of nickel (0.10 wt.%) and cobalt (0.21 wt.%). Sulfuric acid (H<sub>2</sub>SO<sub>4</sub>, analytical grade) was applied as the primary leaching reagent in concentrations ranging from 25 to 175 g/dm<sup>3</sup>. All chemicals used in the experiments were of analytical purity (“hch”, “chda”, “osch”) and suitable for spectroscopic analysis. Deionized water was used to prepare all solutions.

### 2.2. Design and additive manufacturing of the continuous reactor system

#### 2.2.1. Design of the reactor system

The system consists of three reactors (Figure 1) connected in series, operating in continuous flow mode. Feeding of solid and liquid reagents was carried out using peristaltic pumps, and a stepper motor-driven mechanical stirrer ensured thorough mixing. Temperature control was achieved by circulating a heat-transfer fluid through integrated channels within the reactor body, enabling stable operation over a range of 20 to 120°C. The configuration enables the continuous introduction of leaching solution and tailings slurry, efficient mixing, and collection of the product solution.



**Figure 1.** Design of a continuous reactor system for extracting nickel and cobalt from stale tailings

In Reactor 1, roasted pyrite concentrate and a sulfuric acid solution are introduced into the system via peristaltic pumps, where initial mixing and slurry preparation occur under controlled temperature and agitation conditions. Reactor 2 serves as the central unit for acid leaching, equipped with a mechanical stirrer to ensure homogeneous mixing and with integrated heat-exchange elements to maintain a stable thermal regime. Reactor 3 represents the final stage of the process, where leaching reactions are completed, yielding a pregnant solution containing nickel and cobalt ions, which is collected in vials for further analysis and separation.

### 2.2.2. Additive manufacturing of the reactor system

A small, continuous reactor system for extracting nickel and cobalt from stale tailings was designed and manufactured using additive manufacturing (3D printing). The reactor body, lid, stand, stirrer, and heat-exchanger elements were fabricated from PET-G polymer on a Bambu Lab X1 3D printer. Printing parameters were set as follows: nozzle temperature 240-250°C, bed temperature 70-80°C, layer height 0.2-0.28 mm, and infill density 20-40%. After printing, the supports were removed, the surfaces were cleaned, and the parts were assembled into a modular reactor unit.

### 2.2.3. Manufacturing of the reactor components

The manufacturing of reactor system components (reactor lid, stand, reactor body, heat exchanger elements, and stirrer) is carried out as follows (Figure 2). At the initial stage, 3D models of all parts are designed in CAD software, taking into account their structural features, and then exported in STL or 3MF format.



**Figure 2.** AM-based reactor components (main body with heat exchanger and mixer)

The reactor body, lid, stand, stirrer, and heat-exchanger elements were fabricated from PET-G polymer on a Bambu Lab X1 3D printer.

Next, printing parameters are set in Bambu Studio: extruder temperature 240-250°C, bed temperature 70-80°C, layer height 0.2-0.28 mm, infill density 20-40%, and printing speed 80-120 mm/s. Supports are enabled for parts with overhanging elements (such as the lid and stand), and a brim is applied to improve bed adhesion.

After loading the PET-G filament into the printer, automatic calibration is performed, and printing begins. The reactor body is produced as a cylindrical part with uniform cooling to prevent warping, the lid is printed with supports and mounting holes, the stand with vertical columns is printed at a lower speed for stability, the stirrer is manufactured as a separate part to be later connected to a stepper motor and controller, and the heat exchanger elements are produced with high precision to ensure tight connections.

After printing, post-processing is performed, including support removal, surface cleaning, and optional sanding or heat treatment to smooth the layers (Figure 3).



**Figure 3.** AM-based continuous processing reactor system for the extraction of nickel and cobalt from stale tailings (1, 2 and 3 indicate the numbers of the respective reactors)

All parts are checked for dimensional accuracy, then assembled into a single structure: the body is fixed to the stand and lid with bolts, the stirrer is mounted and connected to a stepper motor via a controller for mixing operations, and the heat exchanger elements are installed. Cooling and heating of the reactor are achieved by circulating liquid through the system using peristaltic pumps.

### 2.3 Roasting and leaching procedure

Before leaching, the stale tailings were subjected to oxidative roasting in a fluidized bed furnace at 650-700°C for 60 minutes with an oxygen-enriched air supply (15% O<sub>2</sub>). The obtained calcine was cooled and fed into the continuous reactor system for sulfuric acid leaching.

Leaching was carried out at a solid-to-liquid (S/L) ratio of 1:2, with the slurry continuously circulated through the three-stage reactor unit. Process parameters included acid concentration of 25-175 g/dm<sup>3</sup>, temperature range of 20-120°C, and residence times of 15-240 minutes. Optimal leaching conditions were determined as 100 g/dm<sup>3</sup> H<sub>2</sub>SO<sub>4</sub>, 100°C, and 120 min, under which the maximum extractions of Ni and Co reached 93.01% and 91.49%, respectively.

## 2.4 Analytical methods

Titrimetric and spectrometric methods were used to determine the chemical composition of solid residues and leach solutions. The phase composition of the roasted samples was analyzed by X-ray diffraction (D8 Advance, Bruker) using Cu K $\alpha$  radiation (40 kV, 30 mA). The pH of the solutions was monitored using a pH-150MP pH meter with standard electrodes. Thermodynamic calculations and Pourbaix diagrams for the Ni-S-H<sub>2</sub>O and Co-S-H<sub>2</sub>O systems were generated using the Outotec HSC Chemistry 5 software package.

## 3. Results and discussion

The small-sized continuous reactor system fabricated via additive manufacturing was tested for the extraction of nickel and cobalt from roasted stale tailings of the Sokolovsko-Sarbaisky Mining and Processing Plant (SSGPO, Kazakhstan). The experimental work demonstrated that continuous leaching provides stable operating conditions, adequate mixing, and reproducible recovery of valuable metals.

### 3.1 Effect of sulfuric acid concentration

The concentration of sulfuric acid has a decisive effect on the leaching behavior of nickel, cobalt, and iron from thermally decomposed pyrite concentrate. Figure 4 shows the dependence of the extraction of Ni, Co, and Fe on the concentration of H<sub>2</sub>SO<sub>4</sub>.

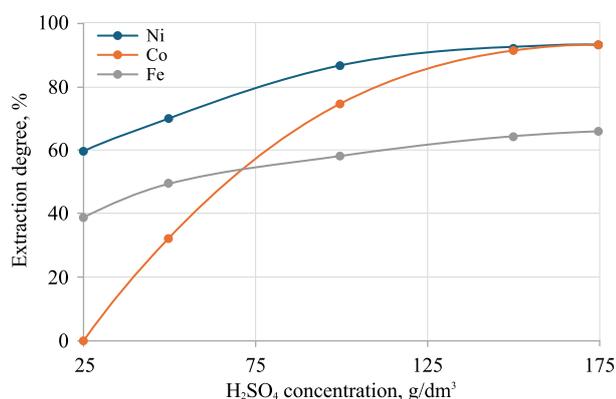


Figure 4. Dependence of the extraction of Ni, Co, and Fe on the concentration of H<sub>2</sub>SO<sub>4</sub>

At a low H<sub>2</sub>SO<sub>4</sub> concentration of 25 g/dm<sup>3</sup>, nickel extraction reaches about 59.6%, cobalt extraction is initially negligible, while iron extraction is around 39.1%. Increasing the acid concentration to 50 g/dm<sup>3</sup> enhances nickel recovery to 70.0%, cobalt to 32.5%, and iron to 50.0%. A pronounced improvement is observed in the 100-150 g/dm<sup>3</sup> range, where nickel extraction increases to 86.7-92.0%, cobalt to 75.0-91.5%, and iron to 58.0-64.4%.

Further increasing the acid concentration up to 175 g/dm<sup>3</sup> results in a saturation effect: Ni and Co recoveries reach about 93%, while Fe extraction increases only slightly to 66.0%. Thus, the optimal acid concentration lies in the range of 100-150 g/dm<sup>3</sup>, ensuring maximum recoveries of nickel and cobalt while maintaining moderate iron dissolution. This creates favorable conditions for subsequent selective separation of the target metals, followed by solvent extraction or precipitation.

### 3.2 Effect of leaching time

The effect of leaching time on the dissolution of nickel, cobalt, and iron from roasted stale tailings was investigated over a range of 5-240 minutes. Figure 5 shows the time dependence of the extraction of Ni, Co, and Fe.

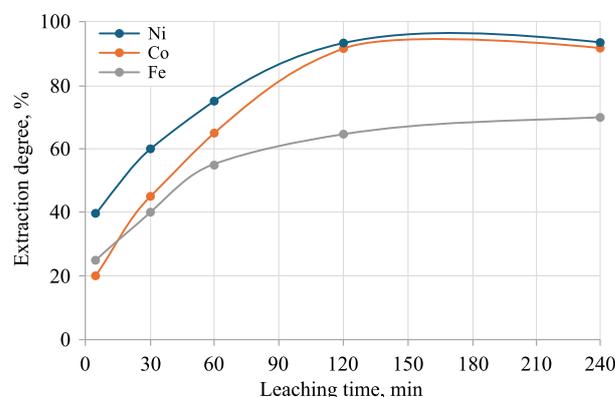


Figure 5. Dependence of the extraction of Ni, Co, and Fe on leaching time

The results show that nickel extraction increases rapidly from 40% at 5 minutes to 75% at 60 minutes, reaching a maximum of 93.0% at 120 minutes. After this, only a slight increase to 93.5% is observed at 240 minutes, indicating that equilibrium has been reached. Cobalt follows a similar trend, with lower initial rates: 20% at 5 minutes, increasing to 65% at 60 minutes. At 120 minutes, the maximum extraction of 91.5% is achieved, with only marginal improvement to 92% at 240 minutes. Iron dissolution is a gradual and continuous process, increasing from 25% at 5 minutes to 64.4% at 120 minutes, and reaching 70% at 240 minutes. These results indicate that the optimal leaching time is 120 minutes, at which nickel and cobalt recoveries exceed 91% while iron dissolution remains moderate. Prolonged leaching beyond this time provides no significant improvement in Ni and Co extraction but increases Fe dissolution, thereby complicating downstream purification and separation processes.

### 3.3 Effect of temperature

The effect of temperature on the extraction of nickel, cobalt, and iron from roasted stale tailings was investigated in the range of 20-120°C. Figure 6 shows the temperature dependence of the extraction of Ni, Co, and Fe.

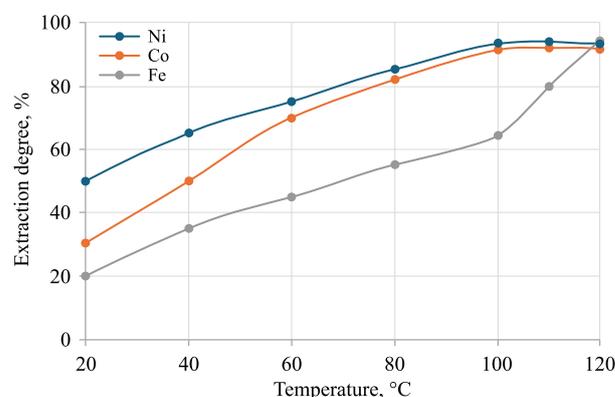


Figure 6. Dependence of the extraction of Ni, Co, and Fe on temperature

At low temperatures (20–40°C), nickel and cobalt recoveries were limited to 50–65% and 30–50%, respectively, while iron dissolution remained at 20–35%. Increasing the temperature to 60–80°C significantly enhanced metal recovery, with nickel extraction rising to 75–85%, cobalt to 70–82%, and iron to 45–55%. The maximum recoveries of nickel (93.0%) and cobalt (91.5%) were achieved at 100°C, accompanied by moderate iron dissolution of 64.4%. Further temperature increases to 110–120°C resulted in only marginal improvements in nickel and cobalt extraction (up to 93.3% and 92.2%, respectively), but were accompanied by a sharp rise in iron dissolution, ranging from 80% to 94.2%. These results indicate that the optimal leaching temperature lies between 100 and 110°C, where high recoveries of nickel and cobalt are achieved while maintaining iron dissolution at a manageable level. Exceeding this temperature range reduces process selectivity and complicates downstream purification due to excessive iron content in the pregnant solution.

#### 4. Conclusions

The study successfully demonstrated the feasibility of fabricating a small-scale continuous reactor system by additive manufacturing (3D printing) and applying it to the hydrometallurgical recovery of nickel, cobalt, and iron from stale tailings of the Sokolovsko-Sarbaisky Mining and Processing Plant.

Pretreatment of the tailings by oxidative roasting significantly improved the subsequent acid leaching efficiency. The optimal operating conditions 100 g dm<sup>-3</sup> H<sub>2</sub>O<sub>4</sub>, 100 °C, and 120 min of residence time yielded recoveries of 93.0 % Ni and 91.5 % Co with moderate Fe dissolution (64.4 %). These results confirm the efficiency of combining thermal pretreatment with continuous sulfuric acid leaching. The research also demonstrated the practical advantages of additive manufacturing for the design of laboratory-scale hydrometallurgical equipment. The modular and cost-efficient 3D-printed system enables rapid prototyping, integration of multifunctional components, and straightforward scaling to pilot-plant operations.

Overall, the findings demonstrate that combining continuous-flow hydrometallurgy with additive manufacturing presents a sustainable technological approach for processing low-grade ores and tailings, promoting efficient resource utilization and minimizing environmental impact.

#### Author contributions

Conceptualization: SD; Data curation: ATK; Formal analysis: YSM; Funding acquisition: MOK; Investigation: MOK; Methodology: ATK; Project administration: ATK; Resources: ATK; Software: YSM; Supervision: YSM; Validation: ANM; Visualization: ATK; Writing – original draft: ATK; Writing – review & editing: SD. All authors have read and agreed to the published version of the manuscript.

#### Funding

This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan, grant number AP22783377.

#### Acknowledgements

The authors express their sincere gratitude to the editor and anonymous reviewers for their constructive comments and valuable suggestions, which have significantly improved the quality of this manuscript.

#### Conflicts of interest

The authors declare no conflict of interest.

#### Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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## Ескірген қалдықтардан никель, кобальт және темір алуға арналған шағын көлемді үздіксіз реакторлық жүйе

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**Андатпа.** Тау-кен жұмыстарынан ескірген қалдықтардың жинақталуының артуы экологиялық тәуекелдерді де, бағалы металдарды қалпына келтіру мүмкіндіктерін де тудырады. Бұл зерттеу Соколов-Сарыбай Тау-Кен Байыту комбинатының (Қазақстан) ескірген пирит қалдықтарынан никель, кобальт және темір өндіруге арналған шағын көлемді үздіксіз реакторлық жүйені әзірлеуге, қоспаларды өндіруге және тәжірибелік тексеруге бағытталған. Реактор жүйесі жылдам прототиптеуге, модульдік құрастыруға, химиялық төзімділікке және үнемді өндіріске мүмкіндік беретін PET-G полимерімен қоспа өндірісін (3d басып шығару) пайдалана отырып жасалған. Жүйе үздіксіз ағын жағдайында жұмыс істейтін бірізді қосылған үш реактордан тұрады. Реагенттер мен суспензияларды беру перистальтикалық сорғылардың көмегімен жүзеге асырылды, ал біртекті араластыру сатылы қозғалтқышпен басқарылатын механикалық араластырғышпен қамтамасыз етілді. Температура 20-120°C аралығында тұрақты жұмыс Істеуге Мүмкіндік Беретін интеграцияланған жылу алмасу арналары Арқылы жылу тасымалдағыш сұйықтықты айналдыру Арқылы бақыланды. Шаймалау алдында ескірген қалдықтар бір сағат ішінде 650-700°C температурада сұйық төсек пешінде тотықтырғыш қуыруға ұшырады, бұл сульфидтердің оксидтерге ыдырауын жеңілдетті. Кейінгі шаймалау тәжірибелері күкірт қышқылының концентрациясы 25-175 г/дм<sup>3</sup>, әр түрлі тұру уақыты және бақыланатын жылу жағдайлары бойынша жүргізілді. Оңтайлы параметрлер 100 г/дм<sup>3</sup> H<sub>2</sub>SO<sub>4</sub>, 100°C және 120 минут ретінде белгіленді, нәтижесінде Ni үшін 93.01% және Co үшін 91.49% қалпына келтірілді, Орташа Fe еруі 64.4% болды.%. Нәтижелер жобаланған үздіксіз реактор жүйесі қайталанатын гидрометаллургиялық өнімділікті, процесті тұрақты басқаруды және масштабталатын әлеуетті қамтамасыз ететінін растайды. Бұл тәсіл төмен сұрыпты және экологиялық тұрғыдан күрделі шикізатты өндеуде үздіксіз ағынды химия мен қоспаларды өндірудің біріктірілген артықшылықтарын көрсетеді.

**Негізгі сөздер:** үздіксіз реактор; қоспалар өндірісі; никель; кобальт; темір; сілтілеу; ескірген қалдықтар; гидрометаллургия.

## Малогабаритная реакторная система непрерывного действия для проведения извлечения никеля, кобальта и железа из лежалых ХВОСТОВ

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**Аннотация.** Растущее накопление залежалых хвостов горных работ создает как экологические риски, так и возможности для извлечения ценных металлов. Данное исследование посвящено разработке, аддитивному производству и экспериментальной проверке малогабаритной реакторной установки непрерывного действия, предназначенной для извлечения никеля, кобальта и железа из отработанных пиритных хвостов Соколовско-Сарбайского горно-обогатительного комбината (Казахстан). Реакторная система была изготовлена с использованием технологии аддитивного производства (3D-печати) с использованием полимера PET-G, что обеспечивает быстрое создание прототипов, модульную сборку, химическую стойкость и экономичное производство. Система состоит из трех последовательно соединенных реакторов, работающих в режиме непрерывного потока. Подача реагентов и суспензии осуществлялась с помощью перистальтических насосов, а однородное перемешивание обеспечивалось механической мешалкой с шаговым приводом. Температура регулировалась путем циркуляции теплоносителя по встроенным теплообменным каналам, что обеспечивало стабильную работу в диапазоне 20-120°C. Перед выщелачиванием залежалые хвосты подвергались окислительному обжигу в печи с псевдоожиженным слоем при температуре 650-700°C в течение одного часа, что способствовало разложению сульфидов на оксиды. Последующие эксперименты по выщелачиванию проводились

с концентрациями серной кислоты 25-175 г/дм<sup>3</sup>, различным временем выдержки и контролируемые тепловыми режимами. Были установлены оптимальные параметры: 100 г/дм<sup>3</sup> H<sub>2</sub>SO<sub>4</sub>, 100°C и 120 минут, в результате чего степень извлечения Ni составила 93.01%, Co – 91.49%, при умеренном растворении Fe – 64.4%. Результаты подтверждают, что разработанная система реакторов непрерывного действия обеспечивает воспроизводимые гидрометаллургические характеристики, стабильное управление процессом и возможность масштабирования. Такой подход подчеркивает преимущества непрерывного химического процесса и производства добавок при переработке низкосортного и экологически опасного сырья.

**Ключевые слова:** *реактор непрерывного действия; аддитивное производство; никель; кобальт; железо; выщелачивание; отработанные хвосты; гидрометаллургия.*

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