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CONTACTS

Phone: **+998 50 737 87 88**

Website: <https://ist-journal.uz>

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MINERALOGICAL OCCURRENCE OF RARE METALS IN THE INGICHKA DEPOSIT AND DEVELOPMENT OF TUNGSTEN EXTRACTION TECHNOLOGY

Shodiyev Abbos Ne'mat ugli

Karshi State Technical University, Karshi
Dean of the Faculty of Oil and Gas and Geology, Associate Professor
Email: abbos.shodiyev.91@mail.ru

Dononov Jasur Uralovich

Karshi State Technical University, Karshi
Department of Geology and Mining Engineering, Associate Professor
Email: jasurdononov@mail.ru

Safarov Gulomjon Tulaganovich

Master's Student, Department of Geology and Mining Engineering

Abstract. Growing global demand for tungsten and the gradual depletion of high-grade primary resources have increased interest in the utilization of technogenic mineral deposits. The mineralogical occurrence of tungsten-bearing minerals in the tailings of the Ingichka deposit was investigated, and the potential for tungsten recovery using combined beneficiation methods was evaluated. Mineralogical and granulometric analyses revealed that tungsten occurs predominantly as hubnerite, whereas scheelite is present in minor quantities. The highest tungsten content was identified in the fine particle-size fractions, particularly within the $-0.1-0.044$ mm size range. The applicability of radiometric separation, gravity concentration, and magnetic separation was assessed. The results demonstrated that radiometric separation is ineffective because of the low contrast characteristics of the material. In contrast, gravity concentration ensured efficient recovery of tungsten from high-density fractions, while subsequent magnetic separation significantly improved concentrate quality. Based on the obtained results, an optimized technological scheme incorporating classification, gravity concentration, centrifugal separation, and high-intensity magnetic separation was developed. The proposed approach enhances tungsten recovery from technogenic tailings and contributes to the sustainable utilization of secondary mineral resources.

Keywords: tungsten, Ingichka deposit, technogenic tailings, gravity concentration, magnetic separation, hubnerite, mineralogical analysis.

Annotatsiya. Volframga bo'lgan global talabning ortib borishi va yuqori sifatli birlamchi xomashyo zaxiralarining bosqichma-bosqich kamayishi texnogen mineral konlarni o'zlashtirishga bo'lgan qiziqishni kuchaytirmoqda. Ingichka koni chiqindilarida uchraydigan volframli minerallarning mineralogik xususiyatlari o'rganildi hamda volframni kombinatsiyalashgan boyitish usullari yordamida ajratib olish imkoniyatlari baholandi. Mineralogik va granulometrik tahlillar natijasida volfram asosan gyubnerit shaklida uchrashi, sheelit esa kam miqdorda mavjudligi aniqlandi. Volframning eng yuqori konsentratsiyasi mayda zarracha o'lchamli fraksiyalarda, ayniqsa $-0,1-0,044$ mm o'lcham oralig'ida kuzatildi. Radiometrik saralash, gravitatsion boyitish va magnit ajratish usullarining qo'llanish imkoniyatlari baholandi. Natijalar radiometrik saralash materialning past kontrast xususiyatlari sababli samarasiz ekanligini ko'rsatdi. Gravitatsion boyitish esa yuqori zichlikdagi fraksiyalardan volframni samarali ajratib olish imkonini berdi, keyingi magnit ajratish jarayoni esa konsentrat sifatini sezilarli darajada yaxshiladi. Olingan natijalar asosida klassifikatsiya, gravitatsion boyitish, markazdan qochma ajratish va yuqori intensivlikdagi magnit ajratishni o'z ichiga olgan optimallashtirilgan texnologik sxema ishlab chiqildi. Taklif etilgan yondashuv texnogen chiqindilardan volframni ajratib olish samaradorligini oshirishga hamda ikkilamchi mineral resurslardan barqaror foydalanishga xizmat qiladi.

Kalit so'zlar: volfram, Ingichka koni, texnogen chiqindilar, gravitatsion boyitish, magnit ajratish, gyubnerit, mineralogik tahlil.

Аннотация. Рост мирового спроса на вольфрам и постепенное истощение высококачественных первичных ресурсов усиливают интерес к использованию техногенных минеральных месторождений. Исследованы минералогические особенности вольфрамосодержащих минералов в хвостах Ингичкинского месторождения и оценены возможности извлечения вольфрама с применением комбинированных методов обогащения. Минералогический и гранулометрический анализы показали, что вольфрам преимущественно представлен гюбнеритом, тогда как шеелит содержится в незначительных количествах. Наибольшая концентрация вольфрама выявлена в мелких фракциях материала, особенно в диапазоне размеров частиц $-0,1-0,044$ мм. Оценена применимость радиометрической сепарации, гравитационного обогащения и магнитной сепарации. Полученные результаты показали, что радиометрическая сепарация является неэффективной вследствие низких контрастных характеристик материала. В то же время гравитационное обогащение обеспечило эффективное извлечение вольфрама из высокоплотных фракций, а последующая магнитная сепарация существенно повысила качество концентрата. На основе полученных результатов разработана оптимизированная технологическая схема, включающая классификацию, гравитационное обогащение, центробежную сепарацию и высокоинтенсивную магнитную сепарацию. Предложенный подход способствует повышению эффективности извлечения вольфрама из техногенных хвостов и обеспечивает более рациональное использование вторичных минеральных ресурсов.

Ключевые слова: вольфрам, Ингичкинский месторождение, техногенные хвосты, гравитационное обогащение, магнитная сепарация, гюбнерит, минералогический анализ.

INTRODUCTION

Tungsten is a strategic metal widely used in the aerospace, defense, electronics, and advanced manufacturing industries due to its high melting point, hardness, and wear resistance [4]. The growing demand for tungsten has increased interest in alternative sources of raw materials, particularly technogenic deposits and beneficiation tailings.

The Ingichka tungsten deposit in Uzbekistan represents one of the largest tungsten resources in Central Asia. Long-term mining and beneficiation activities have generated more than 14 million tons of tailings containing residual tungsten minerals, with an average WO_3 content of approximately 0.06%. Although the grade is relatively low, the large volume of accumulated material makes these tailings a valuable secondary tungsten resource.

Previous processing technologies resulted in significant tungsten losses due to the complex mineralogical composition of the ores and the fine dissemination of tungsten-bearing minerals. Therefore, the development of efficient recovery methods requires a detailed understanding of the mineralogical occurrence, liberation characteristics, and particle-size distribution of tungsten-bearing minerals [12].

This study investigates the mineralogical occurrence of rare metals in the Ingichka deposit and evaluates combined gravity and magnetic separation methods for tungsten recovery from technogenic tailings. The obtained results provide a basis for improving tungsten extraction efficiency and promoting the sustainable utilization of mining waste resources.

LITERATURE REVIEW

Numerous researchers have investigated the beneficiation of tungsten-bearing ores and technogenic resources. According to Lassner and Schubert, tungsten remains one of the most critical strategic metals due to its unique physical and chemical properties. Earlier studies by Burt demonstrated that gravity concentration is among the most effective methods for recovering coarse and liberated tungsten minerals because of their high density.

Research conducted by Bulatovic and other authors showed that the recovery of fine tungsten particles can be significantly improved through the combined application of gravity and magnetic separation methods. Studies conducted in China, Canada, and Australia have further confirmed that integrated beneficiation schemes are effective for processing low-grade tungsten ores and tailings.

Recent investigations have focused on the reprocessing of technogenic deposits as alternative sources of critical raw materials. According to Zhang et al. and Li et al., tungsten-bearing tailings may contain economically valuable amounts of WO_3 that can be recovered using modern beneficiation technologies. However, the efficiency of recovery largely depends on mineralogical characteristics, particle liberation, and tungsten distribution within different size fractions.

Despite the considerable progress achieved in tungsten beneficiation research, limited information is available regarding the mineralogical occurrence of rare metals and tungsten recovery from the Ingichka technogenic tailings. Therefore, detailed mineralogical investigations and the development of an optimized beneficiation technology remain important research objectives.

RESEARCH METHODOLOGY

The study was conducted using tungsten-bearing technogenic tailings accumulated at the Ingichka beneficiation plant located in the Samarkand Region of Uzbekistan. The tailings were generated during the processing of scheelite-wolframite ores and represent a significant secondary tungsten resource. According to historical production records, more than 14 million tons of tailings containing approximately 0.06 wt.% WO_3 have accumulated in the storage facilities of the processing plant [9] (Figure 1).

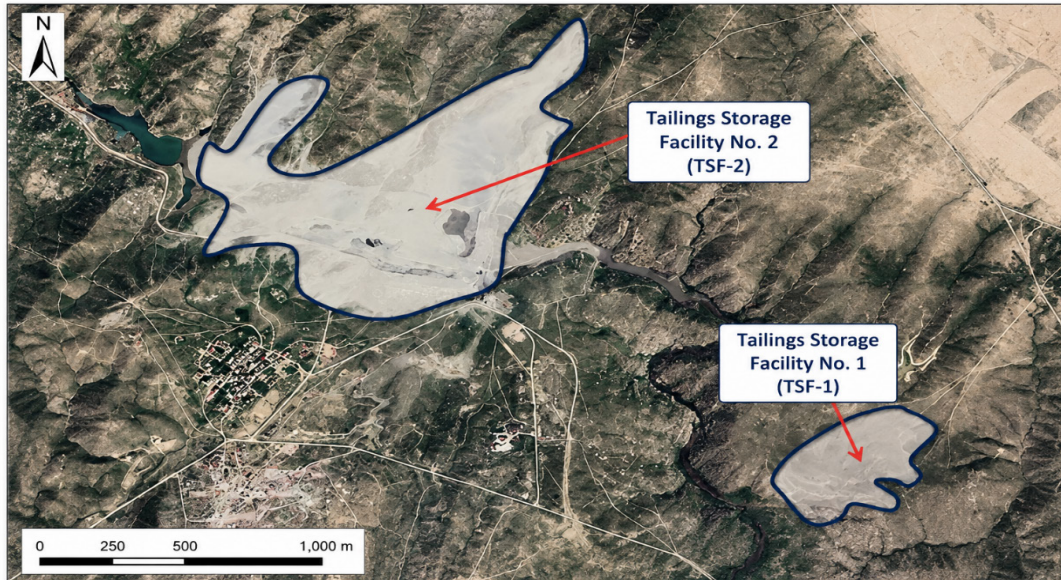


Figure 1. Location of the Ingichka beneficiation plant tailings storage facilities (TSF-1 and TSF-2), Samarkand Region, Uzbekistan.

Figure 1. Location of the Ingichka beneficiation plant tailings storage facilities (TSF-1 and TSF-2), Samarkand Region, Uzbekistan.

Representative bulk samples were collected from different sections of the tailings storage area to ensure adequate characterization of the deposited material [1]. The investigated samples consisted of sandy, silty, and clayey fractions with different particle-size distributions. Preliminary mineralogical observations indicated the presence of scheelite (CaWO_4), hubnerite (MnWO_4), wolframite ($(\text{Fe,Mn})\text{WO}_4$), quartz, feldspars, calcite, fluorite, iron oxides, and sulfide minerals [15].

Particle Size and Mineralogical Analysis

Granulometric analysis was performed using sieve classification and wet-screening methods. The samples were separated into several size fractions, including $-3+1$ mm, $-1+0.5$ mm, $-0.5+0.25$ mm, $-0.25+0.1$ mm, $-0.1+0.044$ mm, and -0.044 mm classes. The mass yield of each fraction was determined, and tungsten distribution was calculated based on chemical analysis results [7].

Mineralogical characterization of the samples was carried out to determine the occurrence forms, degree of liberation, and associations of tungsten-bearing minerals. Special attention was given to the distribution of scheelite and hubnerite within different particle-size classes. The proportion of liberated grains and mineral intergrowths was evaluated to identify the optimal grinding size for subsequent beneficiation operations [3] (Figure 2).

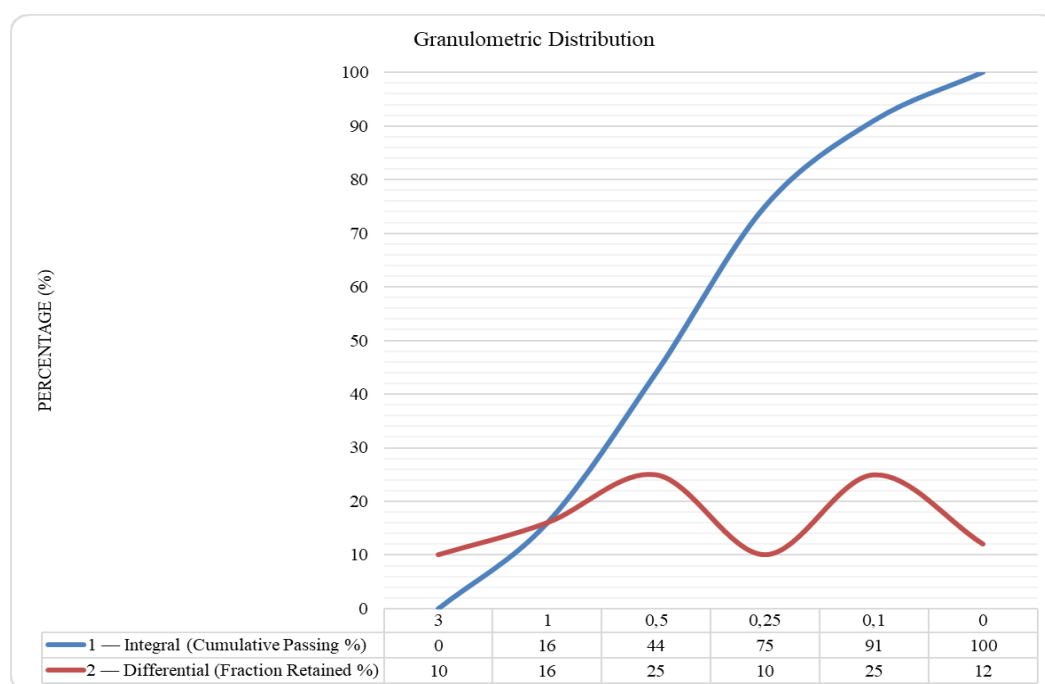


Figure 2. Integral and differential particle-size distribution curves of the Ingichka tailings sample.

Granulometric analysis was performed to determine the particle-size distribution of the investigated tailings. The obtained cumulative and differential distribution curves are presented in Figure 2. The results indicate that approximately 75% of the material is finer than 0.25 mm, while more than 90% passes the 0.1 mm size fraction. Such a distribution suggests a high degree of material comminution and favorable conditions for the gravity concentration of tungsten-bearing minerals.

Phase composition and mineral associations were investigated using X-ray diffraction (XRD), scanning electron microscopy (SEM), and optical microscopy techniques. The chemical compositions of selected samples and beneficiation products were determined using standard analytical procedures [11].

Beneficiation Experiments and Process Performance Evaluation

Based on the mineralogical characteristics of the Ingichka tailings, a combined beneficiation scheme consisting of gravity and magnetic separation was applied. The material was first classified into different particle-size fractions. Gravity concentration was used to recover tungsten-bearing minerals from coarse and medium fractions, while fine fractions were treated to improve the recovery of liberated tungsten particles [5].

The obtained gravity concentrates were subsequently upgraded by magnetic separation, taking advantage of the differences in magnetic susceptibility between tungsten minerals and associated gangue minerals. Magnetic and non-magnetic products were collected and analyzed for WO_3 content [14].

The efficiency of the beneficiation process was evaluated using concentrate grade, tungsten recovery, and metal distribution. Recovery values were calculated based on mass-balance data using product yields and WO_3 contents. Particular attention was given to the $-0.5+0.25$ mm and $-0.1+0.044$ mm fractions, which demonstrated the highest tungsten enrichment and recovery potential [2]. The experimental results were compared to determine the most effective processing conditions for tungsten recovery from the Ingichka technogenic tailings [10].

ANALYSIS AND RESULTS

The mineralogical investigations demonstrated that tungsten is the principal valuable component in the Ingichka tailings, occurring predominantly as hubnerite ($MnWO_4$), whereas scheelite is present only in minor quantities. Liberation analysis revealed that only 15–20% of tungsten-bearing grains are liberated in the as-received material, while grinding to a particle size below 0.1 mm increases the degree of liberation to 80–90%. These results indicate that efficient tungsten recovery requires additional size reduction prior to beneficiation [8].

The possibility of applying radiometric separation was evaluated through the determination of ore contrast characteristics. The calculated contrast coefficients for WO_3 and sulfide sulfur were 0.44 and 0.48, respectively, indicating a low-contrast material [13]. Furthermore, a statistically significant correlation between WO_3 and sulfur content was established ($r = 0.827$). However, the obtained contrast values indicate that radiometric separation has limited applicability for processing the Ingichka technogenic materials, particularly within fine particle-size

fractions. Therefore, radiometric methods are considered supplementary rather than primary beneficiation techniques for tungsten recovery from these tailings [6].

Heavy-liquid separation experiments demonstrated a strong relationship between tungsten distribution and particle density. The yield of the heavy fraction ($>3.6 \text{ g/cm}^3$) increased from 0.71% in the $-3+1 \text{ mm}$ fraction to 20.23% in the $-0.1+0.044 \text{ mm}$ fraction. Simultaneously, tungsten content increased significantly with density, reaching a maximum value of 0.88% WO_3 in the finest heavy fraction. In contrast, the light fraction ($<2.9 \text{ g/cm}^3$), representing more than 70% of the material, contained only 0.01–0.02% WO_3 . These results confirm that tungsten minerals are predominantly concentrated in high-density fractions and become increasingly liberated as particle size decreases.

The distribution of tungsten among different particle-size fractions was investigated to identify the size classes with the highest concentration of valuable minerals. The obtained results are presented in Figure 3.

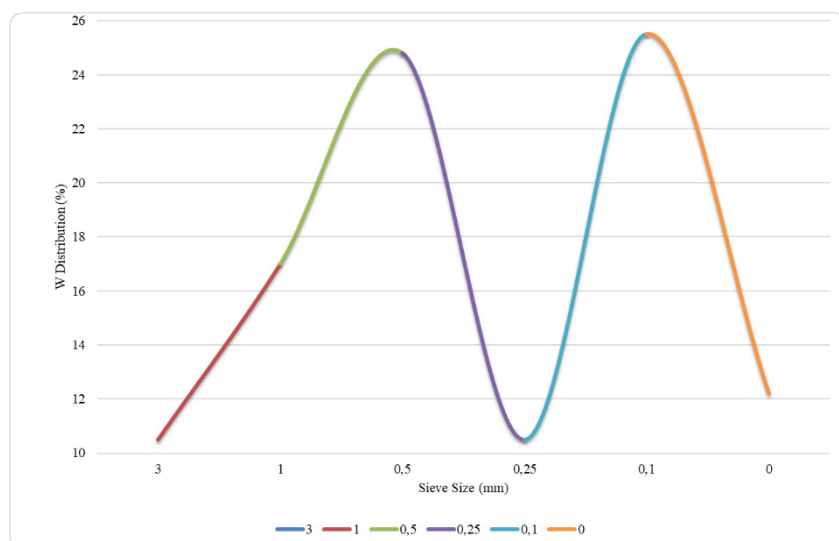
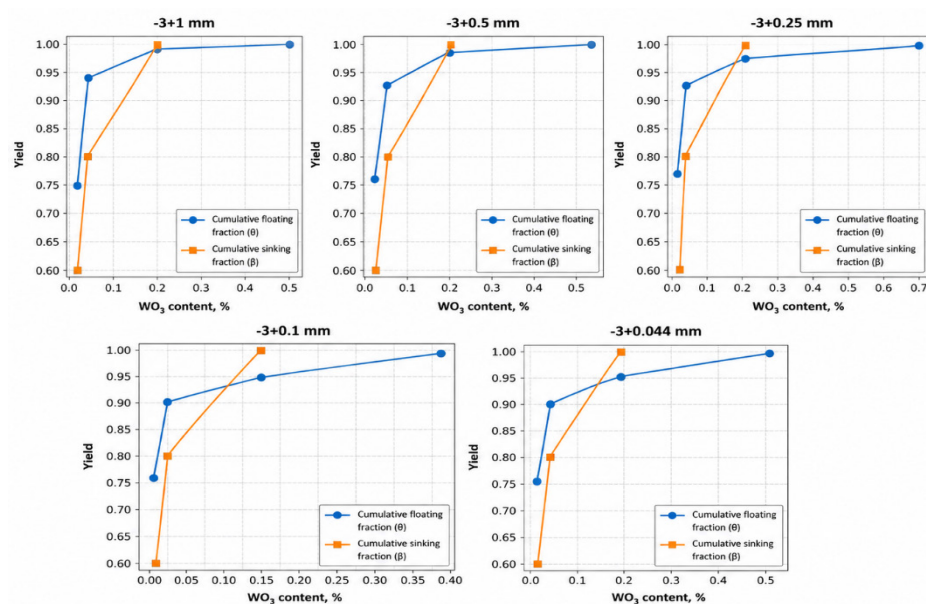


Figure 3. Particle-size distribution of tungsten within the Ingichka tailings sample.

The calculated gravity beneficiation curves further confirmed the favorable gravity-concentration characteristics of the investigated material. The generalized gravity washability analysis showed that the highest concentrate grade was obtained in the $-0.1+0.044 \text{ mm}$ fraction, where the WO_3 content reached 1.017%. The same fraction exhibited the lowest tungsten losses to tailings, indicating that fine grinding followed by gravity concentration provides the most efficient recovery conditions. Consequently, multi-stage gravity concentration was identified as the most suitable primary beneficiation method for the Ingichka tailings.

Magnetic separation studies were conducted on gravity concentrates in order to improve concentrate quality. Electromagnetic fractionation revealed that approximately 76.59% of the heavy fraction consisted of non-magnetic minerals, whereas magnetic and weakly magnetic products represented a considerably smaller proportion of the material. Nevertheless, tungsten enrichment was concentrated mainly within the weakly magnetic fractions, reflecting the magnetic properties of hubnerite. The highest tungsten content was observed in the $-1+0.5 \text{ mm}$ fraction, reaching approximately 42% WO_3 .

Further upgrading of the gravity concentrate by magnetic separation produced a weakly magnetic concentrate containing 40% WO_3 , with a tungsten recovery of 70.3%. Additional grinding of the non-magnetic product to -0.5 mm , followed by repeated magnetic separation, resulted in a second weakly magnetic concentrate containing 24% WO_3 and recovering an additional 25.2% of tungsten. The combined weakly magnetic products contained approximately 34% WO_3 , while total tungsten losses in magnetic and non-magnetic waste products remained below 5%. These results demonstrate the effectiveness of magnetic separation as a cleaning stage for gravity concentrates (Figure 4).



Note: θ – cumulative floating fraction (light fraction); β – cumulative sinking fraction (heavy fraction).

Figure 4. Gravity washability curves of the Ingichka technogenic tailings for different particle-size fractions.

Figure 4. Gravity washability curves of the Ingichka technogenic tailings for different particle-size fractions.

As shown in Figure 4, separation efficiency increases with decreasing particle size, particularly in the $-0.1+0.044$ mm fraction, where the highest tungsten enrichment was achieved. This behavior reflects the improved liberation of hubnerite particles after size reduction and supports the application of multi-stage gravity concentration in the proposed processing flowsheet.

Based on the obtained results, an integrated beneficiation flowsheet was developed for processing the Ingichka technogenic tailings. The proposed technology includes classification, multi-stage gravity concentration, centrifugal separation, and high-intensity magnetic separation. The combined application of these methods enables efficient recovery of tungsten-bearing minerals while minimizing metal losses in tailings. The developed technological scheme is particularly suitable for fine-grained hubnerite-bearing materials and provides a practical approach to the utilization of tungsten-containing technogenic resources accumulated at the Ingichka beneficiation plant.

The obtained results demonstrate that gravity concentration followed by magnetic upgrading represents the most promising technological route for tungsten recovery from the Ingichka tailings. The proposed approach ensures the effective utilization of technogenic mineral resources, improves the recovery of valuable metals, and contributes to the sustainable processing of mining waste.

CONCLUSIONS AND RECOMMENDATIONS

The conducted mineralogical and technological investigations demonstrated that the Ingichka beneficiation plant tailings represent a promising secondary source of tungsten. Mineralogical analysis revealed that tungsten occurs predominantly as hubnerite, while scheelite is present only in minor quantities. The highest tungsten concentrations were observed in the fine particle-size fractions, particularly within the $-0.1+0.044$ mm size range. Radiometric separation exhibited limited applicability due to the low contrast characteristics of the material, whereas gravity concentration demonstrated high efficiency in recovering tungsten from high-density fractions.

The experimental results confirmed that the combined application of gravity and magnetic separation significantly improves tungsten recovery and concentrate quality. Based on the obtained data, an optimized beneficiation flowsheet incorporating classification, gravity concentration, centrifugal separation, and high-intensity magnetic separation was developed. The proposed technology enables efficient recovery of tungsten from technogenic tailings, reduces metal losses, and promotes the sustainable utilization of mining waste resources. The obtained results may serve as a basis for the industrial reprocessing of the Ingichka tailings and the production of marketable tungsten concentrates.

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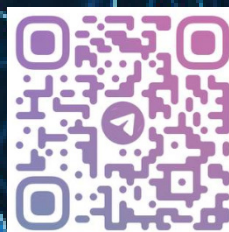
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