

Summary of Physical-Field Mineral Separation and Enrichment Technology

Invention Patent (ZL 2021 1 0446299.3)

China Industrial Solid Waste Management Co., Ltd. · Solid Waste Industry Research Institute

Table of Contents

- I. Basic Information of Core Technology
- II. Background of the Patent Invention
- III. Overview of Technical Scheme
- IV. Analysis of Technical Advancement
- V. Analysis of Market Advantages

Executive Summary

Cut-off Grade Lowering for Lean Uranium Resource Utilization

**0.05% → 0.0034% — Industrial grade
boundary extended by approximately one
order of magnitude**

Maximum Uranium Enrichment Ratio

**Approx. 3,320-fold; maximum uranium grade
of concentrate 11.29%**

Comprehensive Recovery Rate

**≥75%; simultaneous recovery of uranium,
niobium, tantalum, zirconium and rare-earth**

elements

Production Cost (vs. flotation flowsheet)

Approx. 1/5 of flotation; purely physical separation, no flotation reagents

China's External Dependence on Uranium

75%–90%; high uranium price and expanding supply-demand gap

This report analyzes the technical advancement and market advantages of the core physical-field material separation technology. Adopting a purely physical mineral-processing route of "gathered-magnet permanent-magnet high-intensity magnetic separation — radio-frequency dielectric separation — integrated magnetic-gravity separation", this technical system greatly lowers the exploitable cut-off grade for rare, precious and scattered mineral resources. Taking uranium as an example, the cut-off grade drops from the current industrial grade of 0.05% to 0.0034%, achieving around 3,320-fold uranium enrichment as well as simultaneous recovery of niobium, tantalum, zirconium and rare-earth elements. Against the market landscape featuring high external dependence of China's uranium, rapid expansion of nuclear power and sustained rise of uranium prices, the technology shows outstanding application value in unlocking low-grade uranium-bearing resources and collaborative utilization of tailing solid waste, and presents direct synergy with the company's main business of comprehensive solid-waste resource utilization. Meanwhile, the report identifies risks in four dimensions: conceptual expression, economic data accounting, industry access and engineering verification.

I. Basic Information of the Technical System

Item	Content
Technical System Name	Physical-Field Material Separation and Enrichment Technical System

Core Patent No.	ZL 2021 1 0446299.3
Grant Publication No.	CN 113042198 B
Patent Type	Invention Patent
Certificate No.	No. 5331952

II. Research Background of the Technical System

This technical system was proposed by Wang Yuxian, who acts as the academic leader of the research project. Graduated from Jilin University in 1965, majoring in Solid-State Theory of Physics, Mr. Wang was assigned to the Chinese Academy of Geological Sciences. He once served as Director of the Mineral Materials Research Center, Research Fellow of the Institute of Mineral Deposits and Institute of Mineral Resources, and Director of the Mineralogy Laboratory, Chinese Academy of Geological Sciences, as well as Vice-Chairman of the Mineralogy Commission of the Geological Society of China. From 1985 to 1986, he worked as an Alexander von Humboldt Visiting Scholar at the Institute of Mineralogy, University of Marburg, Germany, conducting researches on mineral physics and ultra-low-temperature Mössbauer effect. Currently, he serves as independent director of CIWM and chief consultant of Huzhu Green Building.

Major technical accumulations are as follows:

1. For more than 50 years, he has committed to integrating solid-state physics with mineralogy and mineral-material mineral-processing engineering, and established the "technical system for mineral-resource material processing under physical fields". Separation is realized according to differences in magnetism, electricity and density of minerals, without flotation reagents, heavy media or chemical agents. It features environmental-friendliness, energy-saving and low-cost performance. Relevant instruments and equipment have won the National Science Congress Award, the Third-Class National Invention Award, national invention patents and the Second-Class Achievement Award from the Ministry of Geology and Mineral Resources.
2. The "gathered-magnet permanent-magnet high-intensity magnetic separation technology" was appraised as internationally advanced via national key-project assessment, and has been promoted in purification of metallic and non-metallic ores.
3. He put forward the physical-field coal-preparation technical route for coal upgrading (homologous to technologies such as gathered-magnet permanent-magnet high-intensity upgrading of lignite and ash-sulfur removal for carbon materials).

4. He proposed the method for extracting low-concentration uranium from lean uranium resources, i.e. the present technical system.

Analysis note: This patent is not an isolated achievement. It represents an extension of decades-long physical-field mineral-processing technical system in uranium-resource domain. Long-term technical accumulation supports its advancement and implementability.

III. Overview of the Technical Scheme

This section sorts out the technical route, key technical indicators and application scope.

(I) Technical Route

A purely-physical mineral-processing flowsheet of "gathered-magnet permanent-magnet ultra-high-intensity magnetic separation — radio-frequency dielectric separation — integrated magnetic-gravity separation" is adopted to replace conventional mineral-processing routes dominated by "roasting-flotation-acid leaching". The core flows are listed below:

1. Run-of-mine ore undergoes crushing-screening and grinding-classification into particle-size fractions: 40–120 mesh, 120–200 mesh, 200–300 mesh and above 300 mesh. Weak-magnetic separation (0.3–0.6 T) is performed to separate strongly-magnetic minerals such as iron oxides;
2. Magnetic tailings are re-separated under medium-magnetic condition (0.8–1.2 T);
3. Magnetic tailings are processed by gravity separation to separate light and heavy minerals at the density boundary of 3.5 g/cm³;
4. Heavy minerals are subjected step-by-step to high-intensity magnetic separation (1.6–1.8 T), ultra-high-intensity magnetic separation (2.2 T) and permanent-magnet ultra-high-intensity magnetic separation (2.6 T), to progressively enrich uranium-bearing minerals (pyrochlore, zircon, monazite, xenotime, thorite, etc.) and discard tailings;
5. Radio-frequency dielectric separation is combined with quantitative XRD mineral analysis, electron probe and full chemical-element assay to track uranium enrichment rules and realize simultaneous recovery of target minerals and associated minerals.

(II) Key Technical Indicators

Tested on alkaline-granite-type niobium-tantalum-zirconium deposit (run-of-mine uranium grade merely 0.0034%):

Element / Mineral	Run-of-mine Grade	Concentrate Grade	Enrichment Ratio
-------------------	-------------------	-------------------	------------------

Uranium	0.0034%	11.29% (3%–10%+ high-grade uranium concentrate)	ca. 3,320-fold
Niobium (as Nb ₂ O ₅)	0.0437%	64.51%	ca. 1,480-fold
Tantalum (as Ta ₂ O ₅)	0.031%	4.16%	ca. 134-fold
Zirconium	0.197%	65.15%	ca. 330-fold
Rare-earth elements (as Ce ₂ O ₃)	0.091%	7.10%	ca. 78-fold

The comprehensive recovery rate exceeds 75%. Mineral-processing tests for uranium extraction and comprehensive utilization were completed on a super-large rare-rare-earth deposit in Xinjiang. The deposit hosts 772 million tons of ore, containing associated Nb₂O₅ 322,300 tons, Ta₂O₅ 22,000 tons, zirconium oxides 1.41 million tons and estimated uranium reserves over 100,000 tons. Previously lean and marginal ore is turned into resources of super-large uranium-deposit scale.

(III) Application Scope

- Lower the exploitable cut-off grade of valuable minerals such as uranium from the prevailing industrial grade of 0.05% (minimum industrial grade specified in Uranium Deposit Geological Exploration Specification DZ/T 0199-2002) down to 0.0034% (waste-rock and tailing grade);
- Applicable deposit types include hard rocks (granite, volcanic rock), sandstone, mudstone and lignite, etc.;
- Especially suitable for comprehensive recovery of low-grade resources in deposits hosting associated multiple rare elements (rare-metal, rare-earth, rare-precious, non-ferrous-metal and non-metallic deposits). It can connect with metallurgical procedures to achieve full-range comprehensive resource recovery.

IV. Analysis of Technical Advancement

(I) Breaking the Long-Standing Industrial-Grade Cut-off for Three-Type Rare-Element Minerals

According to Chinese industry standard, uranium ore with grade $\geq 0.05\%$ is defined as mineable resource (DZ/T 0199-2002). Resources below this threshold have long been excluded from exploitable uranium resources. This technical system lowers the exploitable cut-off grade to 0.0034%, expanding the resource boundary by more than one order of magnitude. In other words, massive low-grade uranium-bearing minerals, waste rock and tailings previously classified as "non-uranium resources" can theoretically be re-categorized as usable resources, which bears strategic significance

for China to expand uranium resource reserves and production capacity. This constitutes the most disruptive innovation of the technology.

(II) Purely-Physical Mineral-Processing Route with Remarkable Advantages in Energy-Saving, Environmental-Friendliness and Low-Cost

Compared with conventional "roasting-flotation-acid leaching" routes, its advancement is manifested in the following aspects:

- Energy saving: Permanent-magnet magnetic system consumes negligible electricity; energy input is limited to separation driving power, far lower than roasting and flotation processes;
- Environmental-friendliness: No flotation reagents, heavy media or chemical agents are applied, fundamentally avoiding risks of low-toxic reagent discharge and acid wastewater. It complies with increasingly-stringent regulatory requirements for radioactive-pollution prevention and mine environmental protection;
- Low-cost: Production cost is only about 1/5 of flotation-dominated mineral-processing flowsheet. After high-degree enrichment and tailings-discarding, subsequent metallurgical feed volume and reagent consumption decrease substantially;
- Economic feasibility for low-grade resources: Conventional chemical processes are economically infeasible for resources below 0.05% grade; the low-cost feature of physical separation makes it viable to unlock low-grade resources.

(III) Multi-Thousand-Fold Enrichment and Multi-Element Co-Recovery Mode

The technical system delivers up to ca. 3,320-fold uranium enrichment, and simultaneously recovers niobium, tantalum, zirconium, rare-earth elements and other non-ferrous / non-metallic minerals with recovery rate above 75%. Uranium commonly occurs in pyrochlore, zircon, monazite and other rare-rare-earth minerals. The "uranium-rare-metal-rare-earth" co-recovery pattern transforms single-purpose uranium extraction into multi-metal comprehensive development, significantly diluting unit-product uranium cost. This merit is not available for single-element uranium-leaching technologies such as in-situ leaching, heap leaching and microwave-enhanced leaching, which are mostly applicable only to sandstone-type uranium deposits.

(IV) Comparative Positioning Against Domestic and Overseas Competing Technologies

Technical Route	Target Object	Major Limitations	Relative Advantages of This Patent
Conventional mining-metallurgy (in-situ / heap leaching +	Uranium deposits reaching 0.05% industrial grade	Invalid for ultra-low-grade uranium resources; only uranium can be	Cut-off grade lowered by about one order of magnitude; simultaneous

hydrometallurgy)		recovered	recovery of associated resources
Enhanced leaching (e.g. microwave-activated roasting enhanced leaching)	Low-grade uranium ore	Chemical leaching remains core; high energy consumption, complex flows, large reagent consumption	Purely-physical mineral separation, reagent-free, low energy consumption, cost at 1/5 magnitude
Uranium extraction from seawater	Seawater (uranium concentration ~3.3 mg/ton)	Only kilogram-scale extraction achieved; far away from industrialization	Deposit-scale mineral-processing test data available; clear engineering-implementation path
This patent: physical-field mineral separation	Lean uranium and associated resources of 0.0034%–0.05% grade	Continuous industrial-production data verified by pilot tests	Multi-thousand-fold enrichment, multi-element co-recovery, environmental-friendly

(V) Technical Notes Requiring Clarification

"Low-enriched uranium" concept clarification: The term "low-enriched uranium (3%–10%)" in this document refers to mass concentration (grade) of uranium in mineral-processing products, i.e. high-grade uranium concentrate. It differs from "Low-Enriched Uranium (LEU)" defined by U-235 isotopic abundance in nuclear-fuel cycle (U-235 abundance 2%–20%). This technology belongs to mineral-processing enrichment and does NOT involve isotope separation. The accurate expression shall be "uranium enrichment / preparation of high-grade uranium concentrate" to avoid conceptual misunderstanding.

Caution in citing economic data: The potential value per ton of various solid wastes extracting target valuable minerals shall be calculated based on real-time market prices when quoted.

Degree of engineering verification: All data are obtained from pilot mineral-processing tests. Stability of continuous industrial-scale production and indicator retention after capacity scaling will be verified in four proposed demonstration projects.

V. Analysis of Market Advantages

(I) Market Background: Expanding Uranium Supply-Demand Gap and High

External Dependence

- Demand-side rapid growth: The three-type rare minerals collectively refer to rare-earth, rare-metal and scattered-element minerals. As national strategic critical minerals, they serve as indispensable basic raw materials for new-energy, semiconductor, high-end-equipment and national-defense military industries. Global resources are unevenly distributed. China possesses relatively favorable endowment of three-type rare-element resources and is a major supplier and deep-processor. Nevertheless, scattered elements mostly occur as associated components with few independent deposits, bringing high barriers in mining and purification.
- Supply-demand imbalance: Global energy transition and technological upgrading keep driving market demand. Consumption of three-type rare metals keeps rising in permanent-magnet motors for wind power, new-energy vehicles, photovoltaic industry, display panels and chips. Countries worldwide have rolled out critical-mineral policies to pursue supply-chain self-reliance, intensifying international resource-related game-playing. Domestic regulatory policies implement total-volume control, mining quotas and green-development supervision to curb disordered exploitation, promote comprehensive resource utilization and recycling industry, pushing the sector from extensive mining toward high-quality, high-value-added materials.
- Clear policy orientation: Prices of three-type rare-element products fluctuate sharply subject to supply-demand fundamentals and geopolitical policies. Medium-heavy rare-earth elements, gallium, germanium and other high-value varieties feature strong scarcity. Current industry bottlenecks include high utilization cost for low-grade resources and insufficient capacity for high-purity advanced materials. In the long run, incremental demand from new-energy and electronic-information industries will sustain the strategic value of three-type rare-element minerals. Efficient mineral-processing-metallurgy and circular-utilization technologies will become key development focuses.

(II) Market Value Points of This Technical System

1. Unlock massive marginal resources including tailings, metallurgical slags and lean ore to mitigate import reliance. China hosts huge volumes of low-grade mineral resources, three-type-rare-element-bearing associated deposits and historically-stockpiled tailings. After lowering uranium cut-off grade from 0.05% to 0.0034%, these "inactive deposits" can be converted into available supply. Take the aforementioned Xinjiang deposit as an example: its estimated uranium reserve of more than 100,000 tons accounts for nearly one-third of China's proven total uranium reserves, highlighting prominent strategic value.
2. Cost advantages build competitive moat. Its production cost reaches merely 1/5 of flotation flowsheet. Reagent-free and low-energy-consumption features grant it almost no competing alternatives for low-grade-resource development. Under current high-price cycles for multiple mineral concentrates, marginal-grade resources can achieve considerable profitability.

3. Multi-element co-recovery improves project economy. Niobium, tantalum, zirconium and rare-earth elements are all strategically-scarce minerals with high market prices. Simultaneous recovery diversifies project revenue streams and strengthens resilience against commodity-price cycles, rendering the technology attractive for mine owners and cooperation partners.
4. Green process complies with regulatory requirements and ESG trends. Reagent-free and low-emission physical-separation flowsheet lowers environmental-assessment barriers and environmental-protection investment compared with chemical routes under the revised Law on Prevention and Control of Radioactive Pollution. It represents a typical green-mine technology.
5. High synergy with solid-waste-resource-utilization industry. Tailings and associated-component-bearing resources fall within the scope of collaborative industrial-solid-waste recycling. This technology enables the dual-revenue business model of "solid-waste disposal + strategic-metal recovery", offering large space for business-model replication.

September 18, 2026