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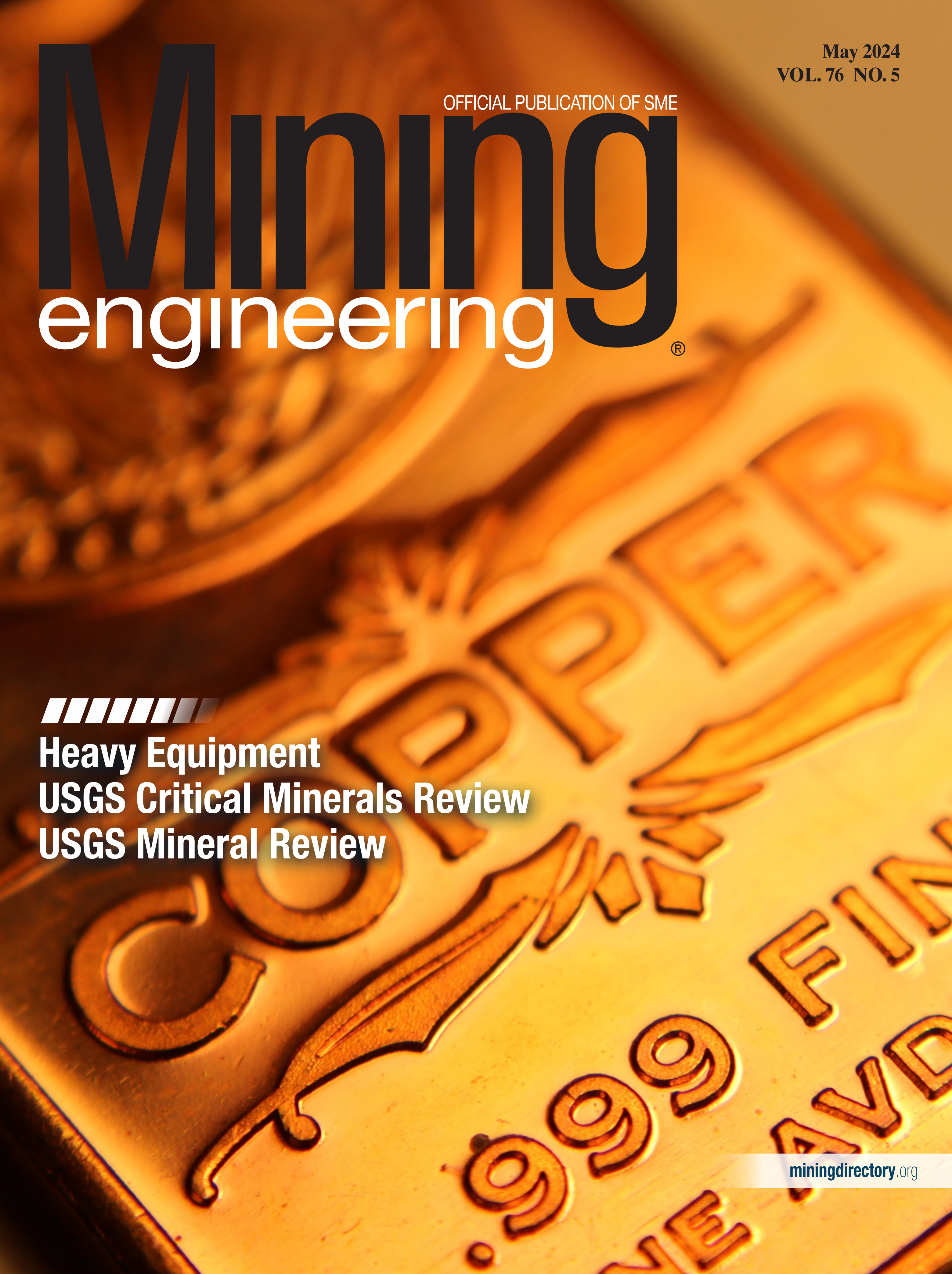

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Feature Articles

Technical-paper Abstracts from *Mining, Metallurgy & Exploration*

(peer-reviewed and approved)

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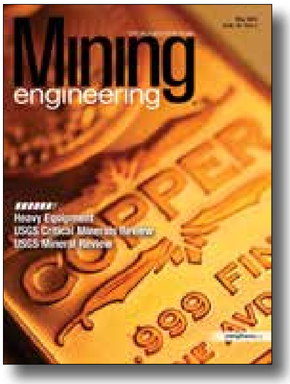
As the world faces an increasing demand for the minerals that will power the green energy transition as well as the technologies that will shape the future, the United States remains more than 95 percent reliant on foreign sources for more than 15 minerals. In this issue, authors from the U.S. Geological Survey provide comprehensive reviews of the mining industry. Coverage begins on page 29. Cover design by Ted Robertson.



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Critical issues that we all must consider;

How will AI and machine learning impact your career?

Marc Herpfer
2024 SME President

I believe we are on the cusp of a tremendous transition for humanity driven by science and technology. This transition will require a multitude of raw materials and elements, all of which are interconnected. Machine learning and artificial intelligence (AI), will enable more change during the next decade than the computer revolution empowered us to accomplish during the last half-century. This transition is dependent on the interconnections between all knowledge, everything around us, and everyone in our world.

Already, many of us question how AI will impact our jobs in five to 10 years and being able to figure out how we can use AI, while still critically thinking for ourselves, will be one of the biggest challenges we face in the coming years.

We all need to think bigger and broader as our discipline is going to be influenced much more by other areas beyond just the classical mining, metallurgy and exploration fields. From scientific, social and economic perspectives everything is critically linked including our technologies that sustain people, and especially from a natural-resources basis that enables and builds everything in our civilization. So I ask every SME member to think about what AI in its current state of evolution can do, or not do, for all of us? How should we approach and best use such rapidly changing computational analytical power, hopefully before it becomes "self-aware," and the paradigm of what it means to be a "thinking man" changes forever? So, please let me know your thoughts on this profound question?

Another aspect is the stewardship of natural resources essential for our society's economic growth and establishment of a secure future. For example, among the thousands of known ore deposits around the world containing "critical minerals," many show no evidence of present or past production, thus representing potential for untapped minerals for us to supply to support the world's needs for various essential elements. With today's many technological tools can we better understand critical elements occurrences and their distributions within host mineral systems and ore deposits, and thus delineate the most prospective geological settings and regions around the globe? Considering the very high priority of "critical minerals" to everyone's economic growth, security and the green-energy transition, a better and deeper understanding of geosciences information to societal needs is of paramount importance to the stewardship of our natural resources and critical decision-making on behalf of future generations.

This impending AI revolution, along with never-ending and increasing raw-material needs, will ultimately reshape the world and require professionals in the mining industry to have a broad range of talents and knowledge. Consequently, SME will also evolve over the next decade, due to this profound impact on how we discover, disseminate and apply knowledge in improving and expanding all facets of mining and utilization of raw materials and critical elements for civilization … which eventually may occur beyond Earth.

I always take "the glass is half-full" approach. While we can't anticipate every change, I am optimistic about what the future holds for all of us as we strive to adapt, foster and accelerate constructive change to be at the forefront of those profound and critical transitions with which we will be living over the next decades.

Together we can achieve great accomplishments … and help carry the global mining industry, as well as our Society, into a brave new future and beyond. ■

Safety Share: Active and abandoned mine sites — Safety tips.

Each year throughout the nation dozens of people are injured or killed while exploring or playing on mine property. The men and women employed in our nation's mines are trained to work in a safe manner. For trespassers, hazards are not always apparent.

Water-filled quarries and pits hide rock ledges, old machinery and other hazards. The water can be deceptively deep and dangerously cold. Steep, slippery walls make exiting the water difficult. Hills of loose material can easily collapse on an unsuspecting biker or climber. Vertical shafts can be hundreds of feet deep and may be completely unprotected or hidden by vegetation.

Source:
U.S. Mine Safety & Health Administration

MP Materials receives $58.5 million for magnet facility

MP MATERIALS HAS received a $58.5 million award to advance its construction of America's first fully integrated rare earth magnet manufacturing facility.

The Section 48C Advanced Energy Project tax credit allocation was issued by the Internal Revenue Service and U.S. Treasury following a competitive, oversubscribed process administered by the U.S. Department of Energy that evaluated the technical and commercial viability and environmental and community impact of approximately 250 projects, MP Materials said in a statement.

Neodymium-iron-boron (NdFeB) magnets are the world's most powerful and efficient permanent magnets. They are an indispensable component found in the electric motors and generators that power hybrid and electric vehicles (EVs), robots, wind turbines, drones, electronics, and critical defense systems. Global demand is expected to triple by 2035.

MP Materials began constructing its Fort Worth, TX, manufacturing facility in April 2022. The company is currently producing magnet precursor materials in a North American pilot facility. It expects to commence commercial production of precursor materials in Fort Worth this summer and finished magnets by late 2025. MP will supply these products to General Motors, its foundational customer, to support its North American EV production.

MP will source the factory's raw-material inputs from Mountain Pass, CA, where it owns and operates America's only scaled and operational rare earth mine and separations facility. At the factory, neodymium-praseodymium (NdPr) oxide produced at Mountain Pass will be reduced to NdPr metal and converted to NdFeB alloy and finished magnets, delivering an end-to-end supply chain with integrated recycling and world-class sustainability.

According to a Section 232 investigation completed by the Department of Commerce in 2022, sintered NdFeB magnets are "required for critical infrastructure" and "irreplaceable in key defense applications," yet the United States is "essentially 100 percent dependent on imports," posing a serious national security risk. More than 90 percent of the world's NdFeB magnets are produced in China.

In other news, Australian billionaire Gina Rinehart's mining firm had taken a 5.3 percent stake in MP Materials, expanding her investments in the mineral ore sector.

In a regulatory filing the company reported that Hancock Prospecting, owned by Australia's richest person Rinehart, holds about 8.8 million shares of MP Materials.

MP Materials is the second-biggest producer of rare earths outside China after Australia's Lynas Rare Earths. Lynas ended talks with MP Materials over a potential merger in February.

The iron ore miner has been building stakes in critical minerals projects, including rare earths..

Hancock's investments include a 6.17 percent stake in Brazilian Rare Earths and a 9.14 precent holding in Arafura Rare Earths, according to LSEG data. ■

Mining ban on federal lands in Colorado finalized

A 20-YEAR BAN ban on new mining and oil and gas development on more than 200,000 acres of federal lands in Western Colorado's Thompson Divide was finalized by the Biden administration on April 3.

The mineral withdrawal involves mostly Forest Service land covering parts of four national forests and about 15,000 acres managed by the U.S. Bureau of Land Management (BLM).

President Joe Biden proposed evaluating the 20-year mineral withdrawal as part of his October 2022 decision to designate the Camp Hale-Continental Divide National Monument, a 53,804-acre site in the state's Eagle Valley region that once served as a World War II Army camp for the 10th Mountain Division that deployed to Italy's northern Apennines in 1945.

E&E News reported that Interior Secretary Deb Haaland signed a public lands order withdrawing the 221,898 acres, the agency said.

"The Thompson Divide area is a treasured landscape, valued for its wildlife habitat, clean air and water, and abundant recreation, ecological and scenic values," Haaland said in a statement. "Today's action has been the goal of a decades-long grassroots effort from a diverse stakeholder group, including hunters, anglers, ranchers, conservation groups, and local governments — and reflects this administration's ongoing commitment to honoring and lifting up locally led conservation efforts."

Interior Department press materials touted the Thompson Divide mineral withdrawal as advancing the Biden administration's "America the Beautiful" initiative to protect 30 percent of the nation's lands and waters by 2030.

Agriculture Secretary Tom Vilsack, in explaining the move, emphasized that it will help preserve the Western Colorado region's recreation economy.

"Around $30 million flows through this region every year thanks to a one-of-a-kind landscape that draws visitors for hiking, biking, fishing, hunting and so much more," Vilsack said in a statement. "This important step will help ensure those scenic, recreation and environmental values remain intact."

The decision to protect the Thompson Divide follows a draft environmental assessment and draft finding of no significant impact in December released by the Forest Service and BLM that "recommended" the alternative approving the 20-year mineral withdrawal.

The proposal had been sharply criticized by the Western Energy Alliance, a Denver-based oil and gas industry trade group. ■

Copper demand expected to remain high;
Reduced mine production continues to loom as a challenge

COPPER'S BULL RUN should continue for at least the next three years, fueled by global supply challenges and hot demand for the metal to power energy-transition and artificial intelligence (AI) technologies, industry analysts say.

The outlook is an optimistic harbinger for Freeport-McMoRan, BHP and other producers as decarbonization and technological shifts fuel copper's latest demand wave after China's rise powered a similar one two decades ago, *Reuters* reported.

But with question marks hanging over a number of key projects, some estimate production will struggle to meet that demand.

Copper, one of the best electrical-conducting metals, is already used worldwide in motors, batteries and wiring, and nicknamed "Dr. Copper" because demand for it is widely seen as a barometer for global economic health.

Data centers to power AI servers will likely require an additional 1 Mt (1.1 million st) of copper by 2030, commodity trader Trafigura said. Further new demand is also expected to come from electric vehicles, which are built with four times more copper than vehicles with internal-combustion engines.

"Copper's second secular bull market this century is taking hold," said Citi analyst Maximilian Layton, who expects demand to outstrip supply by 1 Mt (1.1 million st) during the next three years. "Explosive price upside is possible over the next two to three years."

In a report, Layton and Citi said they expect copper prices to touch $12,000/t by December 2026, a forecast echoed in a similar report from Bank of America. Prices traded near $9,378/t on April 15, near a 14-month high.

Citi encouraged automakers and others to hedge their copper purchases, warning that the price jump could cost unhedged manufacturers an overall $320 billion, equivalent to roughly 0.4 percent of global GDP.

Factoring into the bullish price forecast are recent production struggles by First Quantum, Ivanhoe Mines, Anglo American Codelco and others. Electricity supply challenges in Zambia, Africa's second-largest copper producer, also loom.

As a result of these setbacks, Citi cut its forecast for the global copper supply this year to an increase of just 0.7 percent from its previous forecast for a 2.3 percent rise.

"The much-discussed lack of mine projects is becoming an increasing issue for copper," said Bank of America analyst Lawson Winder.

One of the biggest recent shocks to the copper market came late last year when Panama ordered First Quantum to shutter its Cobre Panama Mine, which supplied roughly 1 percent of the world's copper. The Canadian miner has started arbitration with Panama's government, but analysts do not expect the mine to reopen — if at all — until 2029.

"That was a major catalyst for a tightening in the market," said Jonathan Beigle of Ridgeline Royalties, which buys royalties of copper, lithium and other critical minerals producers. Beigle expects copper prices to eclipse $12,000/t within a few years.

In Arizona, Rio Tinto's plan to

(continued on page 16)

Newswatch contents

Alaska sues EPA over Pebble Mine
prohibitions put in place in 2023

ALASKA SUED THE the U.S. Environmental Protection Agency (EPA) on April 11 seeking to overturn an agency decision that it said effectively blocked development of the Pebble Mine, one of the world's largest copper and gold deposits.

The complaint filed in an Anchorage federal court challenges the EPA's 2023 final determination that prohibited the discharge of mining waste from the Pebble deposit into the state's Bristol Bay.

It comes about a month after a similar lawsuit was filed by the site's developer, Northern Dynasty Minerals.

The Bristol Bay watershed in southwestern Alaska supports the world's largest sockeye salmon fishery.

The EPA in reaching its decision said it was concerned that mining waste would degrade the watershed and harm important fishing ecosystems.

The state said the agency's decision would deny it billions in revenues from taxes and royalties and called the move "a blatant affront to the sovereignty" of the state.

Alaska claimed the EPA's decision arbitrarily failed to properly consider the costs and benefits of its decision in violation of federal administrative law and exceeded its authority under the federal Clean Water Act. It asked the court to set aside the final determination and declare the EPA violated those laws. ■

BHP launches $39 billion for Anglo American;
Combined company would control 10 percent of global copper supply

THE WORLD'S largest mining company, BHP Group, has proposed a $39 billion buyout of Anglo American.

It is a big bet on copper by BHP and would be the largest merger in the mining industry in more than a decade. Should the merger be completed, it would give BHP roughly 10 percent of global copper mine supply cementing BHP's position as the top producer ahead of copper-focused Codelco and Freeport-McMoRan.

This comes at a time in which demand for copper is expected to rise dramatically. Leading commodity trader Trafigura recently reported that it expects 10 Mt (11 million st) of additional copper consumption over the next decade. This surge in demand comes from various sectors, including electric vehicles, power infrastructure, artificial intelligence and automation.

"The energy transition is only just getting started, and if electricity is the lifeblood of this revolution, copper is the veins and arteries," said Peter Arkell, chairman of the Global Mining Association of China (GMAC) told *Reuters*. "There is no way that existing mines can meet the anticipated demand, therefore the major mining companies recognize that copper needs to be a fundamental part of their portfolio."

Global refined copper consumption grew 6.7 percent in 2023 to 27.63 Mt (30.45 million st), World Bureau of Metal Statistics data showed.

Global refined copper demand will rise at a compound annual growth rate of 2.3 percent from now through 2028, according to London-based commodity research firm CRU.

That robust demand outlook is coupled with unexpectedly tight supply of copper concentrate this year, fuelled by the December closure of First Quantum Minerals' massive Cobre Panama Mine.

Also in December, Anglo American cut its copper production guidance by up to 190 kt (210,000 st) for 2024 and as much as 163 kt (180,000 st) for 2025, citing lower grades and ore hardness at the Los Bronces mine in Chile, pushing analysts to revise their market balance forecasts.

CRU predicts a shortage of 176 kt (194,000 st) for global copper concentrate and a shortage of 135 kt (149,000 st) for refined copper this year, and analysts have said they expect the concentrate deficit to widen over the next three years.

Craig Lang, an analyst at CRU, said some miners are struggling to maintain production levels as mines age, which would encourage them to acquire other assets. Smelters are also likely buy stakes in mines in order to secure offtake, he added.

BHP said in a statement that purchasing Anglo would give it value-adding copper growth options.

"BHP has talked about getting more copper for a long time," said Hayden Bairstow, head of research at Australian broker Argonaut. "Anglo's got plans to go to a million tonnes per year in the next 10 years."

Anglo American has long been viewed as a potential target among the largest miners, particularly because it owns attractive South American copper operations at a time when most of the industry is eager to add reserves and production. However, suitors have been put off by its complicated structure and mix of other commodities from platinum to diamonds, and especially its deep exposure to South Africa.

Bloomberg News reported that Anglo has faced a series of major setbacks over the past year as prices for some of its key products plunged, while operational difficulties have forced the company to slash its production targets — driving down its valuation and leaving the company vulnerable to potential bidders.

The company said in a statement that its board was reviewing the proposal, which it confirmed after *Bloomberg* first reported BHP's interest. ■

Baltimore bridge collapse delays some coal exports

COAL EXPORTS FROM the busy U.S. port of Baltimore have been disrupted following the collapse of the Francis Scott Key bridge that was struck by a massive cargo ship in March, rail and coal companies said.

Rail company CSX said its existing coal customers should expect "potential shipment delays" after the accident.

CSX owns the Curtis Bay coal pier in Baltimore, located near the site of the collapse of the Francis Scott Key Bridge, which CSX plans to keep operational for now as it continues to "assess the circumstances," the company told *Reuters*.

CSX said it currently has capacity to dispatch additional trains to CSX-served coal terminals in Baltimore before it reaches pile space limits.

Coal producer CONSOL Energy, which has a marine export terminal in the Port of Baltimore, said that vessel access in and out of its terminal was also delayed.

During the first nine months of 2023, Baltimore was the second-biggest port for U.S. coal exports, behind Norfolk, VA, according to the latest data from the U.S. Energy Information Administration (EIA).

During the first nine months of 2023, Baltimore exported about 18.4 Mt (20.3 million st) of coal, up from 13 Mt (14.3 million st) during the same period in 2022.

About 12 Mt (13.3 million st) of exports from Baltimore during the first nine months of 2023 were steam coal and 6.3 Mt (7.0 million st) were metallurgical coal.

Ranked as the 15th-largest container port in the United States, the Port of Baltimore is ranked as the third-largest port on the East Coast and ninth-largest U.S. port in terms of international cargo tonnage in 2023. The Port of Baltimore exported $3.62 billion of coal in 2023. ■

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Resolution Copper will keep its copper in the US;
Rio Tinto executive commits to domestic goals

RIO TINTO AIMS TO keep all of the copper from its Resolution Mine inside the United States should the long-delayed and controversial project win regulatory approval, a senior executive told *Reuters.*

The Resolution Mine could produce more than 18.1 Mt (40 billion lbs) of copper and supply more than a quarter of U.S. demand, but it is strongly opposed by some Native Americans given concerns the project could destroy a site of religious and cultural import.

That has placed Resolution at the center of a simmering debate about where best to secure copper and other critical minerals for the clean energy transition.

Despite concerns that Rio Tinto would export copper from the mine, Bold Baatar, head of Rio Tinto's copper business told *Reuters* that the company sees strong demand inside the United States.

"Certainly if Resolution comes on stream, all of that copper we would like it to be sold in the U.S.," he said.

Rio Tinto operates Utah's Kennecott copper mine and smelter, with all of its production consumed inside the country. The only other U.S. copper smelter is operated by Freeport-McMoRan.

A Native American group asked all members of a U.S. appeals court to overturn an earlier ruling that granted land to Rio Tinto and minority partner BHP to develop Resolution. U.S. President Joe Biden had separately paused a regulatory decision on the project in 2021.

Baatar said he would be tracking the court case. He and Rio Tinto have long said they believe Resolution can be developed safely.

"The U.S. is endowed with the resources. It's probably one of the most stringent environmental, legal and regulatory frameworks in the world," Baatar said.

"I think the U.S. will be making a choice between 'in our backyard' or 'in somebody else's backyard.' But there's no security of supply if it's somebody else's backyard."

The global copper industry has in recent years faced rising opposition to a slew of projects, including Resolution as well as First Quantum's Cobre Panama Mine, which Panamanian officials forced to close last year, taking away 1 percent of the world's supply of copper.

That has sparked concerns from Baatar and other industry executives about how the world can obtain the copper needed for the energy transition. ■

Final rule on silica dust published by MSHA; **Rule will apply to coal and metal-nonmetal mines**

ON APRIL 18, the U.S. Mine Safety and Health Administration (MSHA) issued its final rule, titled “Lowering Miners’ Exposure to Respirable Crystalline Silica and Improving Respiratory Protection,” to reduce miner exposures to respirable crystalline silica and improve respiratory protection for all airborne hazards.

The final rule lowers the permissible exposure limit (PEL) for respirable crystalline silica to 50 micrograms per cubic meter of air ($\mu g/m^3$) for a full shift, calculated as an eight-hour time-weighted average (TWA) for all miners. It establishes an action level for respirable crystalline silica at 25 $\mu g/m^3$ for a full shift, calculated as an eight-hour TWA for all miners. The new rule includes uniform requirements for controlling and monitoring exposures to respirable crystalline silica at coal and metal and nonmetal (MNM) mines and includes medical surveillance requirements for MNM mines, modeled on the existing medical surveillance requirements for coal mines. The rule also updates existing respiratory protection requirements by incorporating by reference a voluntary consensus standard by the American Society of Testing and Materials (ASTM) that reflects the latest advances in respiratory protection technologies and practices — ASTM F3387-19 Standard Practice for Respiratory Protection.

The final rule will take effect on June 17, 2024. Coal mine operators have 12 months to come into compliance with the final rule’s requirements while MNM mine operators have 24 months to come into compliance (including medical surveillance).

NPR reported that instances of overexposure must be reported to MSHA, a requirement that was not in a regulation initially proposed last year but was inserted after the news organizations' reporting and complaints from mine safety advocates.

The regulation imposes requirements that have never existed for MNM mines, including a health surveillance program with free periodic exams to detect early stages of silica-caused lung disease. The results of those exams must be reported to the National Institute for Occupational Safety and Health, which has monitored the health of coal miners for decades.

The National Mining Association, which represents mine operators, welcomed a key element of the new regulation. “We fully support the new, lower [silica dust] limits contained in the rule and are committed to working to improve the health and safety of our miners,” Ashley Burke, senior vice president, communications told *NPR*. ■

Mining permit issued to Piedmont Lithium; **North Carolina mine can produce 30 kt/a of lithium hydroxide**

PIEDMONT LITHIUM announced that the North Carolina Department of Environmental Quality's (NCDEQ) Division of Energy, Mineral, and Land Resources (DEMLR) has issued an approval of Piedmont's mining permit for the construction, operation and reclamation of the proposed Carolina Lithium project in Gaston County, NC. DEMLR provided the permit approval following a thorough review of the application submitted by Piedmont on Aug. 30, 2021. The mining permit is subject to conditions both customary and specific to Piedmont's type of project.

"This is an exciting day for all of us at Piedmont Lithium. I would like to thank the leadership and staff at NCDEQ and DEMLR for their diligence in the process, as well as the members of our team who worked rigorously for more than two and a half years to ensure that every aspect of the project met the state's high standards for approval," said Piedmont Lithium president and chief executive officer Keith Phillips. "We plan to develop Carolina Lithium as one of the lowest-cost, most sustainable lithium hydroxide operations in the world, and as a critical part of the American electric-vehicle supply chain. The project is expected to contribute billions of dollars of economic output and several hundred jobs to Gaston County and North Carolina's growing electrification economy."

The proposed mine, which can produce 30 kt/a (33,000 stpy) of lithium hydroxide, could become one of North America's largest sources of lithium.

It had run into regulatory hurdles after local residents, worried about the project's environmental impact, raised objections.

"Carolina Lithium is a highly strategic project," continued Phillips. "Located within both the renowned Carolina Tin-Spodumene Belt and the U.S. Battery Belt, the project is being designed as a fully integrated mining, spodumene concentrate and lithium hydroxide manufacturing operation. There are currently no such integrated sites operating anywhere in the world, and the economic and environmental advantages of this strategy are compelling.

"Technical studies have demonstrated that Carolina Lithium could be a low-cost producer of spodumene concentrate and lithium hydroxide, benefitting from exceptional infrastructure, minimal transportation distances, low energy costs, a deep local talent pool, and proximity to cathode and battery customers as well as local markets for the monetization of byproduct industrial minerals. The project is further advantaged by the competitive corporate tax regime offered in the United States, the absence of significant royalties, and the benefits inherent in the Inflation Reduction Act of 2022. After-tax returns are what matter, and we are not aware of any jurisdiction that better combines the benefits of significant spodumene resources, deep customer markets, and low royalty and income tax rates," he added.

"The North Carolina mining permit approval is the precursor for the county rezoning process, and we look forward to continued engagement with the local community and the Gaston County Board of Commissioners. Construction would commence following receipt of all required permits, rezoning approvals, and project financing activities. We have had extensive and ongoing dialogue with possible funding sources for Carolina Lithium, including the U.S. Department of Energy's Loan Programs Office and strategic parties who could provide some combination of capital, offtake and technical support," said Phillips. "We have been encouraged by those discussions and will endeavor to put in place a strong funding plan that will maximize value for Piedmont shareholders." ■

Limits on mining and other development introduced; **Interior Department will reject road to Ambler Mine project**

THE BIDEN administration on April 19 took steps to limit both oil and gas drilling and mining in Alaska, angering state officials who said the restrictions will cost jobs and make the U.S. reliant on foreign resources.

The measures are aligned with President Joe Biden's efforts to rein in oil and gas activities on public lands and conserve 30 percent of U.S. lands and waters to combat climate change.

The U.S. Department of the Interior finalized a regulation to block oil and gas development on 40 percent of Alaska's National Petroleum Preserve to protect habitats for polar bears, caribou and other wildlife and the way of life of indigenous communities.

The agency also said it would reject a proposal by a state agency to construct a 340-km (211-mile) road intended to enable mine development in the Ambler Mining District in northcentral Alaska.

The agency cited risks to caribou and fish populations that dozens of native communities rely on for subsistence.

"I am proud that my Administration is taking action to conserve more than 13 million acres in the Western Arctic and to honor the culture, history, and enduring wisdom of Alaska Natives who have lived on and stewarded these lands since time immemorial," Biden said in a statement.

The NPR-A, as it is known, is a 93 million-ha (23 million-acre) area on the state's North Slope that is the largest tract of undisturbed public land in the United States. The new rule would prohibit oil and gas leasing on 4.3 million ha (10.6 million acres) while limiting development on more than an additional 809,000 ha (2 million acres).

The Ambler Access Project, proposed by the Alaska Industrial and Development Export Authority, would enable mine development in an area with copper, zinc and lead deposits and create jobs, the authority has said.

The U.S. Bureau of Land Management released its environmental analysis of the project, recommending "no action" as its preferred alternative. The project now faces a final decision by the Interior Department.

"When you take off access to our resources, when you say you cannot drill, you cannot produce, you cannot explore, you cannot move it — this is the energy insecurity that we're talking about," Senator Lisa Murkowski said. "We're still going to need the germanium, the gallium, the copper. We're still going to need the oil. But we're just not going to get it from Alaska." ■

Perpetua Resources gets EXIM LOI for $1.8 billion loan; **Loan would be one of Washington's largest investments in a mine**

PERPETUA RESOURCES has received a letter of interest (LOI) from the U.S. Export-Import Bank (EXIM) for a loan worth up to $1.8 billion to develop an antimony and gold mine in northern Idaho, part of Washington's evolving strategy to offset China's critical minerals sector dominance.

The loan, if approved, would be one of Washington's largest investments ever in a mine and reflect the Biden administration's growing comfort using the federal government's balance sheet to fund extractive projects at terms more favorable than those available with private lenders, a practice that Beijing has deployed for years.

Perpetua said EXIM, which acts as the U.S. government's export credit agency, has told the company that it qualifies for two loan programs designed to support those that compete with China.

The loan would have a 15-year repayment term, far longer than likely with private financing. The interest rate would be set at closing, although EXIM has told Perpetua it qualifies for "flexibility" on the rate given the mine's Chinese competitors.

Perpetua would have to arrange a separate equity funding component, likely either through issuing stock or a royalty.

The LOI indicates that Perpetua — which counts hedge fund manager John Paulson as its largest shareholder — has cleared the initial loan requirements to start the formal application process, which is expected to take 12 months. The letter also allows Perpetua to start negotiations with equipment suppliers.

The Pentagon has already committed nearly $60 million to fund permitting for the mine, known as Stibnite, which would entail cleaning and expanding a site that was polluted by World War II-era mining.

"This loan is a big piece of our financing puzzle," said Jon Cherry, who became Perpetua's chief executive officer last month. "It provides a lot of certainty to move this project forward."

In response to a request for comment from *Reuters,* EXIM said: "Letters of interest are nonbinding statements that indicate that EXIM is open for business in the market identified and is willing to consider financing for a given export transaction should an application be submitted."

Located 241 km (150 miles) north of the state capital of Boise, Stibnite contains roughly 189 million lb of antimony, a metal used as a hardening agent for bullets and tanks, as well as in flame retardants and alloys for electric-vehicle batteries. China is the world's largest antimony producer, with a nearly 50 percent market share. Stibnite would be the only American source of the key metal.

The deposit also contains an estimated 6 million ounces of gold, most of which would be exported to international refineries, thus meeting a key requirement for EXIM financing. While gold is not a critical mineral, its production is seen as helping to financially buttress the mine's antimony production and ensure a domestic supply of the metal for the Pentagon.

Concerns have grown that China could try to harm the Perpetua mine's prospects by ramping up its own production of antimony in a bid to gain global market share, something Chinese-linked producers of nickel, cobalt and other critical minerals have systematically done in recent years.

The $1.8 billion loan figure is based on an EXIM formula tied to the number of construction, operation and reclamation jobs at the mine. The project was forecast in 2020 to cost $1.3 billion, a number expected to rise due to post-pandemic inflation.

The backing for Perpetua comes just weeks after the U.S. Department of Energy (DOE) said it would lend Lithium Americas up to $2.26 billion to build Nevada's Thacker Pass lithium project, which will supply General Motors.

DOE rules require the use of union labor and do not allow the funds to be used to dig a mine itself, although processing facilities do qualify. The EXIM financing rules do not have the same restrictions on labor and will allow Perpetua to dig a mine pit.

The Stibnite project has not yet won the support of Idaho's Nez Perce tribe, which is concerned the mine could affect the state's salmon population. The company and the tribe, however, have started discussing water restoration projects.

In addition to the potential loan for Perpetua, EXIM has announced LOIs to Australian Strategic Materials for a rare earths project as well as to niobium miner NioCorp and titanium recycler IperionX. ■

Copper: Data centers and electric vehicles push demand

(continued from page 8)

open one of North America's largest copper mines is mired in complex litigation. The project last month received a favorable court ruling that is expected to be appealed to the U.S. Supreme Court.

In Chile, state-controlled Codelco, which accounts for a quarter of the country's copper production, has been plagued by operational issues that have pushed its output to the lowest level in 25 years.

Regulatory uncertainty from the administration of President Gabriel Boric, a leftist who has had a tense relationship with the mining industry since his 2022 inauguration, initially affected investment, but Boric has been working to mend fences.

"The investment climate has improved a lot in Chile," said Kathleen Quirk, the incoming chief executive officer of Freeport-McMoRan, which had paused an expansion of a mine project in the South American country. "It had been great for a long period of time. Then in 2022 and 2023 it hit some bumps, but now it's much more positive." ■

First fully battery-electric trolley system passes test; **Industry leaders collaborate for testing at Boliden's mine**

BOLIDEN, EPIROC and ABB have passed a new technology milestone by successfully deploying the first fully battery-electric truck trolley system on an 800-m (2,600-ft) long underground mine test track in Sweden, with a 13 percent incline. This means the mining industry is a step closer to realizing the all-electric mine of the future, with sustainable, productive operations and improved working conditions.

The achievement of the collaboration in Boliden's Kristineberg Mine in northern Sweden marks a critical moment for the mining industry as it continues to face rising pressures to balance increased outputs of critical minerals and metals with lower carbon emissions and energy usage. Demand for minerals critical to society's clean-energy transformation is predicted to increase between 1.5 to seven times by 2030 according to the International Energy Agency (IEA), making electrification a priority.

In tandem with reducing carbon emissions, the electrification of mining also promises improved health and safety for the industry's workforce. By deploying this system, the collaboration partners aim to prove that the underground working environment can be significantly improved, with less emissions, noise and vibration while reducing the total cost per ton.

"Over the past three years, we have worked in close collaboration with the ABB and Epiroc teams to bring the electric mine of the future one step closer," said Peter Bergman, general manager Boliden Area, Boliden. "The most important thing for us is of course that the technology works in our own operations, but we also see added value that we together with our partners can drive technology development so that the system can be used in other mines. We are proud to have taken this concept to a live installment."

Each partner has provided a unique set of expertise to this development process, clearly demonstrating the value of industry collaboration. Epiroc has added dynamic charging to its proven battery-electric Minetruck MT42 SG and battery system, and the trolley solution is equipped with ABB's DC converter, HES880 inverters and AMXE motors to enhance the power. The truck features a trolley pantograph connected to an overhead catenary line, a concept which is highly suitable for long haul ramps. The electric trolley line gives additional assistance to the battery-electric mine truck on the most demanding stretches up-ramp while fully loaded, enabling further reach and battery regeneration during drift, which increases productivity drastically for a mining operation. ■

Advantages and risks of the application of TBMs for mining projects

by Dean Brox

Figure 1

TBM assembly/launch cavern inside an underground mine.

Despite the advent of tunnel boring machines (TBMs) more than 70 years ago in the early 1950s, their use for mining infrastructure has been limited to a few access, exploration, drainage and water supply tunnels (Brox, 2013). TBMs have successfully been used for the construction of the majority of tunnels generally longer than 4 km (2.5 miles) for civil, hydropower and oil and gas infrastructure projects with more than 50,000 km (31,000 miles) of tunnels, and more than 10,000 TBMs have been manufactured (Zheng et al., 2014). TBMs offer many advantages over conventional excavation methods including improved safety and working environment, reduced ground support, reduced overbreak, higher advance rate and overall lower cost. Today, TBM suppliers can more easily design TBMs for the anticipated geotechnical conditions and to specifically design for any identified adverse conditions to de-risk the TBM from possible entrapment.

TBMs have successfully completed infrastructure projects, and they continue to be used for the construction of the majority of infrastructure tunnels given the recognized benefits of lower total project costs and shorter duration (earlier completion) of the construction schedule. Given that time is money for most infrastructure projects, especially those involving the generation of revenue upon completion as for energy, water supply and traffic, the importance of the successful application of low-risk, rapid tunnel construction technologies cannot be overemphasized.

In particular, the hydropower industry has reaped and continues to reap the benefits of the application of TBMs in challenging mountainous regions including those of the Andes and Himalayas for the early completion of long and deep tunnels as part of major revenue-generating energy projects for nearly 1,000 km (621 miles) of tunnels. A secondary benefit that has been recognized with the use of TBMs for these projects has been where limited access and/or environmental restrictions may preclude the use of multiple intermediate access adits, thus significantly reducing the construction impact footprint of projects on local communities and environmental resources, including ground water.

The international mining industry is developing an increasing number of ore reserves that are located in ever more remote project sites where long and sometimes deep access tunnels are required. Accordingly, the application of TBMs is being increasingly considered. However, there appears to be a reluctance among many mining developers to fully embrace the use of TBMs for the following key reasons:

- Limited historical use of TBMs for mining projects (limited track record).
- A small number of unsuccessful uses where TBMs should not have been trialed due to unidentified adverse conditions.
- Misconception or misunderstanding that TBMs are prone to be entrapped

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in difficult ground conditions without mitigation solutions to limit overall delays.
- Undesirable curved invert/floor for mining operations.

Overall, there appears to be an ongoing reluctance and negative perception by mining professionals to accept the use of TBMs for mining projects. This continues even where comprehensive technical assessments have concluded TBMs to be of low risk. Notwithstanding that, more than 95 percent of tunnels more than 4 km (2.5 miles) in length have been successfully constructed for civil and hydropower infrastructure and continue to be planned to be constructed using TBMs. Figure 1 presents the TBM assembly and launch cavern used for the 11-km (6.8-mile) TBM-excavated water supply tunnel at the El Teniente Mine in Chile.

Are mining projects unique for TBM use?

A commonly recognized perception in the international tunneling industry is that mining projects are considered to be unique in comparison to other major infrastructure projects as a reason for not using TBMs. However, this perception is actually a misconception for the following reasons:

- Mining projects are no more time and cost sensitive than other major infrastructure projects, especially those that are revenue generating such as hydropower projects, where early completion can mean improved economics and earlier-than-expected payoff and profit-making of the project.
- While it is recognized that most mining projects are located in extremely remote locations, including challenging mountainous terrain locations for access, numerous major tunnels have been constructed using TBMs in similarly remote and high-elevation locations, including the Himalayas, Caucasus and Andes Mountains.
- While mining projects require the early procurement of major equipment

Figure 2

Precast concrete floor decking for a TBM tunnel.

for operations (such as large shovels, haul trucks and crushers) due to long lead times, the significant costs associated with this early procurement is not more onerous than those for the early procurement of a TBM to take advantage of an early start of a major tunnel.

- While most tunnels for a mining project are desired to have a flat floor for traffic during operations and/or for the installation of key equipment (conveyor), the curved invert/floor excavated by a TBM can be easily prepared to meet these requirements by either the backfilling of tunnel spoil as a single one-pass operation behind a TBM as it advances or by the concurrent placement of a precast concrete segmental floor (Fig. 2) as the TBM advances to provide an immediate operating floor after breakthrough of the tunnel.

One aspect where mining projects for major tunnels may in fact be recognized as unique is where there exists adverse geotechnical conditions as a result of major alteration of the prevailing bedrock conditions as well as additional disturbance of the bedrock with additional geological faults. Alteration of the host or site bedrock is quite common in the vicinity of major orebodies and alteration is typically associated with reduced rock strength and quality as well as acidic ground water.

Similarly, the presence of additional geological faults associated with major orebodies is also typically associated with reduced rock strength and quality. Accordingly, the alignment of any proposed tunnel in close proximity to a major orebody should be carefully planned and designed to avoid the presence of any associated adverse geotechnical conditions as much as possible.

Brief history, types and applications of TBMs

History of TBMs. The first use of a fully mechanized TBM was for the construction of a tunnel in low-strength bedrock at the Oahe Dam project in South Dakota in 1952. The success of the construction of this tunnel resulted in the manufacturing of additional TBMs for the construction of long tunnels in stronger bedrock. The early TBMs developed up to the 1980s were of limited power capacity, which resulted in their removals from some projects with extremely strong and abrasive quartzite rock such as in the Himalayas.

A key technological advancement with TBMs is that the power capacity and ability to excavate extremely strong and abrasive rock has greatly increased in the last 20 years. This includes the use of larger-sized cutting discs measuring 483 and 508 mm (19 and 20 in.) that allows for increased thrust, resulting in improved rates of advance.

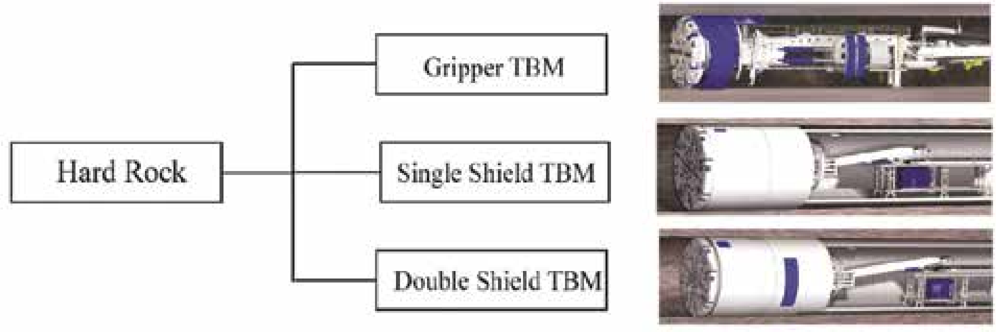
TBMs have been used on about 75 mining projects and 220 km (136 miles) of tunnels to date (Brox, 2014; Zheng et al., 2014), including the completion of dozens of kilometers of tunnels in coal mines in Germany in the 1960s to 1970s. Other early uses include trials in extremely strong and abrasive rock in the deep gold mines in South Africa that were unsuccessful due to the limited power capacity of the TBMs for these extreme conditions. The longest continued and successful use of TBMs for mining applications has been at the Stillwater Mine in Montana, since the 1980s.

Types of TBMs and most suitable applications. There are essentially three main types of TBMs used for the construction of tunnels in rock: (1) open or gripper, (2) single shield and (3) double shield (Fig. 3).

Open/gripper TBMs have been fabricated up to nearly 15 m (50 ft) in diameter and include a fingershield extending behind the cutterhead

Figure 3

Main types of TBMs for mining.



over the forward part of the TBM that provides limited protection of workers but allows for the installation of rock support as soon as the rock becomes exposed before the position of the grippers. These TBMs are most suited to homogeneous and good-quality rock conditions and where a limited number of geological faults are expected. They allow for the easy completion of probe drilling behind the cutterhead that may impact the advancement of the TBM.

Open/gripper TBMs are ideally suited for proposed tunnels in rock that has been characterized with a significant portion of good-quality rock conditions and limited amounts of geological faults.

In comparison, double-shield TBMs include a three-component structural shield around the TBM that typically extends up to three times the diameter back from the cutterhead as well as grippers and rear thrusters. The multicomponent shield allows for the advancement of the forward shield of the TBM while the rear shield remains fixed for gripping, and is capable of achieving high rates of advance in challenging and varying rock conditions.

The distinct advantage of double-shield TBMs is the flexibility to install a variety of tunnel support including standard rock support consisting of rock bolts, mesh and shotcrete as well as precast concrete segments or steel ribs. The TBMs' effective thrust and overall advance may be significantly impacted by squeezing or high-deformation rock conditions that may cause entrapment of the TBM shield.

The use of a double-shield TBM for tunnel excavation through major geological fault zones should therefore be thoroughly evaluated with strong consideration of the implementation of mitigation measures prior to any such excavation. Under such difficult tunneling conditions, double-shield TBMs can, however, utilize the rear thrusters to push off of precast segments or specially designed steel ribs installed as part of the rock support that is typically designed for such conditions.

Double-shield TBMs allow for probe drilling through the rear shield with no impact on TBM advancement. Double-shield TBMs are ideally suited for proposed tunnels in rock that had been characterized with a significant portion of fair-quality rock conditions with substantial amounts of geological faults or potentially unstable rock conditions.

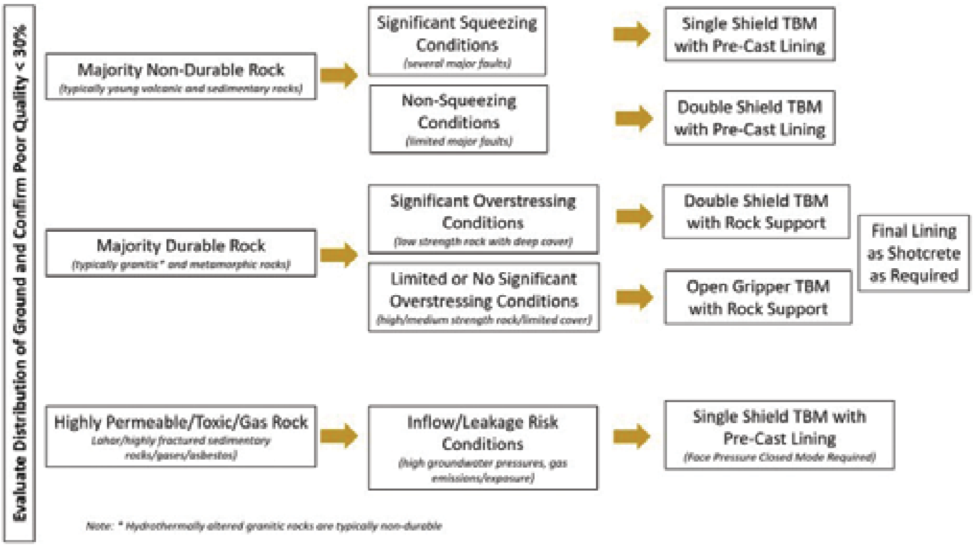
Single-shield TBMs are used much less often for rock tunnels due to their actual lower advance rates in comparison to double-shield TBMs. Single-shield TBMs have typically been used in conjunction with precast concrete segmental lining for the construction of water conveyance tunnels in nondurable rock conditions. The main advantage of single-shield TBMs for such tunnels is the shorter construction schedule in comparison to the use of an open/gripper TBM followed by a cast-in-place concrete lining. The distinct disadvantage of single-shield TBMs for rock tunnels is that they are limited to thrusting off of the segmental lining only, as they do not include grippers. As such, single-shield TBMs are more difficult to get freed when entrapped within a geological fault zone.

The evaluation of the most suitable type of TBM for any particular project should primarily be based on a sound understanding of the anticipated total distribution of the geotechnical conditions and, in particular, the quantity of adverse geotechnical conditions. Brox (2021) presents a simple graphic to assist in the technical evaluation of the most suitable type of TBM for any project (Fig. 4) for which the quantity of adverse geotechnical conditions should not be more than 30 percent.

As included in Fig. 4, TBMs can also be used for early access to underground mining reserves overlain by saturated overburden with the use of face-pressurized TBMs with the concurrent installation of precast concrete segmental linings as per the typical construction approach for metro tunnels in urban areas. For these applications, TBM excavation should continue until "socketed" into low-permeability bedrock with no further elevated ground-water pressures and then should also be considered for the use of predevelopment, such as a ring tunnel configuration around the mining reserves to provide multiple locations for further development of the mining layout by drill-and-blast methods.

Figure 4

Technical evaluation of suitable types of TBM.



Key advantages of TBMs

Improved safety and environment for workers. Each of the main types of TBMs provide different levels of safety for workers subject to the exposed geotechnical conditions during tunnel construction. For open/gripper TBMs, the rock conditions become exposed immediately behind the TBM cutterhead and fingershield, thereby requiring the rapid installation of ground support so workers do not become exposed to any unsupported ground. In comparison, for shielded TBMs, the workers are fully protected inside the shield of the TBM, which prevents any loosened rock from falling into the working area but requires the installation of ground support or precast concrete segmental lining at the end of the shield to stabilize the exposed ground.

Environmental conditions for workers can be greatly improved with the use of TBMs because blasting, with its associated fumes, is not required, though adequate and often enhanced ventilation is required for TBMs as their operation results in elevated temperatures at the advancing tunnel face. If gaseous conditions are or may be present, a TBM can be operated in a "closed mode," whereby the face area is entirely contained within a front chamber of the TBM such that workers will not be exposed to gases such as methane, or the adverse environmental conditions of asbestos.

Reduced excavation overbreak. The limited vibrations associated with TBM excavation prevents damage to and the loosening and dislodgement of potentially unstable rock from a tunnel profile, thereby maintaining stability and preventing overbreak, thus reducing the total volume of excavated material for transport and disposal. The excavation of tunnels by TBMs to the theoretical diameter without any fallout of ground can actually provide a false sense of stability, and all exposed ground should be supported to minimum standards for safety.

Reduced ground support. TBMs cause vibrations but do not impart any form of damage to the surrounding rock other than the redistribution of stresses, and therefore minimizes but does not prevent instabilities from occurring as rock conditions are exposed and prior to the installation of support to maintain stability. Accordingly, ground support quantities in terms of rock bolts, mesh and shotcrete can be reduced as much as 30 percent compared to drill-and-blast excavation.

Higher advance rates. The greatest advantage of TBMs is the ability in fair- to good-quality ground to achieve and sustain high rates of advance that are a minimum of three to four times that of drill-and-blast excavation and a minimum of two times that for excavation using roadheaders, which are restricted for long tunnels due to enhanced ventilation requirements. Figure 5 presents typical TBM advance rates in relation to diameter for various projects, including a limited number of historical mining projects. Maximum daily TBM advance rates in excess of 60 m (200 ft) have been achieved in good-quality rock conditions with an open/gripper TBM with a large diameter (9 m, or 30 ft), operating at great depth, and maximum monthly TBM advance rates in excess of 1,200 m (4,000 ft) have been achieved for moderate diameters (6 m, or 20 ft).

Lower linear and total tunnel costs. Given the reduced overbreak and ground support requirements along with the higher rates of advance associated with TBMs with less labor, the higher costs of a new or previously used TBM are appreciably offset, resulting in much lower linear cost as well as total tunnel cost by as much as 25 percent subject to consideration of all cost factors.

Reduced environmental footprint. TBMs are normally used for the construction of a long tunnel from portal to portal with the majority of construction activities at a single portal site. Accordingly, the use of TBMs removes the need for intermediate access adits as is typically required for drill-and-blast methods, which are associated with greater impacts at the project site with multiple access roads, camps and ongoing supplies during construction, particularly for projects located in close proximity to communities or existing important infrastructure.

Reduced energy impact/footprint. TBMs require an appreciable amount of energy for construction, including more than 10 MW for TBMs with diameters greater than 10 m (32 ft). While TBMs can be operated with diesel generators, there are major cost savings associated with the use of local grid power. Even at remote project sites, it is often planned to install a local substation as part of any early works advanced contract to take advantage of the lower total costs of energy and environmental savings of the use of high volumes of diesel along with the requirements for the supply and transport of diesel to the project site for the total duration of construction.

Possible reuse of tunnel spoil. Unlike the spoil that is generated from drill-and-blast methods, which is contaminated with blasting residues, TBM spoil is relatively clean, assuming it is transported directly from the advancing face via an initial conveyor system to either the railcars typically used for small-diameter tunnels or to a larger main conveyor for larger-diameter tunnels and does not come into contact with hydraulic oils and other contaminated products or chemicals used for TBM tunneling. Accordingly, TBM spoil, with its useful gradation of size of chips, can be used for a variety of purposes within a project site, including the backfilling of areas and as roadbase material, or provided often without charge to the local communities that can often find uses for it.

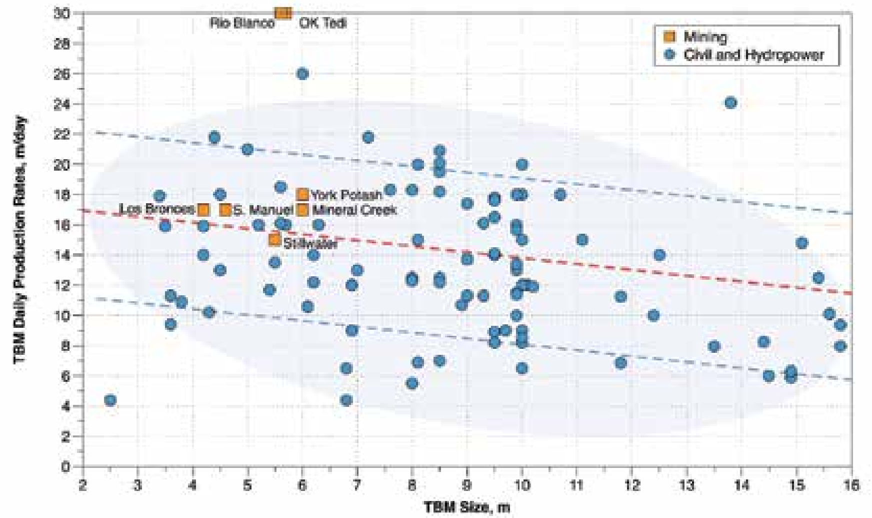
Key disadvantages of TBMs

The key disadvantages associated with the use of TBMs are as follows:

- Long procurement time, minimum of 12 months.
- Possible access challenges for mobilization.
- Minimum large alignment radii dependent on diameter.
- Circular or curved invert/floor.
- Failure of main components including main bearing.
- Key skilled labor required.
- High power demand (offset by earlier completion).
- Deferred overstress behind tunnel face (TBM backup).
- Not applicable for ancillary excavations.
- Limited flexibility for unexpected adverse conditions.

Figure 5

TBM advance rates in relation to diameter.



These disadvantages are not typically applicable to every project, and the risks associated with them can usually be reasonably managed to prevent major delays. In particular, and as with major mining projects, many large infrastructure projects require the early procurement of major equipment of significantly higher costs versus that of a TBM. For remote projects, it is prudent to require spare parts of all major components to be available near the project site in order to limit appreciable delays. With the increasing global demand for the use of TBMs, there is global demand for the required skilled labor, and project clients must be mindful to accept costs that can afford to attract top-level labor (A-Team) in order to complete their projects in a timely manner. Finally, one of the main disadvantages that is often misunderstood is that TBMs do not have acceptable flexibility to advance through unexpected conditions. It should, however, be noted that TBMs can be required to include special de-risking measures and components such as grouting ports in the TBM cutterhead or shield to facilitate advancing through such adverse conditions. In addition, a commonly adopted and successful de-risking

Table 1

Statistics and entrapment rates of TBM manufacturers.

TBM supplier	Total TBMs rock	Total length (km)	Average length (km)	Total entrapments	Entrapment rate (%)
A	128	747	5.9	10	1.3
B	100	885	8.9	5	0.6
C	390	1,268	3.3	3	0.2
D	18	123	6.8	0	0
E	1,011	5,171	5.1	27	0.5
F	33	359	10.9	7	1.9
Totals	1,680	8,553	7.0	52	
Overall industry-weighted average for rate of TBM entrapment					0.61

solution for the entrapment of TBMs is the construction of small bypass tunnels around the TBM to remove any unstable materials. Many bypass tunnels have been successfully constructed on several projects to limit delays to less than one week before resuming TBM excavation.

Risk of TBM entrapment and industry statistics

TBM entrapment risk. TBMs can and have become trapped upon the intersection of unexpected adverse geotechnical conditions, typically consisting of large geological faults that are often associated with weak/soft clay-like conditions that result in squeezing upon intersection during TBM excavation. In some cases, highly fractured conditions may be present that result in the collapse of large volumes onto a TBM, causing entrapment.

The delays caused by such entrapments can vary from a few hours to multiple months, depending on the nature of the geotechnical conditions and the manner in which the TBM became entrapped. The typical reason why unexpected geological faults or other adverse geotechnical conditions may be intersected during the construction of a long tunnel with a TBM is that only limited preconstruction geotechnical investigations were performed and/or limited or inadequate interpretation and analysis of the geotechnical information were undertaken, which may be due to limited available time and/or project budget constraints or due to limited experience of the project designers.

Industry statistics for TBM entrapments. The occurrence of TBM entrapment in rock tunnels has been evaluated based on what is believed to be the first-ever survey of this critical information from the majority of TBM manufacturers in the industry as of 2024. Table 1 presents the statistical data provided by the majority of the international TBM manufacturers in terms of numbers of TBMs manufactured, their use in terms of total tunnel length, and the total number of entrapments.

The majority of TBMs were manufactured by a limited number of companies, and therefore these TBMs have been used the most in the industry, resulting in a greater number of total entrapments. However, the important aspect and metric is that the rate of entrapment, defined in terms of the total number of entrapments per kilometer of tunnel length, is less than 1 percent, which represents an extremely low rate of failure when considering other sophisticated machinery and equipment including those used in the mining industry. From this information, it can be postulated that the probability of TBM entrapment for any given long tunnel project, assuming limited adverse geotechnical conditions and that the application of a TBM is considered to be viable, can be expected to be extremely low. The low probability of entrapment is, however, not applicable for those projects with long tunnels where there is a large proportion of adverse geotechnical conditions and therefore where a TBM should not be considered to be viable, as discussed earlier.

Key requirements and mitigation solutions

Technical design features – Entrapment de-risking. The manufacturing of TBMs has advanced appreciably over the past 30 years to include mitigation solutions as key design features to avoid and reduce the delays associated with TBM entrapment, which can be required to be included for any project by way of technical specifications. In particular, it has been recognized that double-shield TBMs, once thought of as being associated with higher risk of entrapment versus single-shield or gripper TBMs, offer a better ability for the de-risking of entrapments. The following risk mitigation measures can be incorporated into the design of a TBM for the de-risking of TBM entrapment (Grandori, 2016):

- Conical (tapered/stepped) shield designs.
- Retractable shield capability.
- Enhanced steering control for mixed-face conditions.
- Extreme overcut capacity (typically 50 cm on diameter).
- High thrust, power and torque (similar to that for earth-pressure-balance (EPB) TBMs).
- Enhanced ground treatment capability

including multiple ports through the cutterhead, frontshield, tailshield and bulkhead for probe drilling, drainage and grouting.
- TBM spoil control including flood doors to regulate the flow of spoil and water to the conveyor, and to facilitate similar/quasi-EPB closed mode of operation to limit face instability and inrushes/flowing ground.

All of the above de-risking measures can be easily equipped and included in the design of a TBM at the start of a project and the costs associated with these special measures, while not appreciable, still far outweigh the risks associated with the delays of a TBM being entrapped.

Geotechnical investigations during construction. The most important risk mitigation solution to attempt to avoid and/or prevent the entrapment of a TBM is to regularly perform forward investigations ahead of an advancing TBM, consisting of the drilling of long probe holes to detect water and weak/fractured ground. They can be easily managed and performed during maintenance without disruption to normal production. In addition, the TBM tunneling industry has had available a geophysical technique referred to as tunnel seismic prediction, or TSP (Hecht-Mendez and Dickmann, 2016) to explore ahead of an advancing TBM to detect zones of low seismic velocity that typically represent weak and/or fracture zones. The application of probe drilling in conjunction with forward geophysical techniques has slowly become standard international good practice for risk management for the construction of long tunnels using TBMs.

TBM use for major infrastructure projects

Since the early 1990s, there has been an increased use of TBMs and the successful completion of long tunnels as part of the construction of major civil and hydropower projects worldwide. The civil and hydropower industries have recognized the application and have successfully managed the risks associated with TBMs for their projects. In fact, the majority of long tunnels (longer than 4 km, or 2.5 miles) sited in bedrock, as well as the majority of short tunnels (shorter than 4 km, or 2.5 miles) sited in overburden, continue to be constructed using TBMs as the lowest-risk approach of construction, especially for tunnels in urban areas where the disturbance of overlying existing infrastructure must be prevented or limited. For hydropower tunnels, there is an increasing use of precast concrete segmental linings as a low-risk and economic construction approach for long tunnels (Brox and Grandori, 2023) with nearly 1,000 km (621 miles) of tunnels constructed using this approach. In particular, TBMs have been successfully used, and continue to be used, for some of the largest infrastructure projects with challenging geotechnical conditions including:

- Gotthard Base Rail Tunnel — 52-km (32-mile) deep tunnel.
- Kargi Hydropower Tunnel — multiple fault zones requiring bypasses that were faster than drill-and-blast methods.
- Olmos Water Supply Tunnel — deep tunnel subjected to regular rockbursting.
- Nepal Hydropower Tunnels — through major geological faults.
- Lake Mead Water Supply Tunnel — high ground-water pressures.
- India Water Supply Tunnels — abrasive quartzite.
- Brenner Base Rail Tunnel — 64-km (40-mile) deep tunnel.

TBM use in recent and current mining projects

The most recent uses of TBMs in the last decade for mining projects include for 7-km (4.3-mile) access tunnels at the Stillwater Mine, an 8-km (5-mile) exploration tunnel in Chile, and twin 1-km (0.6-mile) decline access tunnels in Australia. The most noted current use of a TBM for a mining project is for the construction of a 36-km (22-mile) conveyor tunnel as part of the Woodsmith polyhalite mine in the northeast of the United Kingdom. A single-shield TBM with diameter of 4.5 m (15 ft) is being used in conjunction with precast concrete segments. TBM tunneling commenced in mid-2019, and a total of 18,000 m (59,000 ft) were completed from a single portal in 1,000 days to present a world record for sustained production. The best daily production was 53 m (173 ft), and the best monthly production was 1,020 m (3,340 ft). The conveyor tunnel is being excavated through the Redcar mudstone formation that includes thin layers of chert where ground stability has been reported as good with no major delays at the tunnel face.

As of October 2023, tunnel advance reached 26 km (16 miles) following a four-month stoppage where appreciable maintenance was completed on the TBM to prepare it to complete the final 18 km (11 miles). At the time of writing, a double-shield TBM with diameter of 8 m (26 ft) was about to be launched for the

Figure 6

TBM launching for mine decline tunnel in China.

construction of a 10.5-km (6.5-mile) decline access tunnel at the Xianshan iron ore mine in China (Fig. 6). Over the past decade and most recently, the use of TBMs has been increasingly considered as part of the construction of major access and drainage tunnels for the following mining projects:

- Soto Norte, Colombia.
- Quebradona, Colombia.
- Olympiad, Russia.
- Tintaya Antapaccay, Peru.
- Escondida, Chile.
- Hu'u Onto, Indonesia.

Reasons for TBMs not being used in key projects

There exist a few major long tunnels where TBMs were not used, and it is interesting to recognize the key reasons for this. TBMs were not used for the following key major tunnel projects:

- Lotschberg Base Rail Tunnel — 2 × 32 km (20 miles).
- El Teniente New Mine Level Access Tunnels — 2 × 9 km (5.6 miles).
- Ceneri Base Rail Tunnels — 2 × 15 km (10 miles).
- NEOM Line Project — 2 × 33 km (20.5 miles).

The postulated reason why TBMs were not used at each of these major projects include abundant inferred adverse geotechnical conditions before the start of construction by the project designers. Squeezing conditions were anticipated at multiple locations for both the Lotschberg and Ceneri Base Rail tunnels located in Switzerland based on previous major tunnels in those areas; however, these adverse conditions were fortunately not realized during construction.

For the new mine access tunnels at the El Teniente Mine in Chile, the most attractive offer for the project client from a total of seven design-build proposals was based on a drill-and-blast approach with multiple intermediate access adits that assumed no interference from the existing mining operations. The second and third most attractive bids were based on the use of a TBM. Unfortunately, the assumed production of 4 m/d at four working faces of the most attractive bid was never achieved during construction due to site interference and other reasons of design changes. The original bid schedule was four years; however, the twin tunnels are now finally nearly complete after 14 years, having faced major delays associated with significant overstress including regular rockbursting that slowed production to 0.5 m/d. The encountered conditions over the majority of these tunnels were considered to be conducive for the use of TBMs as recognized by many professionals involved during the construction of the project.

For the NEOM line project, the tunnel designers did not have extensive TBM tunnel design experience even though the majority of the encountered rock conditions were of good quality.

Key aspects for TBM applicability and success

Technical viability. It is of vital importance to thoroughly investigate the geology of a project to identify the potential challenges and to study the applicability of a TBM as the TBM should be compatible with the anticipated ground conditions.

Brox (2021) presents a criterion that less than 30 percent adverse geotechnical conditions — including geological faults, abrasive ground and extremely high ground-water pressures — should be anticipated for the acceptance of the use of a TBM. This criterion is fundamentally based on the fact that TBMs can achieve production rates of typically about a minimum of three times that of drill-and-blast excavations and therefore any delays due to geotechnical conditions should be limited to the proportion of the advance rates of the different methods. While TBMs are ideal for homogeneous ground conditions, it is recognized that special design features are available for the de-risking of entrapment, which are increasingly specified for many projects with adverse geotechnical conditions. In addition, high-powered TBMs were not previously available in the industry and were the main reason for some historical failures such as high quartzite content at the Parabati II hydropower project in India.

The most important aspect to be evaluated is the technical viability, which should only be performed by an experienced professional without assuming an overly optimistic prediction of the geotechnical conditions.

Correct type of TBM. As there are multiple types of TBMs available in the industry, it is critical to evaluate each type for each project based on the best judgment and interpretation of the anticipated geotechnical conditions. The assessment of the most suitable type of TBM for a particular project should importantly consider historical practice and lessons learned from past projects to avoid being overly optimistic and running into similar shortcomings.

Industry experience. There exist several internationally recognized TBM tunneling contractors that have a wealth of project experience to competently evaluate the most suitable type of TBM for a given project and execute the project with good quality and safety. In addition, there are several TBM manufacturers with competent technical professional staff with a wide spectrum of experience on how their TBMs have performed in various geotechnical conditions. Project clients should always carry out a prequalification process to confirm the experience of all contractors and manufacturers to be considered for bidding.

Fair contracting practice and risk allocation. Project clients should recognize the importance of fair contracting practices with appropriate pricing items of lump sums for well-defined scopes of work and remeasured quantities for uncertain scopes of work such as ground support as well as fair risk allocation with the execution of a geotechnical baseline report (GBR) to provide compensation for more adverse conditions if encountered during construction that have been demonstrated to have impacted the productivity of the contractor.

The practice of GBRs is rapidly increasing throughout the world and has become well established in many countries, with some tunneling contractors refusing to bid if the practice is not included.

Figure 7

Flat-floor TBM tunnel trial at Fresnillo Mine, Mexico.

Accessibility for mobilization/support. The safe and timely mobilization of a TBM to a project site is fundamental in order to avoid any major delays to start of tunnel construction. Project clients should perform access road surveys and inspections of all key existing infrastructure, such as bridges, well prior to bidding during early design to confirm that there are no impediments for TBM mobilization. Access to any project site must also be maintained at all times during construction for the transport of important consumables used for TBM tunnel construction.

Supplier support. The post-delivery support required to be offered and executed by a TBM manufacturer cannot be overemphasized. Such important aspects include the timely provision of consumables (TBM cutters) and spare parts, TBM maintenance as well as possible training, and the provision of a TBM operator for an initial trial period or length of the tunnel. While these services appear to be fully recognized, the realization of sound support services during construction is never guaranteed with an ever-increasing tunneling industry that depends on the use of so many TBMs.

Technological advances for mining projects

At the time of writing, the Robbins MDM5000 flat-floor TBM mining machine is planned for a second trial at a depth of 700 m (2,297 ft) at the Fresnillo Mine in Mexico to excavate an approximately 2-km (1.2-mile) drive for exploration purposes at the mine. Figure 7 shows the flat-floor tunnel excavated from the first trial where an average rate of progress of 8 m/d was achieved in sedimentary bedrock of 60 to 90 MPa. The mine has performed some geotechnical investigations of long horizontal drillholes to allow for the characterization of the anticipated conditions in close proximity and subparallel to the silver-bearing vein deposits that include a limited number but highly adverse geological faults of crushed material with major ground-water inflows.

In addition, Herrenknecht has successfully completed trials of a prototype small-diameter (3 m, or 10 ft)-shaft TBM for the vertical excavation of strong rock conditions at its manufacturing facility in Germany.

Finally, Komatsu has developed a new mining TBM machine for site trials at the Chuquicamata underground mine in Chile to evaluate the performance of the machine to be able to excavate tight radii excavations as required for block cave mining methods and install early ground support.

Each of these examples represents exciting technological advances for the mining industry that will hopefully become standard technology in the future for improved rates of excavation for tunnels and shafts.

Conclusions and recommendations

The following key conclusions and recommendations are presented regarding the applications of TBMs for mining projects:

- Mining projects have similar characteristics to other infrastructure projects in terms of time and cost sensitivity, remoteness of site, ability for early procurement of key equipment due to long lead times, and desire to have a flat tunnel floor for operations.
- There exist multiple types of TBMs, and the viability of a TBM for a given project must be evaluated in terms of the anticipated geotechnical conditions with no more than about 30 percent of adverse conditions, and previous experience in the project region.
- Key advantages for TBMs are improved safety and environment for workers, reduced overbreak and ground support, higher advance rates, lower linear and total costs, reduced environmental footprint, reduced energy consumption for grid connection, and possibly reuse of spoil.
- Key disadvantages for TBMs are long procurement times of minimally 12 months, possible access challenges for mobilization, minimum large alignment radii dependent on diameter, circular or curved invert/floor, failure of main components including main bearing, key skilled labor required, high power demand, not applicable for ancillary excavations, and limited flexibility for unexpected adverse conditions.
- A key risk with the use of TBM is entrapment; however, based on an industry survey of TBM manufacturers the rate of entrapment is less than 1 percent in terms of tunnel lengths.
- The new generation of TBMs can be and should be specified to include key mitigation solutions to prevent entrapment including conical shield designs, retractable shield capability, enhanced steering control for mixed face conditions, extreme overcut capacity, high thrust, power and torque, enhanced ground treatment capabilities, and TBM spoil control.
- The best mitigation against entrapment is the performance of proactive investigations during TBM tunneling including forward probe drilling and geophysical survey techniques.
- The key aspects for TBM applicability and success are a comprehensive technical viability assessment, the correct selection of type of TBM, industry experience of TBM manufacturers and TBM contractors, fair contracting practice and risk allocation, accessibility for timely mobilization, and ongoing support from the TBM supplier during construction.
- Technological advances continue to be made for the use of TBMs in increasingly challenging site conditions. ■

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USGS critical minerals review

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As the science agency for the Department of the Interior, the U.S. Geological Survey (USGS) provides scientific information to support policy decisions on the stewardship of natural resources essential for economic and national security. Recent legislation reaffirms the original mission of the USGS articulated in the Organic Act of 1879 (43 U.S.C. 31) as "the classification of the public lands and examination of the geological structure, mineral resources, and products of the national domain" and focuses research and assessment efforts on critical minerals.

The 2022 Final List of Critical Minerals includes 50 critical minerals (U.S. Geological Survey, 2022a) supported by a published methodology (Nassar and Fortier, 2021; Nassar et al., 2020). Because supply risk reflects market dynamics and evolving mineral commodity supply chains, monitoring of commodity statistics (U.S. Geological Survey, 2024a) is essential for maintaining a robust critical minerals list and methodology. Pursuant to the Energy Act of 2020 (30 U.S.C. 1606), a draft list is prepared, revised, finalized and published in the Federal Register on a three-year cycle.

The Infrastructure Investment and Jobs Act (43 U.S.C. 311), also known as the Bipartisan Infrastructure Law, directed the USGS Earth Mapping Resources Initiative (Earth MRI) to complete an initial comprehensive national modern surface and subsurface mapping and data integration effort. The initiative emphasizes the recoverable critical minerals in surface or subsurface deposits and prioritizes mapping and critical mineral assessments. Earth MRI activities reinforce the goals of the USGS Energy and Mineral Resources Mission Area to conduct research and assessments that focus on the location, quantity and quality of mineral and energy resources, including the economic and environmental effects of resource extraction and use.

This article reviews the ongoing research activities on critical minerals conducted by the USGS Mineral Resources Program in 2023. Contributions range from (1) Earth MRI activities on data acquisition, mine wastes and geochemical characterization, (2) critical mineral investigations in the United States, (3) international collaboration and (4) a better understanding of the supply chains of byproduct critical minerals. Although it is impractical to highlight all the important work carried by USGS staff and scientists, these selected contributions convey the depth and breadth of research activity on critical mineral priorities and partnerships.

Earth Mapping Resources Initiative (MRI)

In 2019, Congress provided funds to the USGS for a new initiative, Earth MRI, to cover the nation with an optimal mix of high-resolution geoscience data and derivative map types and interpretations required to address future needs for critical mineral resources, as well as other national, regional or local needs. Earth MRI was established as a long-term, multiyear effort to support our nation's understanding of its subsurface geology and critical mineral resources by acquiring and interpreting new high-resolution 3D geophysical, geologic and topographic (elevation) data across the nation. In 2021, supplemental funding through the Infrastructure Investment and Jobs Act (43 U.S.C. 311) significantly accelerated collection of these fundamental geologic datasets, broadened Earth MRI's scope to include evaluation of potential aboveground resources and mine waste, and provided new opportunities for data integration and analysis. Earth MRI was established initially as a partnership between the USGS and state geological surveys. The close cooperation between federal and state geologists has been a hallmark of this initiative and key to its accomplishments. In the five years since its inception, Earth MRI has established relationships with additional federal, state and industry partners that may be leveraged to build new partnerships and develop new products to increase the nation's knowledge of its subsurface and aboveground geology, topography and potential critical mineral resources.

To guide Earth MRI data collection efforts across the nation, the USGS delineated focus areas for 23 mineral systems throughout the United States that could potentially host mineral deposits enriched in critical minerals (Dicken et al., 2022). These focus areas were developed in partnership with state geological surveys, and provide an initial, broad screening tool for targeting areas for new data acquisition. A mineral systems framework encompasses all the deposit types and the various mineral commodities that are known or suspected to occur within the system, and it highlights all possible critical mineral associations for each system whether they occur as a primary commodity or as a potential coproduct or byproduct (Hofstra and Kreiner, 2020; Hofstra et al., 2021). The USGS also developed a new database that identifies individual mineral deposits that have documented critical mineral associations, which includes published information about the size and status of each entry (Hammarstrom et al., 2023). In the database, individual deposits are given a ranked value determined from their critical mineral status (that is, past, current or potential future producers) and the presence or absence of known reserves or resources. Among 681 known deposits contained in the database, more than 200 entries are identified as having documented critical minerals but no evidence of present or past production, thus representing potential for untapped critical mineral resources in the nation. This mineral deposit database was designed to be used in conjunction with the focus area map and associated geospatial database (Dicken et al., 2022) to better understand critical mineral occurrences and their distribution within host mineral systems and mineral deposits, and to identify the most prospective geologic settings and regions for new data collection through Earth MRI.

The early emphasis of Earth MRI data collection was on updating geophysical, geologic and topographic (elevation) datasets across the nation. Since its inception, Earth MRI has funded 12 new lidar surveys through the USGS 3D Elevation Program (3DEP), contributing new high-resolution topographic data that cover more than 700,000 km^2 of the United States. To date, 80 geologic and geochemical mapping projects have been funded across 32 different states to better understand connections between the bedrock geologic framework and contained mineral resources in each area. Some projects involve detailed geologic mapping, whereas others involve systematic sampling for modern geochemical data and span multiple states. Earth MRI has acquired 24 airborne magnetic and radiometric surveys, more than doubling the amount of high-quality magnetic data for the conterminous United States and covered the entire island of Puerto Rico. Earth MRI also funded five airborne magnetic surveys in Alaska published by the Alaska Division of Geological and Geophysical Surveys, more than quadrupling the amount of previously available high-quality magnetic data. Airborne magnetic and radiometric surveys are essential for mapping and modeling the bedrock geologic framework in regions that have limited bedrock exposure or younger sedimentary cover. In some instances, airborne magnetic and radiometric data can be used to directly identify and map mineralized areas (for example, Shah et al., 2021; Wang et al., 2023). The Earth MRI Acquisitions Viewer (https://ngmdb.usgs.gov/emri/#3/40/-96) is a regularly updated web portal that provides information on data collection activities, project status, brief project descriptions, points of contact, and links to data for completed projects.

In 2023, Earth MRI funded nine high-quality airborne magnetic and radiometric surveys that will cover more than 300,000 km^2 of the United States. Two additional surveys designed and contracted by Earth MRI staff were supported by Federal Disaster Supplemental Funding (Florida) or state funding (Wyoming). Planned surveys in the eastern part of the United States focus on a variety of mineral systems in the Adirondack lowland regions of northwestern New York, on Piedmont crystalline rocks and on Atlantic Coastal Plain sediments in North Carolina and surrounding states. The North Carolina survey expands prior work in the region (for example, Shah et al., 2021), extending coverage across the Fall Line into bedrock terranes of the southeastern Appalachian Mountains. The magnetic and radiometric survey planned for northern and central Florida can support geologic mapping and research for industrial and critical minerals over areas hosting phosphates, heavy mineral sands and mine waste. In the central United States, a large magnetic and radiometric survey is ongoing for the Cuyuna Iron Range of northcentral Minnesota, targeting iron-bearing strata with unusually high concentrations of manganese. The survey outline also encompasses other mineral systems that include known magmatic sulfide deposits. Another regional survey covering western Kentucky, northwestern Tennessee and parts of surrounding states targets a large buried magnetic anomaly and is designed to meet complementary needs related to geologic mapping, earthquake hazards and mineral resource research. This area includes well-known lead-zinc mining districts that have potential for additional critical mineral resources. When completed, the Kentucky-Tennessee survey can be merged with other Earth MRI magnetic and radiometric surveys to provide complete, high-quality coverage over an area extending from eastern Kentucky to southern Arkansas. This expanded coverage can be used to map mineral systems and model deeper crustal boundaries inferred to control overlying system geometries and possibly influence fluid flow and mineralization at a variety of scales (McCafferty et al., 2023a).

Five different magnetic and radiometric surveys were funded in 2023 in the western United States. In the Southwest, a large survey was designed over a portion of the porphyry copper belt in southeastern Arizona. The Arizona survey extends a 2022 survey of the New Mexico portion of the porphyry belt and the two can be merged to provide continuous coverage across the state boundary. The new high-resolution survey data can help define potential concealed mineral resources under extensive Cenozoic basin fill and complement ongoing mapping and geochemical studies underway by the USGS and the Arizona Geological Survey. A new survey in southwestern Utah is focused on important mineral-rich regions, including the Goldstrike, Iron Axis and Tutsagubet mining districts. These districts contain critical minerals such as antimony, barite, gallium and germanium, in addition to other important minerals such as copper, gold, iron, phosphorus, selenium and silver. Data from the Utah Iron Axis survey can help identify bedrock features in large areas under cover and help map the geology of the shallow subsurface. When this survey is merged with a similar survey funded in 2022, high-resolution magnetic and radiometric data will extend across western Utah from Provo to the Arizona border. In Colorado, a new magnetic and radiometric survey will cover the middle and southwestern portions of the Colorado Mineral Belt. The new survey overlaps with an active Earth MRI geologic mapping project being conducted by the Colorado Geological Survey in the La Plata mining district, where mapping and geophysical data can provide new insights into mineralizing events in the region. In central Wyoming, the Wyoming State Geological Survey contributed funding for a magnetic and radiometric survey extending from the southern Wind River Mountains east to the Granite Mountains (U.S. Geological Survey, 2024b). The survey is focused on the areas encompassing the Oregon Trail Structural Belt, which might represent a suture between Precambrian terranes. This is an area with a rich history of past and current mineral exploration with known and suspected mineral systems of high interest for their critical mineral potential. In the northwestern United States, two new surveys were funded in eastern Idaho and western Montana. The Montana survey extends coverage from a 2022 survey to the west, encompassing the Boulder Batholith and the Butte, Philipsburg and Hecla mining districts. Combining the data with geologic mapping and sampling by the Montana Bureau of Mines and Geology can help to develop an improved understanding of the geologic framework and mineral systems that underpin these well-known mining districts, which can aid assessment of and exploration for associated critical mineral commodities. In Idaho and westernmost Montana, a new survey is focusing on a large area of the Idaho Cobalt Belt and the western edge of the Montana-Idaho porphyry belt. These areas have the potential to host cobalt, titanium, niobium and rare earth elements (REEs), and the new airborne survey data can aid active geologic mapping projects by the Montana Bureau of Mines and Geology and Idaho Geological Survey.

In Alaska, Earth MRI funding in 2023 was used to continue airborne magnetic and radiometric data collection in the Kuskokwim Mountains region of the state. The second phase of the Kuskokwim Mountains survey, designed to Rank 2 specifications (Drenth and Grauch, 2019), covers more than 35,000 km^2. The Kuskokwim region of interior Alaska contains multiple overlapping mineral systems and numerous gold deposits that are the focus of active placer mining and regional mineral exploration. The region also contains known tin, REE, tungsten and antimony deposits and has high potential for additional undiscovered critical mineral deposits.

In addition to the new airborne magnetic and radiometric surveys outlined above, Earth MRI funded 14 new geologic and geochemical mapping projects that are being conducted by 18 different state geological surveys. Geologic mapping projects address topics such as Mississippi-Valley-type mineral deposits in Arkansas and Wisconsin, lithium-bearing strata in southeastern California, and copper and cobalt deposits in central Maryland. Reconnaissance geochemical mapping projects, many of which involve multiple states, are addressing large regional systems such as metalliferous black shales in the eastern and central United States and REEs in granitic regolith in the Southeast. Multiple western states are partnering with USGS to modernize legacy geochemical data for samples collected by the National Uranium Resource Evaluation (NURE) program in the late 1970s and early 1980s. The NURE samples are archived at the USGS campus in Denver, CO, and geochemical reanalysis using advanced methods can provide new and important information about the concentration of critical elements in these archived materials.

Beginning in 2022, Earth MRI was able to expand its scope of data collection activities to include airborne electromagnetic surveys, regional and district-scale hyperspectral remote sensing studies, and new projects focused on aboveground resources in mine waste. Four different airborne electromagnetic (AEM) surveys were conducted through 2023 in three regions of the United States. Electromagnetic surveys in eastern Alabama and western Alaska are focused on graphite-bearing mineral systems. Two AEM surveys in the Great Basin of western Nevada cover areas containing multiple mineral systems but are focused on those that have known or suspected potential to host lithium resources.

The USGS and NASA have partnered to generate modern hyperspectral surveys over 1.3 million km^2 in the semi-arid regions of the southwestern United States. Data are being acquired using NASA's Airborne Visible InfraRed Imaging Spectrometer (AVIRIS) sensors. The project will produce visible- to short-wavelength infrared (VSWIR) mineral maps of soils and exposed rocks that can provide new information on the location and formation of mineral systems with related hydrothermal alteration and rock-weathering processes. Additional data are being acquired using one of several thermal infrared (TIR) sensors, which support discrimination, identification and mapping of primary rock-forming minerals across the region. More targeted, district-scale hyperspectral surveys were funded over multiple areas in Florida to aid mapping in areas that are actively mined for phosphate-bearing rocks and gypsum. Another hyperspectral survey in Florida is being planned and contracted by Earth MRI staff using Federal Disaster Supplemental Funding, and the data and derived mineral maps are expected to provide actionable information about the location and distribution of critical and industrial minerals that can be used to produce fertilizer and aid in construction efforts related to hurricane recovery and resiliency. The data can also aid in geologic mapping and mine waste sampling work conducted by the Florida Geological Survey and funded by Earth MRI.

Finally, Earth MRI has also contributed consistently to the preservation of legacy data related to critical minerals through the USGS National Geological and Geophysical Data Preservation Program (NGGDPP). Support from Earth MRI through NGGDPP sponsors a variety of activities that can include development of strategic plans for addressing critical mineral resources in each state, legacy data collection and curation related to state mineral deposits or districts, rescue of abandoned drill core and preservation and potential geochemical reanalysis of legacy rock samples and drill core. In 2023, 32 state geological surveys were supported by NGGDPP, enabling them to preserve vital geologic and geophysical data and samples. Results of these projects are made publicly available through multiple sites that may include published reports by state geological surveys, the USGS National Index of Borehole Information (NIBI, https://webapps.usgs.gov/nibi/), and the USGS Registry of Scientific Collections (ReSciColl, https://webapps.usgs.gov/rescicoll/index.html).

Mine waste inventory. North and South America have long histories of mining, extending from well before European settlement to the present. For metallic mineral deposits, the concentrations of precious metals are typically measured in grams per metric ton, whereas base metals such as copper, lead and zinc typically come from orebodies with only a few percent, or less, of the commodity of interest. Most metallic mineral deposits have mine waste piles that are approximately equivalent to the total tonnage of processed material. Changes in mining technology, mineral processing, extractive metallurgy and mineral economics through time have enabled the recovery of metals with progressively lower grades, so that material that was low grade or waste in the past might now be economic to recover. In addition, more than half of the commodities on the United States' critical minerals list could be recovered as byproducts that contribute little to the overall revenue of mining operations (Nassar and Fortier, 2021). Many of these byproduct critical elements were not sought or recovered in the past, but developments in modern technology throughout the economy have increased the demand for commodities such as gallium, germanium, indium, rhenium, tellurium and other commodities. Therefore, some mine waste features may contain critical minerals or other commodities that could be recovered from reprocessing to help address the national need. Furthermore, reprocessing mine waste might remove or decrease the concentration of minerals that weather to form acid mine drainage or release toxic metals to the environment. For waste features that need remediation, reprocessing waste material could be a win-win situation, with revenue from commodities helping to offset the costs of remediation.

The Infrastructure Investment and Jobs Act of 2021 directed the USGS Earth MRI to collect data for areas containing mine waste

Figure 1

Map of the United States showing the funded Earth MRI mine waste characterization projects in fiscal years 2022 (FY22) and 2023 (FY23).

to increase understanding of aboveground critical mineral resources in previously disturbed areas. The USGS' Mineral Deposit Database project (USMIN) is collaborating with state geological surveys to build a comprehensive and authoritative inventory of nonfuel mine waste for the United States. In 2022, USMIN collaborated with state, federal and tribal agencies to develop the structure of the database that hosts mine waste records. The intent was to incorporate essential fields that would summarize the important characteristics of individual mine waste attributes, such as average geochemical grades of waste features, but not to provide details — such as geochemical analyses of multiple samples — that can be linked to from other databases. The database has two feature classes: points and polygons, and three tables: geology, resources and references. The points feature class provides the location of the mine waste feature, the name of the mine and mining district, and the surface management agency of the land where the feature occurs. This is a general field that is populated with first-order information, such as Bureau of Land Management, state or private. The polygon feature class captures the areal extent of each mine waste feature, and the database is meant to only capture features that are larger than 2,000 m^2. The geology table provides information for each feature about commodities, deposit type, mineral system, ore minerals and gangue minerals. The resources table has fields for reported volume, calculated volume, tonnage factor, grade and contained amount of each commodity. Populated records must use data that are available in the public domain, but not necessarily peer-reviewed, and the completed database must provide citations and references for these data. Each feature class and table have a citation field that indicates the source of the compiled data, and the references table provides the full reference for each citation.

In 2023, the USGS released a Notice of Funding Opportunity to fund state geological surveys to populate the mine waste database (U.S. Geological Survey, 2023b). Thirteen states were funded to undertake this work, and USMIN personnel have completed training at 11 of those agencies, where work is currently progressing. The vision is that state geological surveys will help build the database by completing records for their states, and USMIN personnel will populate records for additional areas to help complete this national database.

Mine waste characterization. Earth MRI is funding state geological surveys to (1) conduct mine waste characterization studies at sites that may have potential for critical minerals and (2) assist in the development of a national database of abandoned mine sites. The first year of the program (2022) focused on developing a set of standard operating procedures and analytical methods to ensure that a nationally comparable dataset emerges from this effort. Three states were enlisted to help in this effort: Colorado, Florida and New Mexico. In 2023, seven additional states received funding for mine waste characterization studies: Illinois, Iowa, Missouri, New York, North Carolina, Montana and Washington (Fig. 1).

Collectively, the studies funded in 2022 and 2023 are investigating mine waste from more than 11 mineral deposit types that could contain more than 41 critical mineral commodities (Table 1). The 2024 proposal process is currently underway to fund additional states to conduct mine waste characterization studies to assess critical mineral potential.

Table 1

Selected mineral deposit types being investigated by the Earth MRI mine waste characterization program. (Critical mineral potentials based on Hofstra and Kreiner, 2020.)

Mineral deposit type	Potential critical mineral commodities
Arsenide veins	As, Bi, Co, F, Ni, REEs, Te, W, Zn
Iron oxide apatite (copper-gold)	Co, REEs
Low and intermediate sulfidation epithermal	As, Bi, Ga, Ge, In, Mn, Sb, Te, W
Mississippi Valley-type and sedimentary exhalative	Co , Ga, Ge, In, Sn, Zn
Pegmatite	Be, Cs, Li, Nb, Sc, Sn, Ta
Phosphorite	Cr, F, REEs
Porphyry copper	PGEs, Re, Sc, Te, Bi, Co

Critical mineral investigations in the United States

USGS research on critical minerals has continued on multiple fronts. Earth MRI adopted a mineral systems approach to outline broad areas of the United States that could host critical mineral deposits (Hofstra and Kreiner, 2020; Kreiner et al., 2023). Working with state geological surveys, the USGS developed a national map that shows the footprints of 23 different mineral systems that could host a variety of different mineral deposit types (Hammarstrom et al., 2023). Porphyry systems, for example, can include a range of related deposit types such as porphyry copper deposits, skarns, polymetallic veins, epithermal deposits and lithocaps, all of which can host critical minerals as principal commodities or as potential byproducts. More than 800 individual focus areas representing one or more mineral systems provide a basis for identifying areas where acquisition of new mapping, airborne geophysics and geochemical data are most needed to evaluate the critical mineral potential of the United States. Kreiner et al. (2023) summarized some of the early results of Earth MRI data acquisition efforts and showed how new data can be integrated using the mineral systems approach to develop mineral potential maps.

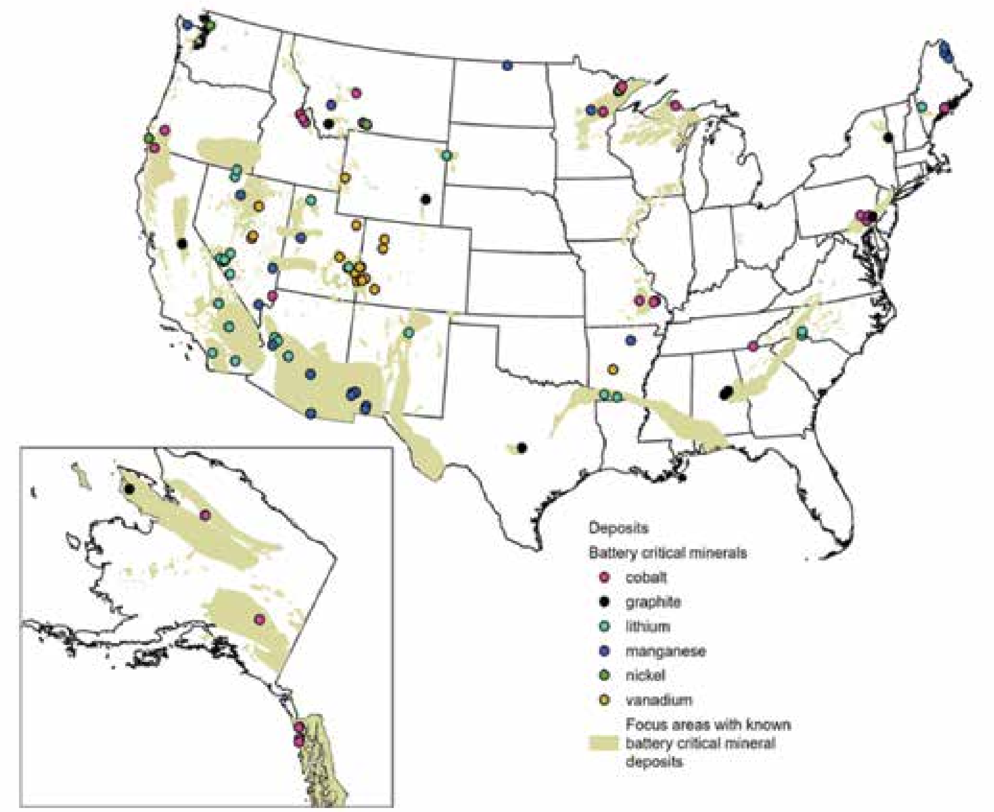
Historically, the United States produced all of the minerals included on the current critical minerals lists, albeit in some cases with wartime government subsidies and by small-scale mining operations (Kelly and Matos, 2014). In 2022, however, the United States was more than 50 percent import reliant for some 43 of the 50 individual critical mineral commodities (U.S. Geological Survey, 2023a). A new compilation of U.S. deposits that are known to contain critical minerals from either past or current production data or from documented resource information includes more than 600 sites (Hammarstrom et al., 2023; Woodruff et al., 2023). Of these, only 28 deposits have reported critical mineral production since 2015 and not all of those 28 deposits were active in 2024. The geographic information system (GIS) and data tables include the mineral system, deposit type, and focus area for each deposit. Focus areas with known critical mineral deposits highlight areas of the country most likely to represent near-term domestic sources of critical minerals should development be possible. Areas of the country most likely to provide battery critical mineral resources, for example, include the Great Basin for lithium in brines and clays, the eastern United States for lithium in pegmatites, cobalt and nickel in mafic magmatic mineral systems in Minnesota and Michigan, cobalt from the iron oxide-copper-gold system in the Idaho Cobalt Belt, and the Seward Peninsula in Alaska for graphite (Fig. 2).

Noteworthy accomplishments over the past year include a comprehensive compilation of information about domestic deposits and resources of critical minerals in subduction-related hydrothermal systems (Vikre et al., 2023), petrochemical and geochronological studies in the vicinity of the Mountain Pass REE deposit in the Mojave Desert (California) to better understand the metallogeny of the region (Watts et al., 2024), and laboratory-based hyperspectral and satellite-based multispectral surveys of uranium deposits in Texas advanced the application of these techniques to both mine waste assessment and mineral exploration (Hubbard et al., 2023, 2024). In addition, the USGS continued its collaboration with state geological surveys to evaluate the critical mineral potential of mine waste through its Earth MRI mine waste characterization program.

Mineral systems that form in subduction-related tectonic terranes are significant producers of several important commodities such as copper, zinc, lead, gold and silver as well as other critical mineral commodities (Vikre et al., 2023). These mineral systems account for much of the mine production in the western United States and Alaska. Important mineral systems include the porphyry copper-molybdenum (Cu-Mo) system and porphyry deposits, several skarn and replacement deposit types, and epithermal deposits among others; the porphyry tin (Sn) system, which includes porphyry and skarn deposits; and several mineral deposit types that are unclassified

Figure 2

Map showing the distribution of a subset of focus areas that contain deposits with past production or identified resources of critical minerals used in electric-vehicle battery technologies. (Focus areas from Dicken et al., 2022; deposits from Hammarstrom et al., 2023).



relative to mineral systems, but are important sources of arsenic, antimony, beryllium, gallium, germanium, tungsten and fluorite (Vikre et al., 2023). Vikre et al. (2023) highlighted significant inventories of aluminum, antimony, potassium and tungsten in unmined deposits, equivalent to two to eight years of domestic consumption, and several decades of domestic consumption of arsenic, bismuth, fluorite, gallium, germanium and indium. They also noted that inventories of numerous critical minerals in porphyry Cu-Mo deposits, owing to their large size could supply domestic needs for periods ranging from decades to centuries on a commodity-by-commodity basis. However, they cautioned that these quantities should not be considered consumable supplies without formal definition of reserves and the development of viable mining plans and recovery strategies.

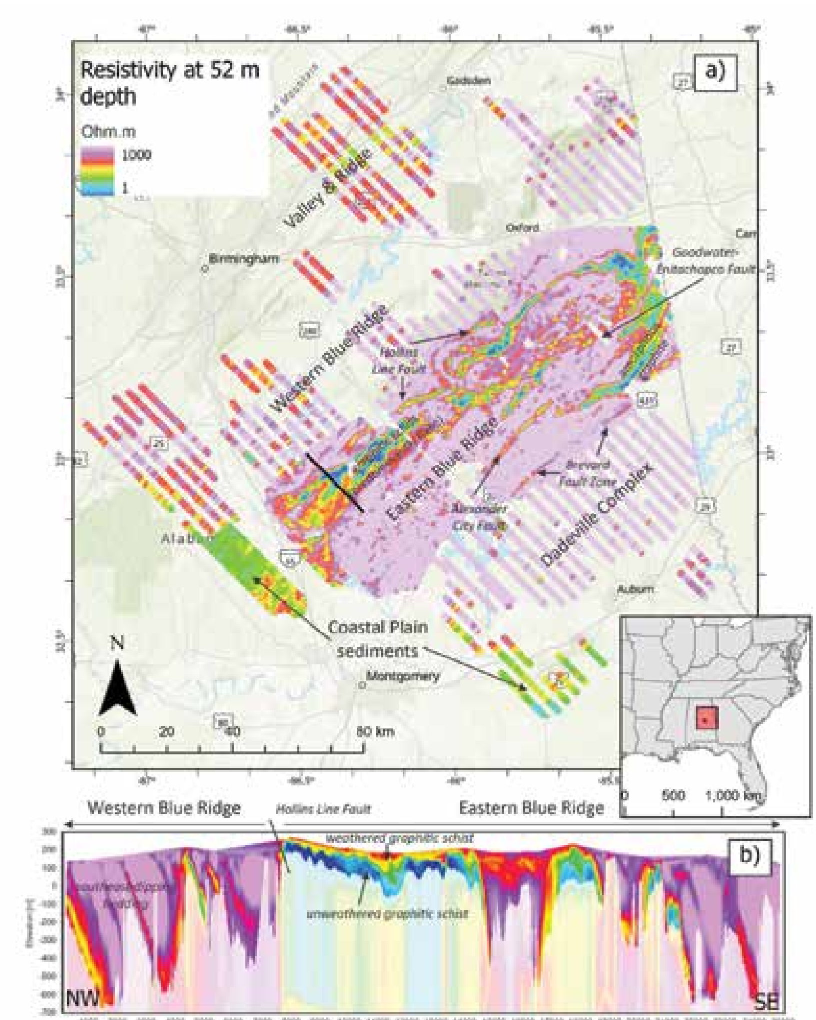
Watts et al. (2024) extended the scope of recent study of the geochemistry and geochronology of the magmatic rocks at the Mountain Pass REE deposit in the Mojave Desert, CA (Watts et al., 2022), to include the prospective Bobcat Hills region, 65 km southeast of Mountain Pass. Mountain Pass is the most economically significant REE deposit in the United States. Watts et al. (2022) were able to demonstrate spatial and temporal links between alkaline and carbonatitic intrusive activity at Mountain Pass. The Bobcat Hills REE-rich mafic alkaline magmatism is slightly older than magmatism at Mountain Pass. An important contrast between these two sites is that Bobcat Hills represents a single, short-lived intrusive event with limited crustal interaction, whereas Mountain Pass experienced multiple intrusive pulses that spanned tens of millions of years and included significant crustal assimilation. The authors suggested that the protracted intrusive history at Mountain Pass was a prerequisite for shallow emplacement of the carbonatite magmas that formed the ore.

The spectral reflectance signatures of sandstone-hosted uranium deposits and mine wastes in the Texas Coastal Plain were the subject of a satellite-based multispectral study (Hubbard et al., 2023; 2024). Uranium is not considered a nonfuel critical mineral; however, sandstone-hosted uranium deposits have historically been important sources of vanadium. Vanadium is a critical mineral that has been used extensively to strengthen steel and has growing importance in the emerging development of vanadium redox-flow batteries (Kelley et al., 2017). The laboratory-based hyperspectral study utilized spectra measured from archived rock cores, cuttings and other sample splits, which were then compared to mineral-specific spectral libraries. Collectively, these studies underscore the limitations of archived, satellite-based surveys, but highlight the promise of fixed-wing and new satellite-based hyperspectral sensors. Nevertheless, the results of these studies can aid mapping of waste materials from uranium mining and future exploration for sandstone-hosted deposits and their associated critical minerals.

In August 2023, the USGS in collaboration with the Defense Advanced Research Projects

Figure 3

(a) Depth slice through the resistivity models obtained from the 2023 Earth MRI survey of the Alabama Graphite-Vanadium Belt; colors correspond to resistivity at 52 m depth. Thick black line marks the location of the cross section. (b) Cross section through the belt, showing low-resistivity, graphite-bearing lithologies (blue) and higher-resistivity nongraphitic units (reds and pinks). Semitransparent regions are below the depth-of-investigation provided by the data. (AEM data available from U.S. Geological Survey, 2024c).



Agency (DARPA) and Advanced Research Projects Agency–Energy (ARPA-E) initiated the Critical Mineral Assessment with Artificial Intelligence Support (CriticalMAAS) program (https://www.darpa.mil/program/critical-mineral-assessments-with-ai-support). The program's objective is to drastically reduce the amount of time required to conduct mineral resource assessments for materials critical for the energy transformation. The program expands on a machine-learning competition (USGS, 2022b) on automating georeferencing and feature extraction from geologic maps. In addition to the winners of the competition, teams representing small businesses, research institutions and universities are engaging in critical mineral resource assessments from four technical areas, consisting of (1) extracting data from maps, (2) extracting knowledge from structured and unstructured source documents, (3) mineral prospectivity mapping and (4) human-in-the-loop interfaces. The 12-month program proceeds according to a milestone schedule including hackathon events focused on specific applications of the technical solutions to real-world assessment problems.

Airborne electromagnetic survey in Alabama. Earth MRI has accelerated acquisition of geophysical data over areas with the potential to contain critical mineral resources. Whereas the areas chosen for surveys under this program host mineral systems likely to contain critical minerals, the resulting geophysical maps and models are also being used for a range of geologic, hydrologic and hazard-related research.

To support an ongoing assessment of domestic graphite resources, the USGS conducted an airborne electromagnetic (AEM) survey of the Alabama Graphite-Vanadium Belt within the Southern Appalachian Mountains and surrounding regions (Fig. 3). Electromagnetic surveys are ideal for mapping graphite lithologies due to the extremely low resistivity (high conductivity) of graphite-bearing rocks. Graphite contents as low as 1 weight percent can drop bulk resistivity by orders of magnitude (to less than 1 Ω·m) relative to similar nongraphitic lithologies.

The AEM survey covered the mapped extent of the belt and beyond, permitting construction of a 3D model of subsurface electrical resistivity to depths in excess of 500 m. The model directly images the extent of graphite-bearing lithologies, the thickness of a surficial weathered graphite zone (the source of most historic mining), and the geometry of the belt itself (MacQueen et al., 2023). Additionally, extensions of the belt are imaged beneath the Coastal Plain and to the northeast of the traditionally defined belt. The resistivity model is further aiding geologic mapping efforts in this complex structural corridor where traditional geologic mapping is difficult. Finally, key subsurface structures and faults are revealed that inform the tectonic evolution of the region and controls on mineralization.

International collaboration

The USGS continues active collaborations with international partners that support critical mineral resources research and investigate options that mitigate strategic mineral resource vulnerabilities. Recent collaboration efforts include work carried out in Algeria, Uzbekistan and Kazakhstan and the Critical Minerals Mapping Initiative (CMMI), an ongoing collaboration with Geoscience Australia and the Geological Survey of Canada. In the first two countries, multidisciplinary teams prepared quantitative and semiquantitative mineral resources assessment that emphasized critical minerals. The USGS also provided training to colleagues on various field and office techniques, including the three-part quantitative assessment method, as well as in geophysics, geochemistry, geochronology and remote sensing. A similar effort is just starting in Kazakhstan, to assist that country with their multiple interests in mineral exploration for critical minerals, the extraction of minerals from mine waste, and conventional and unconventional energy sources.

Critical Minerals Mapping Initiative. The broader goals of CMMI are to advance our collective understanding of critical mineral resources in Australia, Canada and the United States by engaging in data and knowledge sharing (Emsbo et al., 2021; Kelley, 2020). CMMI is continuing efforts to expand a unified Critical Minerals in Ores (CMiO) database (Champion et al., 2021) with additional modern geochemical data. Future updates of the database are planned to include analyses from approximately 20,000 samples from the USGS (Granitto et al., 2021) and the Geological Survey of Queensland using the mineral systems classification of Hofstra et al. (2021). CMMI continues to seek contributions from external sources to fill data gaps among deposits and deposit types, particularly in other foreign countries. As the CMiO database continues to grow, users can gain progressively better understanding of the distributions of critical minerals across systems and deposit types and deposits. These data can be used to guide future research on fundamental controls on critical mineral endowments.

Another effort of the CMMI collaboration has been developing critical mineral prospectivity methods that combine geologic, geophysical and temporal data using knowledge and data-driven approaches. The initial focus was on basin-hosted lead-zinc deposits (Mississippi Valley-type and clastic dominated lead-zinc), which are present in all three countries, and contain other critical minerals, including gallium, germanium, indium and nickel. Knowledge-driven and data-driven modeling (Lawley et al., 2022) utilizes national-scale geologic and geophysical data and derivative layers, along with basin-hosted zinc-lead (Zn-Pb) mineral sites for Australia, Canada and the United States (McCafferty et al., 2023a). These data can be used as important underpinning evidence layers for regional- to national- to continental-scale prospectivity modeling and follow-on assessments. Some of the derivative products have already proven impactful within for USGS research, such as guiding Earth MRI targeting of areas for high-resolution magnetic and radiometric surveys (McCafferty et al., 2023b) and development of artificial intelligence/machine learning (AI/ML)-assisted prospectivity tools.

Byproduct critical mineral supply chains

Byproducts constitute a subset of critical minerals that depend on the production of a host mineral that may or may not be designated as a critical mineral and exist in sufficient quantities to be recovered during processing or refining. Understanding the supply chains of byproduct critical minerals necessitates knowledge of ore mineralogy and geochemical concentration, behavior of different minerals and elements during beneficiation and recovery processes, primary commodity production quantities, and trade flows of mined and intermediate products. Two case studies, focused on cobalt and rhenium, are summarized here as instructive examples for better understanding the supply risk and dynamics of byproduct critical minerals.

Cobalt. Demand for cobalt as a cathode material in various lithium-ion battery chemistries has nearly tripled from 2013 to 2023, with cobalt in batteries accounting for the majority of total usage. The rising demand for cobalt has raised concerns over ethical sourcing with governments, producers and end-users focusing on mining practices as part of an overall environmental, social and governance (ESG) effort. According to data compiled by the USGS, the Democratic Republic of the Congo (DRC) accounted for 74 percent of global mined cobalt production in 2023 (USGS, 2024a).

Since the collapse of the DRC copper-cobalt industry in the 1990s, a portion of DRC cobalt mine production has come from artisanal cobalt miners (Gulley, 2022). Research on artisanal cobalt mining has revealed human rights abuses,

Figure 4

Increases in artisanal production follow price increases, underscoring the role of artisanal mining as a "swing producer." Declines in artisanal production from 2010 to 2016 correspond to low cobalt prices (Gulley, 2023).

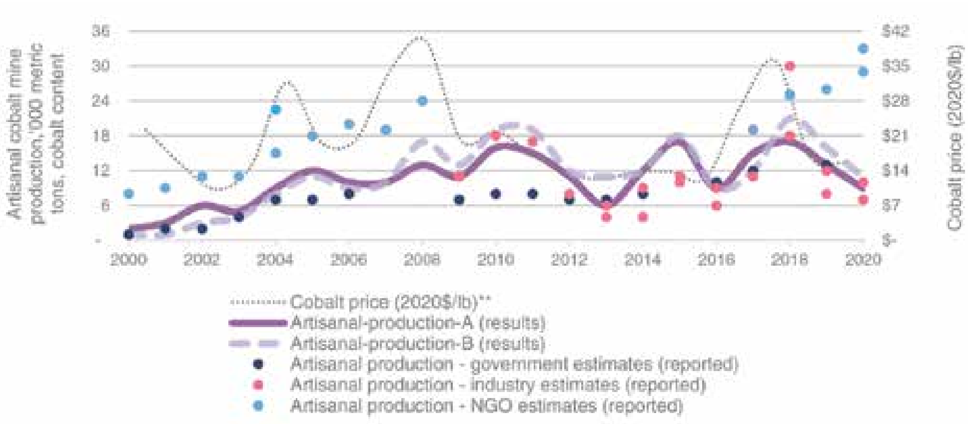


Figure 5

DRC artisanal production as a share of total DRC cobalt mine production and as a share of total world cobalt mine production (Gulley, 2023).

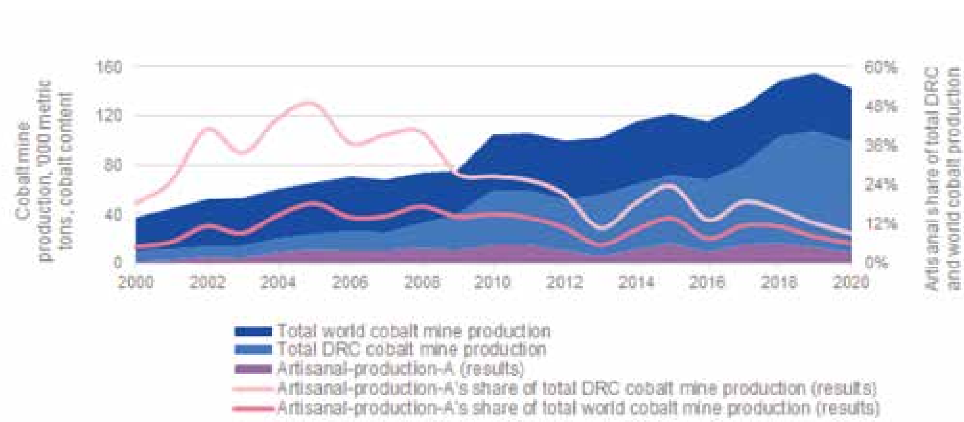
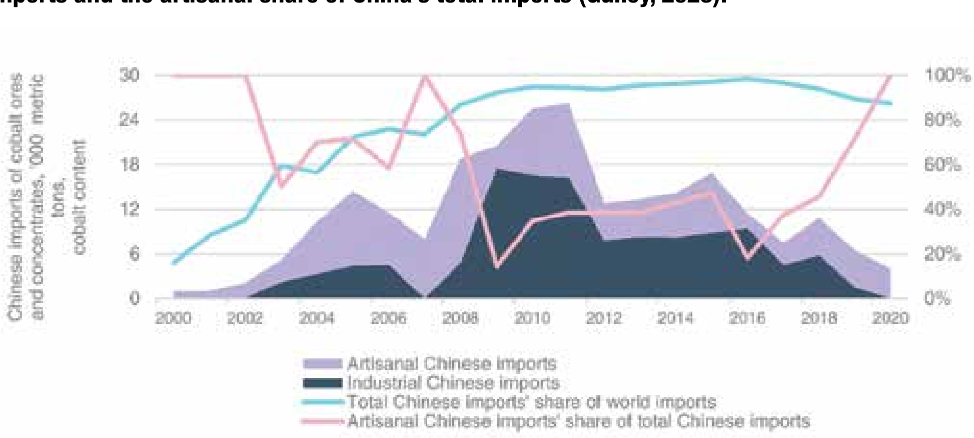


Figure 6

China's imports of cobalt ores/concentrates from the DRC along with China's share of world imports and the artisanal share of China's total imports (Gulley, 2023).



as well as forced and child labor (U.S. Department of Labor, 2024). Although key to addressing these issues, attempts to systematically quantify artisanal cobalt production or identify its destinations have proven elusive.

Building upon an earlier analysis of Congolese cobalt production since 1924, Gulley (2023) used data from the DRC government, mining companies, third-party data sources and international trade flows to estimate the production of cobalt from artisanal mines using two approaches. Method A calculated the difference between total reported cobalt production in the DRC and the reported production of so-called "industrial" or "large-scale" mines operating in the DRC. Industrial mines are formally organized companies that operate under license from the DRC government, are highly mechanized and employ a highly skilled work force. Method B consists of two components: (1) estimates of the quantity of artisanal cobalt production that is processed into intermediate cobalt products in the DRC, and (2) calculations of artisanal exports as the difference between total Chinese imports and exports of industrial cobalt from the DRC to China.

In the early 2000s, most of the industrial cobalt mines operating in the DRC were either owned by or under long-term contracts with Western companies (Gulley, 2022). The rapid growth of China's cobalt refinery sector in the period from 1999 through 2005 entailed the arrival of Chinese traders and processing companies to the DRC in search of cobalt ore. Because most of the industrial cobalt ore/concentrate was locked into offtake agreements, Chinese entities turned to the informal sector to meet their feedstock requirements (Fig. 4).

Figure 5 shows how artisanal production shares of total DRC and world cobalt production peaked at 49 and 18 percent, respectively, in 2005 before trending down to 9 and 6 percent in 2020 (Gulley, 2023). In contrast, average nongovernmental-organization (NGO) estimates show peaks of DRC artisanal mines' shares at 93 and 31 percent, respectively, in 2004. For the years 2000 through 2006, the years when estimates from both NGOs and governments are available, NGO estimates are nearly four times larger than government estimates (Gulley, 2023).

Artisanal imports to China increased from 1 kt in 2000 to 14 kt in 2008 reflecting China's growing demand for feedstock for its refinery sector (Fig. 6). Artisanal imports started to trend down from a peak in 2010 as the DRC's industrial sector began to recover and reflects the rise of artisanal processing in the DRC in addition to increasing production of crude cobalt hydroxide in the DRC's industrial sector. The share of Chinese imports attributed to artisanal production averaged 39 percent from 2010 through 2017 as the DRC's industrial mining sector expanded production (Gulley, 2023). However, this share increased to 100 percent in 2020 as two DRC industrial miners ceased concentrate exports to produce crude cobalt hydroxide (Gulley, 2023). Despite the high share in 2020, the volume of China's imports of artisanal cobalt from the DRC was quite low by historical standards.

The USGS estimation results largely follow those of governments and industry. Specifically, the USGS results are on average 18 percent higher than those presented by governments and industry. In contrast, estimates of artisanal cobalt production in the DRC from NGOs are 2.2 to 3.1 times higher than those of government, industry or the USGS. Because artisanal mining represents between 9 and 11 percent of total DRC cobalt production, a random sampling of cobalt sourcing would mean that an end-user would have a 90 percent chance of sourcing from industrial (nonartisanal) sources, based on this analysis. According to seven in-person artisanal cobalt mine site studies published between 2017 and 2021 — the results of which the USGS re-reported as found and did not attempt to independently verify — children were present at roughly one in four artisanal cobalt mine sites studied. Given this estimate, and the results above, the chance of an end-user sourcing from an artisanal producer using child labor may be as low as 2 percent. The large inconsistencies between different methods of estimation underscore the importance of thoroughly understanding cobalt supply-chain dynamics.

Rhenium. Rhenium is produced as a byproduct of copper and molybdenum and serves as a critical component in high-temperature alloys used in aerospace and gas power generation turbines. Rhenium has a particularly complex supply chain, because molybdenum is itself a byproduct of copper. Thus, rhenium is a "byproduct of a byproduct" and is subject to the market dynamics of both copper and molybdenum. Further, international trade in rhenium-bearing molybdenum concentrates adds yet another layer of intricacy to the rhenium supply chain.

Advances in superalloys used in high-temperature aerospace and energy applications have increased the demand for rhenium from essentially zero in the 1940s to approximately 75 tons in 2019 (Brainard, 2023). Despite its important end-uses, quantifying recoverable supplies of rhenium has proven difficult due to the difficulty of tracking primary production combined with the high level of aggregation of trade flows of rhenium.

By compiling data on rhenium grade in deposits and in the flow of production and trade, estimates of rhenium supply are possible (Brainard, 2023). In brief, rhenium supply can be estimated through just a few pieces of information: (1) rhenium grade in the ore, (2) the annual production of the parent material and the recovery rate of rhenium from that production and (3) international trade flows of rhenium-bearing molybdenum and copper (Brainard, 2023). These estimation techniques have indicated that less than 12 percent of rhenium present in the ore is currently captured owing to technical recovery limits. Additional rhenium production beyond technical recovery limits may only be realized through increases in the mining of copper and molybdenum.

Data compiled by the USGS demonstrate a correlation between rhenium grade in whole rock and molybdenum grade (Brainard, 2023). This correlation permits estimates of rhenium grade of unknown deposits. For example, according to a regression analysis, molybdenum grading of 0.01 percent would correlate to a rhenium content of approximately 0.015 ppm (Brainard, 2023). It would therefore be reasonable to assign this rhenium content to other molybdenum deposits of similar grade but with an unknown (or unreported) rhenium

Figure 7

Time series of rhenium content in ore (green line) and recoverable rhenium content (blue line) with 95 percent confidence intervals (C.I., shaded regions), compared to copper and molybdenum production (dotted lines, Brainard, 2023).

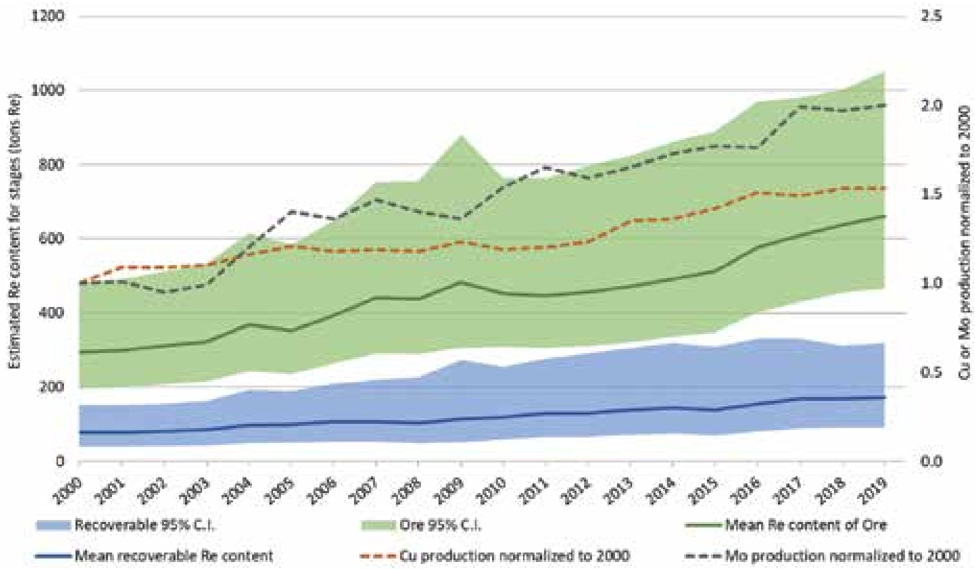
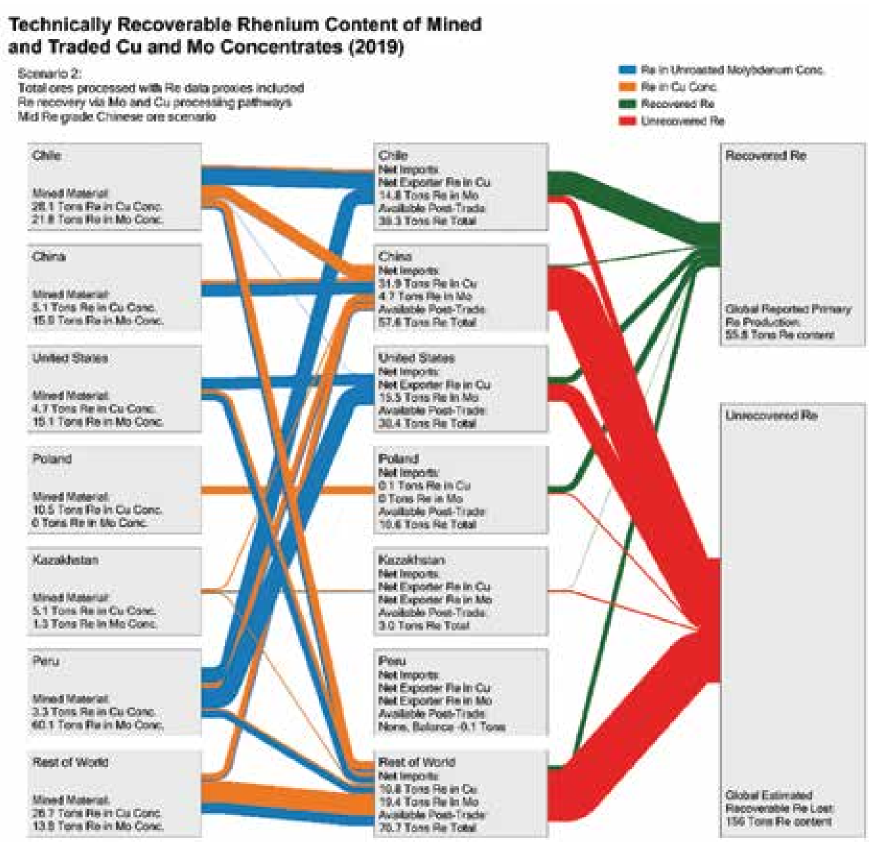


Figure 8

Diagram of rhenium material flows by country, form and processing stage (Brainard, 2023).



content. This estimate could be adjusted for uncertainty using a 95 percent confidence interval. The need for estimation is limited, however, because rhenium contents are reported for 70 percent of copper production and 80 percent of molybdenum production (Brainard, 2023). The data in Fig. 7 represent only available reported data and data for China adjusted by using the mid-point based on the composition of all Chinese molybdenum deposits to account for "missing" molybdenum production. Shaded regions represent the range of the rhenium data 95 percent confidence intervals. Production of copper (orange dashed) and molybdenum (gray dashed) are added for comparison of rhenium with host commodity growth, where production is normalized to production in 2000 (that is, two would be twice the production in 2000).

The next step in determining rhenium supplies is to assess the quantities of rhenium embedded in international trade flows of copper and molybdenum. This is important because the countries that mine copper and/or molybdenum do not always liberate the rhenium contained therein (Brainard, 2023). Therefore, tracking international trade flows of copper concentrates and unroasted molybdenum concentrates is essential for a comprehensive quantitative assessment of rhenium availability. Once the rhenium content of these trade flows is known, net imports can be added to domestic production to get an estimate of a country's apparent consumption of rhenium (Fig. 8). From another perspective, apparent consumption informs the amount of rhenium available to a nation post-trade.

The key takeaway from the trade data is that only a few nations participate in the mining, trade and roasting of copper and molybdenum concentrates to extract rhenium. In other words, the supply and potential supply of rhenium undergoes significant redistribution due to these trade flows. Chile, for example, is involved in all three aspects (mining, importing concentrates, roasting), whereas Peru simply exports all its rhenium-bearing molybdenum (Brainard, 2023). Due to these idiosyncrasies, assessment of a country's rhenium extraction potential should be conducted post-trade (Brainard, 2023).

The USGS's work on estimating accessible rhenium supply helps fill a knowledge gap between reported rhenium production and what is theoretically possible from both known and unknown deposits.

These estimates could be improved through greater transparency from mining and processing companies that currently treat these data as proprietary. Given the criticality of rhenium and other byproduct minerals, an accurate assessment of available supply is essential for sound policy and investment decisions.

Conclusion

Through various research activities across critical mineral supply chains, USGS contributions help to define the nation's critical mineral supply chain issues, acquire the fundamental data needed to address these problems, and provide authoritative information needed to guide policy decisions. Considering the high priority of critical minerals to economic and national security as well as the energy transformation, critical minerals research and assessments remain key components of the overall USGS mission. The application of geoscience information to societal issues is of paramount importance to the stewardship of natural resources and decision-making on behalf of future generations. ■

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USGS mineral review

by Staff, U.S. Geological Survey, National Minerals Information Center

In 2023, the estimated total value of nonfuel mineral production in the United States increased by 4 percent, in nominal terms, to $105 billion, from the revised value of $101 billion in 2022. The estimated value of metals produced domestically decreased slightly to $34.9 billion, and the estimated value of industrial minerals produced domestically increased by 7 percent to $69.9 billion (Table 1).

Increases in production of some nonfuel mineral commodities and increases in prices of some industrial minerals contributed to the total value of domestic nonfuel mineral production increasing in 2023. For the industrial minerals sector, increased construction and materials for energy and infrastructure projects as well as other manufacturing sectors led to increased production value. The largest percentage increases in production value were in bromine, helium, iodine, peat, pumice, sand and gravel (industrial), stone (crushed) and vermiculite. For the metal sector, production decreased for several mineral commodities and prices decreased for several metals due to oversupply. Cobalt, copper, lithium, nickel, palladium, rare earths and zinc had some of the largest percentage decreases in production value.

Mineral industry performance

Discussion of mine production is commonly segmented according to the type of materials produced within the broad categories of metals and industrial minerals (also known as nonmetallic minerals). Industrial minerals can be further subdivided as natural aggregates and other industrial minerals. Metals tend to have higher unit values but lower production quantities compared with those of industrial minerals, such as crushed stone or construction sand and gravel, which have higher production quantities but lower unit values. Therefore, for discussion and analysis of the performance of the nonfuel minerals industry, the value of production is used rather than the tonnage

*All data are based on information available as of, or prior to, Jan. 31, 2024. Data source: U.S. Geological Survey, 2024, Mineral Commodity Summaries 2024: U.S. Geological Survey, https://doi.org/10.3133/mcs2024
**All measurements are expressed in metric unless otherwise indicated.

Table 1

U.S. mineral industry trends. (Sources: U.S. Geological Survey, U.S. Department of Energy and U.S. Department of Labor)

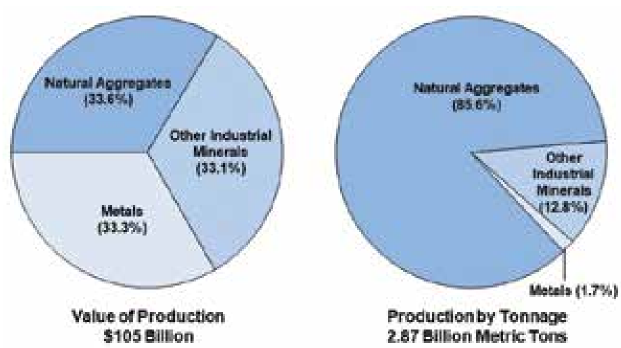
	2019	2020	2021	2022	2023[e]
Total mine production (million dollars):					
Metals	26,900	27,600	36,900	35,400	34,900
Industrial minerals	56,500	54,000	58,200	65,300	69,900
Coal	25,500	16,800	21,000	32,300	31,700
Employment (thousands of workers):					
Coal mining, all employees	51	40	38	40	41
Nonfuel mineral mining, all employees	140	136	138	143	150
Chemicals and allied products, production workers	559	537	541	570	570
Stone, clay and glass products, production workers	312	296	300	315	310
Primary metal industries, production workers	301	272	270	282	290
Average weekly earnings of workers (dollars):					
Coal mining, all employees	1,617	1,517	1,618	1,762	1,800
Chemicals and allied products, production workers	1,066	1,065	1,103	1,119	1,200
Stone, clay, and glass products, production workers	968	981	1,017	1,086	1,100
Primary metal industries, production workers	1,027	1,006	1,073	1,172	1,200

[e]Estimated.

Annual Review 2023: Mining

Figure 1

Evaluation of the performance of the minerals industry by sector. In terms of the value of production, the three segments shown are relatively similar in their contribution to the U.S. economy. If measured by tonnage, natural aggregates dwarf the performance of the other sectors.



produced. Tonnages of natural aggregates are orders of magnitude greater than those for most other mineral commodities, thus making direct comparisons based on weight less useful than value comparisons (Fig. 1).

As shown in Fig. 2, minerals are fundamental to the U.S. economy, contributing to the real gross domestic product at several levels, including mining, processing and manufacturing finished products. Net exports of mineral raw materials and old scrap were $4.7 billion and $17 billion, respectively. Domestic raw materials, along with domestically recycled materials, were used to produce mineral materials worth $890 billion. These mineral materials, including aluminum, brick, cement, copper, fertilizers and steel, along with net imports of processed mineral materials (worth about $102 billion) were, in turn, consumed by downstream industries with value added to the gross domestic product estimated to be $3,840 billion, a 6 percent increase from the revised value in 2022.

In 2023, domestic production of 14 mineral commodities was valued at more than $1 billion each. These were, in decreasing order of value, crushed stone, construction sand and gravel, cement, gold, copper, iron ore, industrial sand and gravel, salt, lime, zinc, phosphate rock, soda ash, molybdenum and helium.

In 2023, 10 states had more than $3 billion worth of publishable nonfuel mineral commodities production value and another 13 states had more than $1.5 billion. The publishable mineral production of these 23 states, combined, accounted for about 80 percent of the total nonfuel mineral production value (Fig. 3).

Based on total nonfuel mineral production value, including withheld data, the top 10 states were, in descending order of production value, Texas, Arizona, Nevada, Minnesota, California, Florida, Alaska, Michigan, Wyoming and Missouri (Table 2).

In 2023, the United States continued to rely on foreign sources for many raw and processed mineral materials. Imports supplied more than 50 percent of apparent consumption for 49 nonfuel mineral commodities, and the United States was 100 percent net import reliant for 15 of those (Fig. 4). Figure 5 shows the countries from which the majority of nonfuel mineral commodities with greater than 50 percent net import reliance were imported and the ranges of the number of nonfuel mineral commodities for which each country was a leading supplier. China and Canada supplied the largest number of these nonfuel mineral commodities. The countries that were the leading sources of imported mineral commodities with greater than 50 percent net import reliance were China,

Figure 2

The role of nonfuel minerals in the U.S. economy in 2023 (estimated values). (Sources: U.S. Geological Survey and U.S. Department of Commerce)

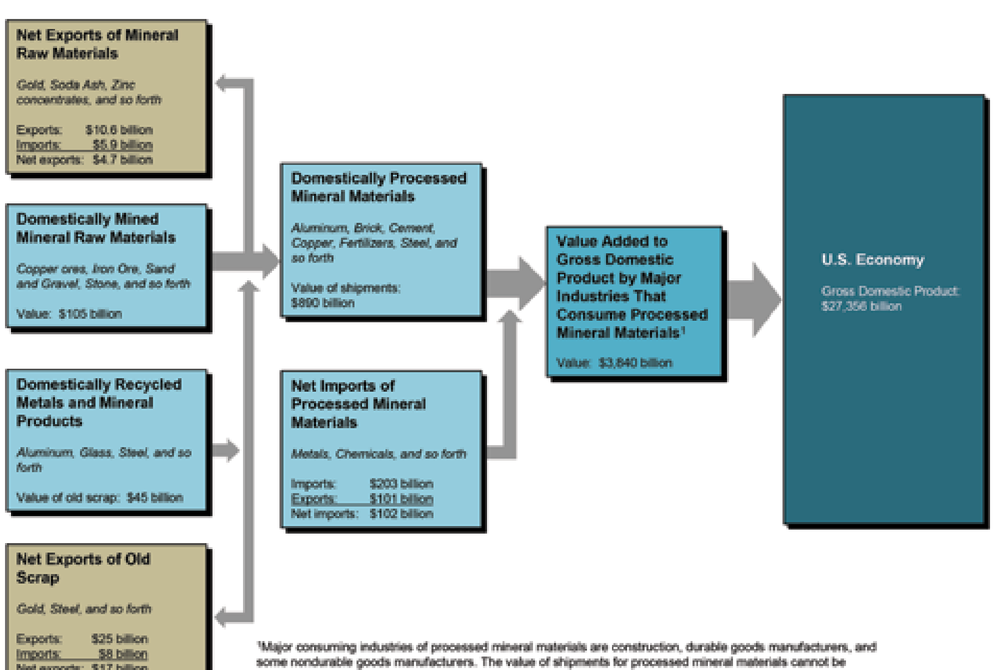
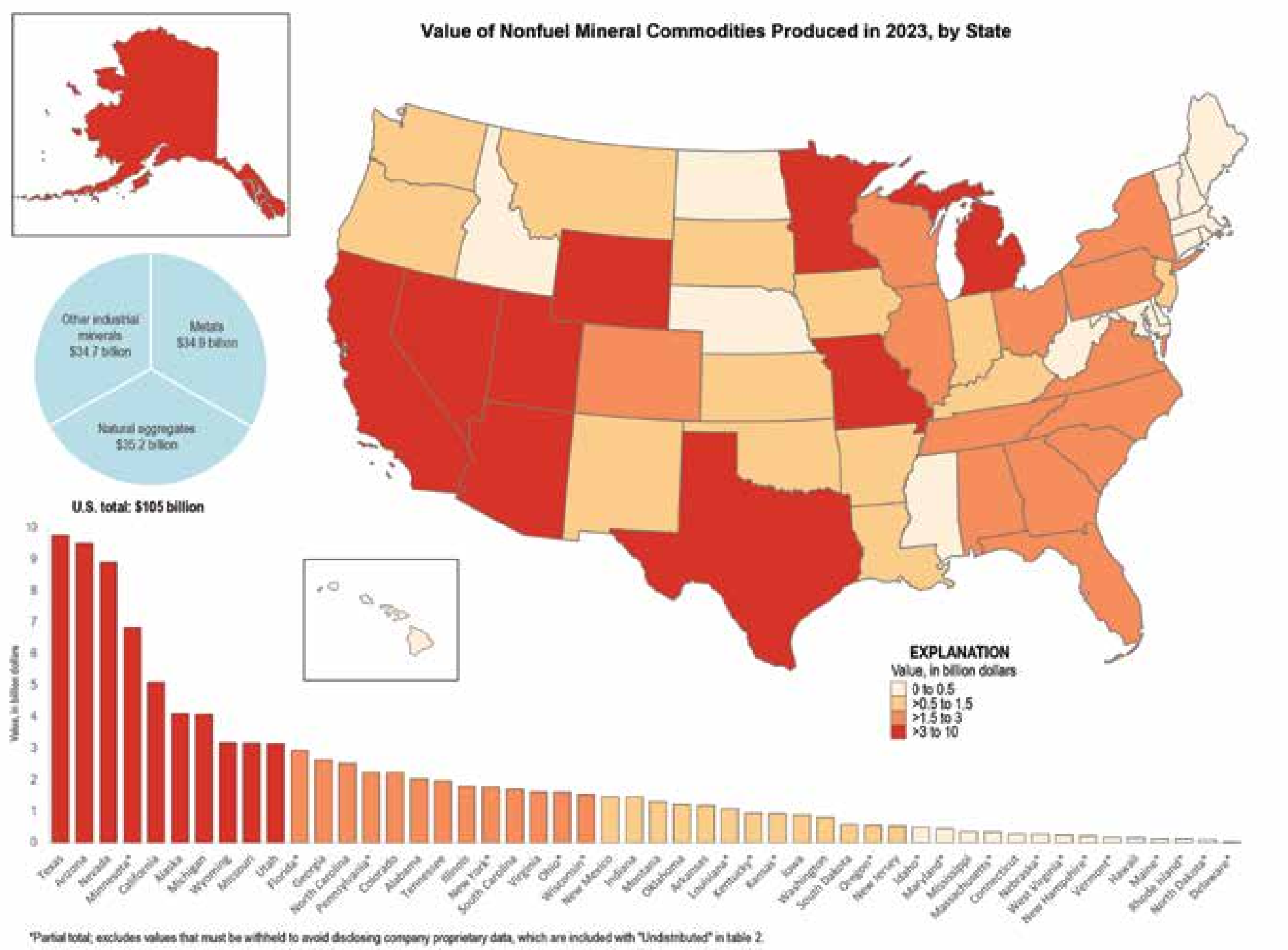


Figure 3

Map of the United States indicating the value of nonfuel mineral production by state in 2023, with charts ranking the states and proportions of production, by type of material.



24 mineral commodities; Canada, 23; Germany, 12; Brazil, 10; and Belgium, Mexico, Russia and South Africa, eight each. Of the more than 90 nonfuel mineral commodities evaluated, the United States was a net exporter of 20 mineral commodities.

The Defense Logistics Agency (DLA) Strategic Materials is responsible for the operational oversight of the National Defense Stockpile (NDS) of strategic and critical materials. Managing the security, providing environmentally sound stewardship and ensuring the readiness of all NDS stocks is the mission of the DLA Strategic Materials. The NDS currently contains 50 unique commodities stored at nine locations within the continental United States. In fiscal year 2023, the NDS added four materials along with additional quantities of four other materials, and approximately $41.17 million of excess materials were sold.

Foreign trade

In April 2023, a 200 percent ad valorem tariff on aluminum articles and derivative aluminum articles from Russia was put in place. In May 2023, the suspension of the 25 percent ad valorem tariffs imposed under section 232 of the Trade Expansion Act of 1962 for steel articles and derivative steel articles from Ukraine was extended for another year.

In 2023, the additional tariffs placed on imports from China remained while the Office of the United States Trade Representative (USTR) was conducting its four-year review of the actions imposed under section 301(b) of the Trade Act of 1974 (19 U.S.C. 2411, as amended): China's acts, policies and practices related to technology transfer, intellectual property and innovation.

In December 2023, China implemented export bans and export restrictions on certain strategic materials and technologies in the "Catalogue of Technologies Prohibited and Restricted from Export in China." Export bans prohibited any materials or technology from leaving China. Those items under an export ban included a category called "Nonferrous Metal Smelting and Processing Industry." Export restrictions required exporters to

Table 2

Value of nonfuel mineral production in the United States and principal nonfuel mineral commodities produced in 2023.[p,1,2]

State	Value (millions)	Rank[3]	Percent of U.S. total[4]	Principal nonfuel mineral commodities[5]
Alabama	$2,010	18	1.92	Cement, lime, sand and gravel (construction), sand and gravel (industrial), stone (crushed).
Alaska	4,100	7	3.91	Gold, lead, sand and gravel (construction), silver, zinc.
Arizona	9,500	2	9.07	Cement, copper, molybdenum mineral concentrates, sand and gravel (construction), stone (crushed).
Arkansas	1,180	30	1.12	Bromine, cement, sand and gravel (construction), sand and gravel (industrial), stone (crushed).
California[6]	5,080	5	4.85	Boron minerals, cement, rare earths, sand and gravel (construction), stone (crushed).
Colorado	2,220	15	2.12	Cement, gold, molybdenum mineral concentrates, sand and gravel (construction), stone (crushed).
Connecticut	264	43	0.25	Sand and gravel (construction), stone (crushed), stone (dimension).
Delaware[7]	17	50	0.02	Magnesium compounds, sand and gravel (construction), stone (crushed).
Florida[6,7]	2,900	6	2.77	Cement, clay (attapulgite and kaolin), phosphate rock, sand and gravel (construction), stone (crushed).
Georgia[6]	2,620	12	2.50	Cement, clay (common clay, kaolin, montmorillonite), sand and gravel (construction), sand and gravel (industrial), stone (crushed).
Hawaii	154	46	0.15	Sand and gravel (construction), stone (crushed).
Idaho[7]	482	32	0.46	Lead, phosphate rock, sand and gravel (construction), silver, stone (crushed).
Illinois	1,770	20	1.69	Cement (portland), magnesium compounds, sand and gravel (construction), sand and gravel (industrial), stone (crushed).
Indiana	1,440	25	1.37	Cement, lime, sand and gravel (construction), stone (crushed), stone (dimension).
Iowa	879	33	0.84	Cement (portland), lime, sand and gravel (construction), sand and gravel (industrial), stone (crushed).
Kansas[7]	915	26	0.87	Cement, helium, salt, sand and gravel (construction), stone (crushed).
Kentucky[7]	919	27	0.88	Cement, clay (common clay), lime, sand and gravel (construction), stone (crushed).
Louisiana[7]	1,070	31	1.02	Clay (common clay), lime, salt, sand and gravel (construction), sand and gravel (industrial), stone (crushed).
Maine[7]	116	47	0.11	Cement, peat, sand and gravel (construction), stone (crushed), stone (dimension).
Maryland[7]	431	35	0.41	Cement, sand and gravel (construction), stone (crushed), stone (dimension).
Massachusetts[7]	329	41	0.31	Clay (common clay), lime, sand and gravel (construction), stone (crushed), stone (dimension).
Michigan	4,060	8	3.87	Cement, iron ore, nickel sulfide concentrates, sand and gravel (construction), stone (crushed).
Minnesota[7]	6,820	4	6.51	Iron ore, lime, sand and gravel (construction), sand and gravel (industrial), stone (crushed).
Mississippi	338	42	0.32	Clay (ball clay, bentonite, common clay, montmorillonite), sand and gravel (construction), sand and gravel (industrial), stone (crushed).
Missouri	3,160	10	3.01	Cement, lead, lime, sand and gravel (industrial), stone (crushed).
Montana	1,290	28	1.23	Copper, molybdenum mineral concentrates, palladium, platinum, sand and gravel (construction).

State	Value (millions)	Rank[3]	Percent of U.S. total[4]	Principal nonfuel mineral commodities[5]
Nebraska[7]	$260	40	0.25	Cement (portland), lime, sand and gravel (construction), sand and gravel (industrial), stone (crushed).
Nevada	8,880	3	8.47	Copper, gold, lime, sand and gravel (construction), stone (crushed).
New Hampshire[7]	203	44	0.19	Sand and gravel (construction), stone (crushed), stone (dimension).
New Jersey	515	38	0.49	Sand and gravel (construction), sand and gravel (industrial), stone (crushed).
New Mexico	1,450	24	1.38	Cement, copper, potash, sand and gravel (construction), stone (crushed).
New York[7]	1,750	16	1.67	Cement, salt, sand and gravel (construction), stone (crushed), zinc.
North Carolina	2,500	13	2.39	Phosphate rock, quartz (high-purity), sand and gravel (construction), sand and gravel (industrial), stone (crushed).
North Dakota[7]	78	49	0.07	Lime, sand and gravel (construction), sand and gravel (industrial), stone (crushed).
Ohio[7]	1,580	17	1.51	Cement, lime, salt, sand and gravel (construction), stone (crushed).
Oklahoma	1,210	29	1.15	Cement, iodine, sand and gravel (construction), sand and gravel (industrial), stone (crushed).
Oregon[7]	527	36	0.50	Cement (portland), diatomite, perlite, sand and gravel (construction), stone (crushed).
Pennsylvania[7]	2,220	14	2.12	Cement, lime, sand and gravel (construction), sand and gravel (industrial), stone (crushed).
Rhode Island[7]	109	48	0.10	Sand and gravel (construction), sand and gravel (industrial), stone (crushed).
South Carolina	1,680	21	1.60	Cement, gold, sand and gravel (construction), sand and gravel (industrial), stone (crushed).
South Dakota	549	37	0.52	Cement (portland), gold, lime, sand and gravel (construction), stone (crushed).
Tennessee	1,950	19	1.86	Cement, sand and gravel (construction), sand and gravel (industrial), stone (crushed), zinc.
Texas	9,750	1	9.31	Cement, lime, sand and gravel (construction), sand and gravel (industrial), stone (crushed).
Utah	3,140	11	3.00	Cement (portland), copper, gold, potash, salt.
Vermont[7]	160	45	0.15	Sand and gravel (construction), stone (crushed), stone (dimension), talc (crude).
Virginia	1,590	23	1.52	Cement, lime, sand and gravel (construction), sand and gravel (industrial), stone (crushed).
Washington	796	34	0.76	Cement, diatomite, lime, sand and gravel (construction), stone (crushed).
West Virginia[7]	231	39	0.22	Cement, lime, sand and gravel (construction), sand and gravel (industrial), stone (crushed).
Wisconsin[7]	1,510	22	1.44	Lime, sand and gravel (construction), sand and gravel (industrial), stone (crushed), stone (dimension).
Wyoming	3,170	9	3.02	Clay (bentonite and common clay), helium, sand and gravel (construction), soda ash, stone (crushed).
Undistributed	4,900	XX	4.68	XX
Total	**105,000**	**XX**	**100.00**	

[p]Preliminary. XX = Not applicable.
[1]Includes data available through Dec. 21, 2023.
[2]Data are rounded to no more than three significant digits; may not add to totals shown.
[3]Based on total, unadjusted state values.
[4]Calculated to two decimal places.
[5]Listed in alphabetical order.
[6]California, Florida and Georgia also produce significant quantities of titanium mineral concentrates and zirconium mineral concentrates. Breakdown by state is not available to avoid disclosure of company proprietary data.
[7]Partial total; excludes values that must be withheld to avoid disclosing company proprietary data, which are included with "Undistributed."

Figure 4

U.S. net import reliance for selected nonfuel minerals in 2023.

2023 U.S. Net Import Reliance[1]

Commodity	Net import reliance as a percentage of apparent consumption in 2023	Leading import sources (2019–22)[2]
ARSENIC, all forms	100	China,[3] Morocco, Malaysia, Belgium
ASBESTOS	100	Brazil, Russia
CESIUM	100	Germany
FLUORSPAR	100	Mexico, Vietnam, China, South Africa
GALLIUM	100	Japan, China, Germany, Canada
GRAPHITE (NATURAL)	100	China,[3] Mexico, Canada, Madagascar
INDIUM	100	Republic of Korea, Canada, Belgium
MANGANESE	100	Gabon, South Africa, Australia, Georgia
MICA (NATURAL), sheet	100	China, Brazil, India, Belgium
NIOBIUM (COLUMBIUM)	100	Brazil, Canada
RUBIDIUM	100	China, Germany, Russia
SCANDIUM	100	Japan, China, Germany, Philippines
STRONTIUM	100	Mexico, Germany, China
TANTALUM	100	China,[3] Germany, Australia, Indonesia
YTTRIUM	100	China,[3] Germany, France, Republic of Korea
GEMSTONES	99	India, Israel, Belgium, South Africa
ABRASIVES, fused aluminum oxide	>95	China,[3] Canada, Brazil, Austria
NEPHELINE SYENITE	>95	Canada
RARE EARTHS,[4] compounds and metals	>95	China,[3] Malaysia, Japan, Estonia
TITANIUM, sponge metal	>95	Japan, Kazakhstan, Saudi Arabia, Ukraine
BISMUTH	94	China,[3] Republic of Korea, Belgium, Mexico
POTASH	91	Canada, Russia, Belarus
STONE (DIMENSION)	87	Brazil, China,[3] Italy, Turkey
DIAMOND (INDUSTRIAL), stones	84	India, South Africa, Russia, Congo (Kinshasa)
PLATINUM	83	South Africa, Switzerland, Germany, Belgium
ANTIMONY, metal and oxide	82	China,[3] Belgium, India, Bolivia
ZINC, refined	77	Canada, Mexico, Peru, Republic of Korea
BARITE	>75	India, China,[3] Morocco, Mexico
BAUXITE	>75	Jamaica, Turkey, Guyana, Australia
IRON OXIDE PIGMENTS, natural and synthetic	75	China,[3] Germany, Brazil, Canada
TITANIUM MINERAL CONCENTRATES	75	South Africa, Madagascar, Australia, Canada
CHROMIUM, all forms	74	South Africa, Kazakhstan, Russia, Canada
PEAT	74	Canada
TIN, refined	74	Peru, Bolivia, Indonesia, Malaysia
ABRASIVES, silicon carbide	73	China,[3] Brazil, Canada, Netherlands
SILVER	69	Mexico, Canada, Poland, Switzerland
COBALT	67	Norway, Canada, Finland, Japan
GARNET (INDUSTRIAL)	67	South Africa, Australia, China,[3] India
RHENIUM	60	Chile, Canada, Germany, Kazakhstan
ALUMINA	59	Brazil, Australia, Jamaica, Canada
VANADIUM	58	Canada, Brazil, Austria, Russia
NICKEL	57	Canada, Norway, Finland, Russia
DIAMOND (INDUSTRIAL), bort, grit, and dust and powder	56	China,[3] Republic of Korea, Ireland, Russia
MAGNESIUM COMPOUNDS	52	China,[3] Israel, Canada, Brazil
GERMANIUM	>50	Belgium, China, Canada
IODINE	>50	Chile, Japan
MAGNESIUM METAL	>50	Canada, China,[3] Israel, Taiwan
SELENIUM	>50	Philippines, Mexico, Germany, Canada
TUNGSTEN	>50	China,[3] Germany, Bolivia, Vietnam
SILICON, metal and ferrosilicon	<50	Brazil, Russia, Canada, Norway
COPPER, refined	46	Chile, Canada, Mexico
ALUMINUM	44	Canada, United Arab Emirates, Bahrain, Russia
PALLADIUM	37	Russia, South Africa, Italy, Canada
LEAD, refined	35	Canada, Mexico, Republic of Korea, Australia
MICA (NATURAL), scrap and flake	28	China, Canada, India, Finland
PERLITE	26	Greece, China, Mexico
LITHIUM	>25	Argentina, Chile, China, Russia
TELLURIUM	>25	Canada, Germany, Philippines, Japan
SALT	25	Canada, Chile, Mexico, Egypt
BROMINE	<25	Israel, Jordan, China[3]
ZIRCONIUM, ores and concentrates	<25	South Africa, Australia, Senegal, Russia
CEMENT	22	Turkey, Canada, Greece, Mexico
VERMICULITE	20	South Africa, Brazil, Zimbabwe

[1]Not all mineral commodities covered in this publication are listed here. Those not shown include mineral commodities for which the United States is a net exporter (abrasives, metallic; beryllium; boron; cadmium; clays; diatomite; gold; helium; iron and steel scrap; iron ore; kyanite; lime; molybdenum; rare earths, mineral concentrates; sand and gravel, industrial; soda ash; titanium dioxide pigment; wollastonite; zeolites; and zinc, ores and concentrates) or less than 20% net import reliant (feldspar; gypsum; iron and steel; iron and steel slag; nitrogen (fixed)—ammonia; phosphate rock; pumice; sand and gravel, construction; stone, crushed; sulfur; and talc and pyrophyllite). For some mineral commodities (hafnium; mercury; quartz, high-purity and industrial cultured crystal; thallium; and thorium), not enough information is available to calculate the exact percentage of import reliance.

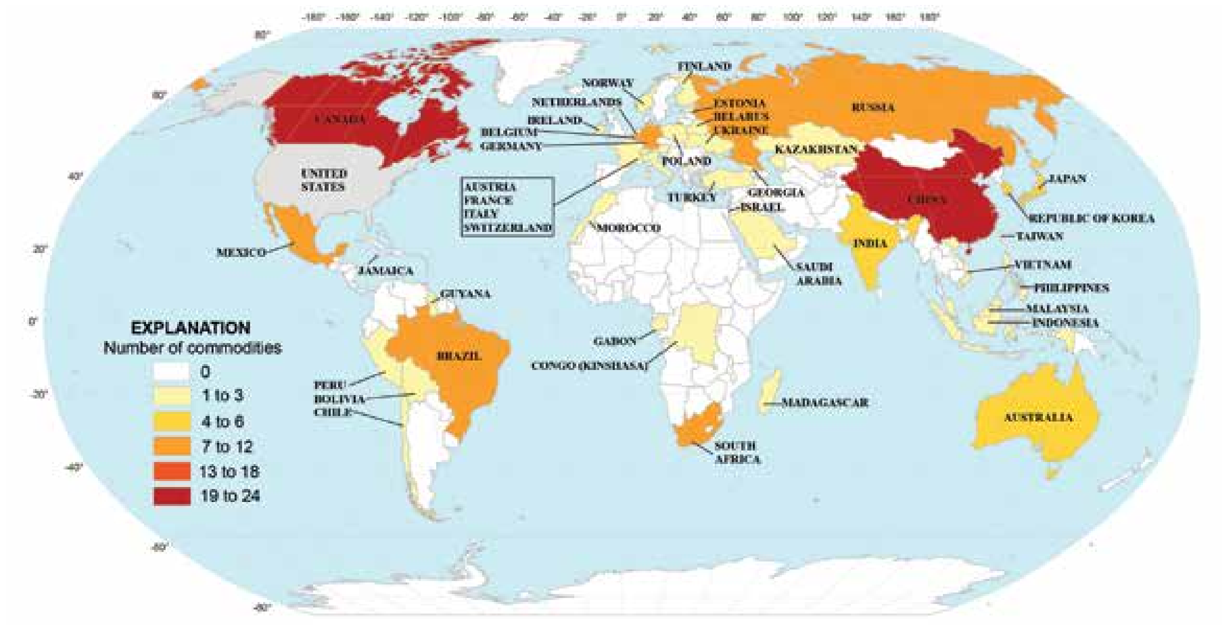
[2]Listed in descending order of import share.

[3]Includes Hong Kong.

[4]Includes lanthanides cerium, dysprosium, erbium, europium, gadolinium, holmium, lanthanum, lutetium, neodymium, praseodymium, samarium, terbium, thulium, and ytterbium.

Figure 5

World map highlighting major import sources (2019-2022) for nonfuel mineral commodities for which the United States was more than 50 percent import dependent. The countries are color-coded to indicate the number of mineral commodities for which the country was considered a major supplier to the United States. China, followed by Canada, supplied the largest number of nonfuel mineral commodities. (Source: U.S. Geological Survey)



apply for a license, which, according to some sources, required export contracts, technical product specifications and the identity of the end user as well as the specific end use. Export restrictions included nonferrous metal mining technology, smelting and processing. China was the dominant global producer for many of the materials, and many of the materials were on the U.S. critical minerals list.

Critical minerals

On Feb. 24, 2022, pursuant to section 7002 of the Energy Act of 2020 (Public Law 116–260) and using the definition of "critical mineral" and the criteria specified therein, the U.S. Geological Survey (USGS) published the "2022 Final List of Critical Minerals" in the Federal Register (87 FR 10381). The 2022 list of critical minerals, which revised the U.S. critical minerals list (CML) published in 2018 (83 FR 23295), included 50 mineral commodities instead of 35 mineral commodities or mineral groups (Table 3). The changes in the 2022 CML from the 2018 CML were the addition of nickel and zinc, listing out individual platinum group metals and rare earth elements, and the removal of helium, potash, rhenium, strontium and uranium. The CML is to be updated at least every three years and revised as necessary, consistent with available data.

A series of actions by the government in recent years addressed domestic supply-chain vulnerabilities for critical minerals, beginning with Executive Order 13817, "A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals," which was issued on Dec. 26, 2017, and initiated a whole-of-government call to action to identify critical minerals and develop a strategy to address U.S. supply-chain vulnerabilities. Subsequently, there have been additional actions including the following:

1. The USGS published the 2018 CML.
2. The U.S. Department of Commerce with interagency input published the "2019 Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals."
3. Several Presidential determinations directed the use of Defense Production Act (DPA) title III authorities to strengthen the U.S. industrial base for rare earth elements.
4. Executive Order 13953 was issued "Addressing the Threat to the Domestic Supply Chain Reliance on Critical Minerals from Foreign Adversaries and Supporting the Domestic Mining and Processing Industries."
5. The Energy Act of 2020 was passed by Congress and signed into law.

Several congressional acts and other government actions have focused on investments for clean energy projects; critical mineral mapping, production, recycling, reclamation and resource assessments; domestic production of batteries; infrastructure projects;

Table 3

The 2022 U.S. critical minerals list.[1]

Critical mineral	Applications
Aluminum	Metallurgy and many sectors of the economy.
Antimony	Flame retardants and lead-acid batteries.
Arsenic	Pesticides and semiconductors.
Barite	Hydrocarbon production.
Beryllium	Aerospace and defense.
Bismuth	Medical, metallurgy, and atomic research.
Cerium[2]	Catalytic converters, ceramics, glass, metallurgy, and polishing compounds.
Cesium	Research and development.
Chromium	Metallurgy.
Cobalt	Batteries and metallurgy.
Dysprosium[2]	Data storage devices, lasers, and permanent magnets.
Erbium[2]	Fiber optics, glass colorant, lasers, and optical amplifiers.
Europium[2]	Nuclear control rods and phosphors.
Fluorspar	Cement, industrial chemicals, and metallurgy.
Gadolinium[2]	Medical imaging, metallurgy, and permanent magnets.
Gallium	Integrated circuits and optical devices.
Germanium	Defense and fiber optics.
Graphite	Batteries, fuel cells, and lubricants.
Hafnium	Ceramics, nuclear control rods, and metallurgy.
Holmium[2]	Lasers, nuclear control rods, and permanent magnets.
Indium	Liquid crystal displays.
Iridium[3]	Anode coatings for electrochemical processes and chemical catalysts.
Lanthanum[2]	Batteries, catalysts, ceramics, glass, and metallurgy.
Lithium	Batteries.
Lutetium[2]	Cancer therapies, electronics, and medical imaging.
Magnesium	Metallurgy.
Manganese	Batteries and metallurgy.
Neodymium[2]	Catalysts, lasers, and permanent magnets.
Nickel	Batteries and metallurgy.
Niobium	Metallurgy.
Palladium[3]	Catalytic converters and catalysts.
Platinum[3]	Catalytic converters and catalysts.
Praseodymium[2]	Aerospace alloys, batteries, ceramics, colorants, and permanent magnets.
Rhodium[3]	Catalytic converters, catalysts, and electrical components.
Rubidium	Research and development.
Ruthenium[3]	Catalysts, electronic components, and computer chips.
Samarium[2]	Cancer treatments, nuclear, and permanent magnets.
Scandium	Ceramics, fuel cells, and metallurgy.
Tantalum	Capacitors and metallurgy.
Tellurium	Metallurgy, solar cells, and thermoelectric devices.
Terbium[2]	Fiber optics, lasers, permanent magnets, and solid state devices.
Thulium[2]	Lasers and metallurgy.
Tin	Metallurgy.
Titanium	Metallurgy and pigments.
Tungsten	Metallurgy.
Vanadium	Batteries, catalysts, and metallurgy.
Ytterbium[2]	Catalysts, lasers, metallurgy, and scintillators.
Yttrium	Catalysts, ceramics, lasers, metallurgy, and phosphors.
Zinc	Metallurgy.
Zirconium	Metallurgy and nuclear.

[1]The 2022 Final List of Critical Minerals published Feb. 24, 2022, by the U.S. Geological Survey (87 FR 10381).

[2]Included in the Rare Earths chapter.

[3]Included in the Platinum-Group Metals chapter.

research and development; ports and rail improvements; semiconductor supply-chain projects; telecommunications broadband networks and water systems. These actions have included the following:

1. Congress passed, and the President signed the $1.2 trillion Bipartisan Infrastructure Law (Infrastructure Investment and Jobs Act, H.R. 3684, Public Law 117–58) in November 2021.
2. A Presidential determination on March 31, 2022, authorized the use of DPA title III authorities to strengthen the U.S. industrial base for large-capacity batteries and specifically increasing domestic mining and processing of critical materials for the large-capacity

battery supply chain such as cobalt, graphite, lithium and nickel.

3. The Ukraine Supplemental Appropriations Act of 2022 provided $600 million for DPA title III funds for missiles and munitions in support of Ukraine and strategic and critical materials to expand domestic capacity.
4. The CHIPS and Science Act of 2022 (Public Law 117–167) provided $280 billion in funding over the next 10 years for domestic research, commercialization, and manufacturing of semiconductors.
5. The Inflation Reduction Act of 2022 (Public Law 117–169) was signed into law with the aim to reduce inflation. Specifically related to critical minerals, it authorized $391 billion in funding for climate change and domestic energy production including targeted tax incentives aimed at manufacturing U.S.-sourced materials such as batteries, electric vehicles, solar and wind parts and technologies.
6. In October 2022, the "American Battery Materials Initiative" was launched to leverage and maximize ongoing efforts throughout the U.S. Government to meet resource requirements and bolster energy security.
7. In December 2022, the $858 billion National Defense Authorization Act included a provision requiring a federal strategy be developed to recycle and recover critical minerals from batteries used in the federal electric vehicle fleet.

Several investments were announced in 2023 to address the domestic availability and supply of critical minerals. On Jan. 13, 2023, the Loan Program Office (LPO) at the U.S. Department of Energy (DOE) offered a conditional commitment to lend up to $700 million to a company in Nevada to develop a domestic supply of lithium carbonate for electric-vehicle batteries. On April 4, 2023, the DOE announced $16 million in funding from the Bipartisan Infrastructure Law (Infrastructure Investment and Jobs Act, H.R. 3684, Public Law 117-58 signed into law November 2021) to support projects in West Virginia and North Dakota for the development of a first-of-a-kind extraction and separation refinery for rare earth elements and other critical minerals. On June 15, 2023, the U.S. Department of Defense (DOD) awarded $15 million to a company in Idaho to support feasibility studies to enhance the definition and characterization of currently known cobalt resources as well as to assess requirements of a domestic cobalt refinery. On July 13, 2023, the DOE announced $32 million in funding for projects to build facilities that produce rare earth elements and critical minerals and materials from domestic coal-based resources. Subsequently, on Aug. 21, 2023, the DOE announced $30 million in funding to help lower the costs of the onshore production of rare earths and other critical minerals and materials from domestic coal-based resources. On July 17, 2023, the DOD awarded $37.5 million to a graphite project in Alaska and on Nov. 29, 2023, awarded $3.2 million to support a graphite project in Alabama. On Sept. 12, 2023, the DOD awarded $20.6 million to advance nickel exploration and mineral resource definition at a project in Minnesota and awarded $90 million to support the reopening of a lithium mine in North Carolina. The company in North Carolina estimated that the lithium mine would resume operations between 2025 and 2030. On Oct. 30, 2023, the DOD awarded $12.7 million to a company in Virginia to increase titanium powder production for defense supply chains.

In November 2023, production was restarted at a high-purity granular polysilicon facility in Washington, which had been idled for four years. The material produced was to be shipped to a new fully integrated solar manufacturing facility in Georgia, scheduled to open in phases in 2024, that will produce silicon ingots wafer, and cells for solar module production. There has been no production of solar-grade wafers in the United States since 2016. Tax incentives for domestically sourced materials for renewable energy, such as solar wafers and cells, in the Inflation Reduction Act of 2022 were cited as the drivers for investments in these facilities.

In addition to critical minerals production investments, there were investments made in critical minerals recycling projects. On Feb. 9, 2023, the LPO at the DOE announced a conditional loan commitment of $2 billion to a Nevada company for the construction and expansion of a battery materials campus that will support the growing electric-vehicle market in the United States. On Feb. 27, 2023, the LPO at the DOE announced a conditional loan commitment of $375 million to a New York company for the construction of a lithium-ion battery resource recovery facility and to help the company expand its operations. From the fourth quarter of 2022 through 2023, DOE funding through the Bipartisan Infrastructure Law totaled $3 billion for five domestic lithium-ion recycling facilities.

In 2023, the value of domestic primary mine production of critical minerals was $4.1 billion, a 24 percent decrease from $5.4 billion in 2022. Reduced prices for these mineral commodities contributed the most to the reduced value and delayed new production or restarting production of some critical minerals. A total of 13 individual mineral commodities and the rare earths group of minerals (without specification of the specific lanthanides) were produced in the United States. The United States was 100 percent net import reliant for 12 of the 50 critical minerals and more than 50 percent net import reliant for an additional 29 critical minerals (including 14 lanthanides, which are listed under rare earths). The United States had secondary production for 14 critical minerals, which resulted in net import reliance being less than 100 percent. The total value of critical minerals domestically recycled in 2023 was $10 billion, 23 percent of the total value of domestically recycled old scrap.

China was the leading producing nation for 29 of 43 critical minerals (including 14 lanthanides, which are listed under rare earths) for which information was available to make reliable estimates. The other leading producing nations of critical minerals were Australia and South Africa with three critical minerals each and Congo (Kinshasa) with two critical minerals (Table 4). For 29 critical minerals (including 14 lanthanides, which are listed under rare earths), production was highly concentrated (50 percent or more) in a single country, of which five critical minerals had 80 percent or more of global production dominated by one country, two critical minerals with 70 percent to less than 80 percent of global production dominated by one country, 20 critical minerals (including 14 lanthanides, which are listed under rare earths) with 60 percent to less than 70 perecent of global production dominated by one country, and two critical minerals with 50 percent to less than 60 percent of global production dominated by one country.

Metals

The estimated value of domestic metal mine production in 2023 was $34.9 billion, slightly less than the revised value in 2022. Cobalt, copper, nickel, palladium, rare earth elements and zinc had some of the largest percentage decreases in production value. Principal contributors to the total value of metal mine production in 2023 were gold (29 percent), copper (28 percent), iron ore (22 percent), zinc (7 percent), and molybdenum (5 percent), all with production values of more than $1 billion. The remaining nine percent of metal mine production value was from 14 other metals and (or) metal ore concentrates.

Ferrous metals. The estimated value of U.S. iron ore production in 2023 was $7.5 billion, a 22 percent increase from the value in 2022. Iron ore production and trade were estimated to have increased likely owing to restocking and increased consumption for intermediate products. Mines in Michigan and Minnesota shipped 98 percent of the usable iron ore produced in the United States. Seven openpit iron ore mines (each with associated concentration and pelletizing plants) and four iron metallic plants, including direct-reduced iron and hot-briquetted iron producers, operated during the year to supply steelmaking raw materials. Almost all iron ore was concentrated before shipment. In April, one company restarted production, at a limited capacity, at a domestic mine that was idled in 2022, citing increases in steel production and designating the plant as a "swing operation" to fill needed capacity. In May, one company received approval for state mineral leases that were expected to supplement iron ore for a domestic mine formerly anticipated to idle in 2025 and extend the mine life for an additional 20 years. The United States was estimated to have produced 1.8 percent of the 2.5 Gt of global iron ore output in 2023.

The U.S. iron and steel industry produced raw steel in 2023 with an estimated value of about $110 billion, a 15 percent decrease from $128 billion in 2022. Pig iron and raw steel were produced by two companies operating integrated steel mills in 12 locations. Raw steel was produced by 49 companies at 105 minimills. Indiana accounted for an estimated 24 percent of total raw steel production, followed by Ohio, 12 percent; Pennsylvania and Texas, 5 percent each; no other state having more than 4 percent of total domestic raw steel production. Construction accounted for an estimated 30 percent of total domestic shipments by market classification, followed by service centers, 24 percent. In the United States, the apparent consumption of finished steel products was estimated to have decreased slightly in 2023 owing to interest rate increases that negatively affected manufacturing and residential construction. Increases in the commercial building and automotive sectors were attributed to the 2022 Inflation Reduction Act and the 2021 Bipartisan Infrastructure Law.

Nonferrous metals. The value of U.S. copper mine production decreased by 11 percent in 2023 to an estimated $9.9 billion, production was estimated to be 1.1 million metric tons (Mt). Analysts attributed the decreased copper prices primarily to the strengthening of the U.S.

Table 4

Estimated salient critical minerals statistics in 2023[1] (metric tons, mine production, unless otherwise stated).

Critical mineral	United States: Primary production	Secondary production	Apparent consumption	Net import reliance as a percentage of apparent consumption	Primary import source (2019–22)	World: Leading producing country	Production in leading country	Percentage of world total	World production total
Aluminum (bauxite)	W	—	[2]1,800,000	>75	Jamaica	Australia	98,000,000	25	[3]400,000,000
Antimony	—	4,000	22,000	82	China[4]	China	40,000	48	83,000
Arsenic	—	NA	[5]6,400	100	China[4]	Peru	[6]27,000	45	[6]60,000
Barite	W	—	W	>75	India	India	2,700,000	32	[3]8,500,000
Beryllium	190	NA	150	E	Kazakhstan	United States	190	58	330
Bismuth[7]	—	80	1,400	94	China[4]	China	16,000	80	20,000
Chromium	—	100,000	380,000	74	South Africa	South Africa	18,000,000	44	41,000,000
Cobalt	500	2,100	6,400	67	Norway	Congo (Kinshasa)	170,000	74	230,000
Fluorspar	NA	—	370,000	100	Mexico	China	5,700,000	65	8,800,000
Gallium	—	—	[2]19	100	Japan	China	600	98	610
Germanium[7]	—	NA	NA	>50	Belgium	China	NA	NA	NA
Graphite (natural)	—	—	76,000	100	China[4]	China	1,230,000	77	1,600,000
Indium[7]	—	—	[5]300	100	Republic of Korea	China	650	66	990
Lithium	W	NA	W	>25	Argentina	Australia	86,000	48	[3]180,000
Magnesium[7]	W	100,000	[2]55,000	>50	Canada	China	830,000	88	[3]940,000
Manganese	—	—	690,000	100	Gabon	South Africa	7,200,000	36	20,000,000
Nickel	17,000	W	[8]190,000	57	Canada	Indonesia	1,800,000	50	3,600,000
Niobium	—	NA	8,400	100	Brazil	Brazil	75,000	90	83,000
Palladium	10	42	82	37	Russia	Russia	92	44	210
Platinum	3	9	70	83	South Africa	South Africa	120	67	180
Rare earths (compounds and metals)[9]	250	NA	8,800	>95	China[4]	China	240,000	69	350,000
Scandium	—	—	NA	100	Japan	China	NA	NA	NA
Tantalum	—	NA	370	100	China[4]	Congo (Kinshasa)	980	41	2,400
Tellurium[7]	W	—	W	>25	Canada	China	430	67	[3]640
Tin	—	16,900	39,000	74	Peru	China	68,000	23	290,000
Titanium (metal)[7]	W	W	[5]42,000	>95	Japan	China	220,000	67	[3]330,000
Tungsten	—	W	W	>50	China[4]	China	63,000	81	78,000
Vanadium	—	5,700	14,000	58	Canada	China	68,000	68	100,000
Yttrium	NA	—	200	100	China[4]	China	NA	NA	NA
Zinc[7]	[10]220,000	([10])	970,000	77	Canada	NA	NA	NA	NA
Zirconium (ores and concentrates)	<100,000	NA	<100,000	<25	South Africa	Australia	500,000	31	1,600,000

E Net exporter. NA Not available. W Withheld to avoid disclosing company proprietary data. — Zero.

[1]Critical minerals as published in the Federal Register on February 24, 2022 (87 FR 10381). Not all critical minerals are listed here. Cesium, hafnium, iridium, rhodium, rubidium, and ruthenium are not shown because available information is insufficient to make estimates of U.S. or world production.

[2]Reported consumption.

[3]Excludes U.S. production.

[4]Includes Hong Kong.

[5]Estimated consumption.

[6]Arsenic trioxide.

[7]Refinery production.

[8]Nickel in primary metal and secondary scrap.

[9]Data include lanthanides cerium, dysprosium, erbium, europium, gadolinium, holmium, lanthanum, lutetium, neodymium, praseodymium, samarium, terbium, thulium, and ytterbium.

[10]Primary production includes both primary and secondary metal production.

dollar relative to other global currencies and concerns regarding economic growth in China and inflation. Arizona was the leading copper-producing state and accounted for an estimated 70 percent of domestic output. Copper was also mined in Michigan, Missouri, Montana, Nevada, New Mexico and Utah. In the United States, copper was recovered or processed at 25 mines (17 of which accounted for 99 percent of mine production), two primary smelters, two electrolytic refineries and 14 electrowinning facilities. Globally, the United States was the fifth-leading producer of mined copper, accounting for about 5 percent of the total in 2023.

Five lead mines in Missouri, plus four mines in Alaska and Idaho, that produced lead as a coproduct, accounted for all domestic lead mine production. The value of domestic lead mine production in 2023 was an estimated $660 million, unchanged from 2022. Nearly all lead concentrate production has been exported since the last primary lead refinery in the United States closed in 2013. In 2023, domestic secondary smelter production of lead was 1 Mt, essentially unchanged from 2022. Nearly all secondary smelter production was recovered from old scrap, mostly lead-acid batteries.

The estimated value of zinc mined in 2023 was about $2.4 billion, a 23 percent decrease from 2022. Zinc was mined in five states at seven mining operations by five companies. Three smelter facilities, one primary and two secondary, operated by two companies, produced commercial-grade zinc metal. Of the total reported zinc consumed, most was used in galvanizing. The United States ranked fifth in global zinc mine production, accounting for about 6 percent of the world total in 2023.

Precious metals. In 2023, domestic gold mine production was estimated to be slightly less than in 2022, and the value was estimated at $10 billion. Gold was produced at more than 40 lode mines in 11 states, at several large placer mines in Alaska, and at numerous smaller placer mines (mostly in Alaska and in the Western States). The top 27 operations yielded about 97 percent of the mined gold produced in the United States. Nevada was the leading gold-producing state, accounting for about 73 percent of total domestic production. Commercial-grade gold was produced at about 15 refineries. A few dozen companies, out of several thousand companies and artisans, dominated the fabrication of gold into commercial products.

In 2023, U.S. mines produced silver worth an estimated $760 million. Silver was produced domestically at four silver mines and as a byproduct or coproduct from 31 base- and precious-metal mines. Alaska continued as the country's leading silver-producing state, followed by Nevada. Commercial-grade silver production was reported by 24 domestic refiners. The estimated domestic uses for silver were primarily physical investment (34 percent), followed by electrical and electronics (27 percent). World silver mine production increased slightly in 2023, principally as a result of increased production from mines in Mexico and Chile as new silver mines were starting or ramping up.

One company in Montana produced platinum group metals (PGMs) with an estimated value of about $510 million in 2023. Small quantities of primary PGMs also were recovered as byproducts of copper-nickel mining in Michigan; however, this material was sold to foreign companies for refining. Production at a domestic mine continued but was constrained owing to an incident that occurred in March 2023 and damaged equipment in a vertical shaft.

Refractory and specialty metals. The value of several refractory and specialty metals and minerals mined in the United States — including cobalt, nickel and rare earths — decreased significantly in 2023. The value of beryllium, molybdenum and titanium mined in the United States increased significantly in 2023.

In 2023, a mine in Michigan produced cobalt-bearing nickel concentrates, which were exported for processing. A company in Missouri built a flotation plant and produced nickel-copper-cobalt concentrates from historic mine tailings and was building a hydrometallurgical processing plant near the mine site. Ore extraction commenced at a cobalt-copper-gold mine in Idaho, but commissioning was suspended in March owing to low cobalt prices. Most U.S. cobalt and nickel supplies were imported or recovered from domestically produced scrap materials. Globally, cobalt is mostly mined as a byproduct of copper or nickel. Congo (Kinshasa) continued to be the world's leading source of mined cobalt, supplying 74 percent of the world cobalt mine production in 2023. China was the world's leading producer of refined cobalt, most of which was produced from partially refined cobalt imported from Congo (Kinshasa). China was the world's leading consumer of cobalt, with nearly 87 percent of its consumption used by the lithium-ion battery industry. Stainless and alloy steel and nickel-containing alloys typically account for more than 85 percent of domestic consumption of nickel, and superalloys, mainly in aircraft gas turbine engines, was the main use for cobalt in the United States.

Domestic mine production of molybdenum decreased slightly to 34,000 t of contained molybdenum in 2023 compared with 34,600 t in 2022. The estimated average molybdic oxide price increased by 34 percent compared with 2022. The United States ranked fourth in global mine production of molybdenum, behind China, Chile and Peru. Molybdenum ore was produced as a primary product at two mines — both in Colorado — and six copper mines (four in Arizona and one each in Montana and Utah) recovered molybdenum as a byproduct.

Domestic rare earths were mined as a primary product in Mountain Pass, CA and produced as a byproduct from heavy-mineral-sands mining and processing in the southeastern United States. An estimated 43 kt of rare earths were mined in 2023, compared with 42 kt in 2022. Additionally, an estimated 250 t of mixed rare earth compounds were produced. Global mine production was estimated to have increased by 17 percent compared with 2022. The estimated value of rare earth compounds and metals imported by the United States in 2023 was $190 million, a 7 percent decrease from $208 million in 2022.

Domestic production of titanium mineral concentrates took place at surface mining operations in Georgia and Florida. An additional company processed existing mine tailings to recover a mixed heavy-mineral concentrate in California. Abrasive sands, monazite and zircon were coproducts of these operations. An estimated 95 percent of titanium mineral concentrates were consumed domestically to produce titanium dioxide pigment. The remaining 5 percent was used in welding-rod coatings and for manufacturing carbides, chemicals and titanium metal.

Industrial minerals

The value of output of industrial minerals and materials from mines in the United States was $69.9 billion, 7 percent higher than in 2022. More than 6,500 companies contributed to this output, producing from more than 12,000 mines, quarries and processing facilities. Overall, in 2023, the production of industrial minerals, by tonnage, decreased slightly compared with 2022. In addition to mined materials, the United States is a major producer of industrial minerals that are recovered from processes other than mining. These materials, including iron and steel slag, nitrogen, sulfur and synthetic gypsum, contributed additional value to the industrial minerals industry.

Agricultural minerals. Overall industrial mineral use in agricultural production and consumption increased in 2023 and was dominated by nitrogen, phosphate rock, potash and sulfur, the first three of which are used in fertilizers to provide nutrients for plants. Sulfur (as sulfuric acid) is essential for processing phosphate rock, but also plays a role in plant nutrition.

In 2023, phosphate rock ore was mined at nine mines in four states and processed into an estimated 20 Mt of marketable product, valued at $2 billion. Phosphate rock was produced in Florida, Idaho, North Carolina and Utah. Domestic production and consumption of phosphate rock were higher in 2023, owing to increased phosphoric acid and fertilizer production. Favorable weather conditions in the planting seasons helped to increase fertilizer consumption and reduce phosphate fertilizer stocks that had accumulated in 2022. World production was estimated to have decreased by about 4 percent, with China, Morocco and the United States remaining the leading producers.

In 2023, the domestic sales value of marketable potash was estimated to have decreased by 20 percent to $570 million. The majority of U.S. production was from southeastern New Mexico, where two companies operated two underground mines and one deep-well solution mine. U.S. apparent consumption was estimated to have increased by about 4 percent compared with 2022. World potash consumption in 2023 for fertilizers was estimated to have increased to 37.1 Mt from 35.7 Mt in 2022. Global potash production decreased by an estimated 5 percent in 2023 from 2022, owing to producers drawing down potash inventories that had increased in 2022. Canada was the leading producer, accounting for about 33 percent of production, followed by Russia and China, accounting for 17 percent and 15 percent of the world total, respectively.

Nitrogen is commercially recovered from air as ammonia, which is produced by combining nitrogen in the atmosphere with hydrogen from natural gas. Nitrogen production was essentially unchanged in 2023 compared with 2022. A long period of generally stable and low natural-gas prices in the United States made it economic for companies to upgrade existing ammonia plants and construct new nitrogen facilities. The additional capacity has reduced ammonia imports. Expansion in the U.S. ammonia industry in the next five years is expected to increase capacity by about 2 percent, which includes decarbonized ammonia projects. Global ammonia capacity is expected to increase by a total of 6 percent during the next four years. Capacity additions were expected in places with low-cost natural gas such as in central and eastern Asia, eastern Europe, and North America. As part of the capacity increase, decarbonized ammonia plants have been proposed in several countries, but mainly in North America. Consumption of ammonia for fertilizer is expected to increase by 1 percent per year depending on availability and cost, with the largest increases expected in Latin America and south Asia.

Elemental sulfur is recovered as a byproduct of natural-gas processing and petroleum refining, and byproduct sulfuric acid is recovered at nonferrous metal smelters. Total U.S. sulfur production in 2023 was estimated to be unchanged from 2022, and shipments were unchanged from those in 2022. Domestic production of elemental sulfur from petroleum refineries and recovery from natural-gas operations was unchanged from 2022. Domestically, refinery sulfur production is expected to remain about the same as refining utilization remains high. Domestic byproduct sulfuric acid is expected to remain relatively constant, unless one or more of the remaining nonferrous-metal smelters close. World sulfur production was unchanged compared with 2022. Starting in 2023, sulfur production from the Middle East owing to upgrades and new refining projects increased sulfur availability. Also, an increase in nickel production from high-pressure acid leach projects to produce battery materials will begin to increase sulfur demand.

Chemical minerals. Many factors affect production and consumption of mineral materials used predominantly in the chemicals industry, including the state of the U.S. economy in general, the severity of winter conditions that determine the consumption of salt for deicing purposes, the performance of the steel industry and its need for lime, and numerous other influences. Because several of these commodities have significant export components, for example, boron and soda ash, their domestic production also reflects the economic conditions in other regions of the world. Worldwide economic downturns or growth can have an impact on the domestic production of these export-dependent commodities.

The quantities of domestically produced minerals used in the chemical industry ranged from 42 Mt of salt (reported as sold or used) to a group of other minerals that totaled about 2 kt. In addition to salt, major chemical minerals production included lime, 17 Mt; soda ash, 11 Mt; and sulfur for chemical uses not associated with agricultural uses. The combined value for all minerals predominantly used as raw materials for chemical products, excluding sulfur, which is not mined, was about $9 billion in 2023, essentially unchanged from 2022. Salt was valued at $2.6 billion; lime, $2.6 billion; soda ash, $1.9 billion; and other materials combined, $1.8 billion (boron, bromine, iodine, lithium carbonate, magnesite, and magnesium compounds).

Commercial-scale lithium production in the United States was from one continental brine operation in Nevada. Lithium was also commercially produced from the brine-sourced waste tailings of a Utah-based magnesium producer. Two companies produced a range of downstream lithium compounds in the United States from domestic or imported lithium carbonate, lithium chloride and lithium hydroxide. Excluding U.S. production, worldwide lithium production in 2023 increased by 23 percent to approximately 180 kt from 146 kt in 2022 in response to strong demand from the lithium-ion battery market. Seven mineral operations in Australia, one mineral tailings operation in Brazil, two brine operations each in Argentina and Chile, two mineral operations in Canada, five mineral and four brine operations in China, and one mineral operation in Zimbabwe accounted for the majority of world lithium production. Owing to the rapid increase in demand of lithium in 2023, established lithium operations worldwide increased or were in the process of increasing production. Lithium supply security has become a top priority for technology companies in Asia, Europe and the United States. Strategic alliances and joint ventures among technology companies and exploration companies continued to be established to ensure a reliable, diversified supply of lithium for battery suppliers and vehicle manufacturers.

Construction minerals and materials. More than 2.5 Gt of construction minerals and materials, which were dominated by cement, construction sand and gravel, and crushed stone, were mined and processed in the United States during 2023, a 3 percent decrease from 2022. Other minerals used in construction include certain types of clays, diatomite, dimension stone, gypsum, iron oxide pigments, mica, perlite, pumice and pumicite, staurolite, talc and pyrophyllite, tripoli, vermiculite and wollastonite. The estimated value of these materials was $48 billion.

Natural aggregates (crushed stone and construction sand and gravel) were mined or processed in all 50 states and were valued at $35.2 billion, 72 percent of the total value of construction minerals. Nearly three-quarters of the aggregates sold were used in road construction. Of the 2.4 Gt of natural aggregates produced (3 percent less than the quantity in 2022), crushed stone accounted for 62 percent of the tonnage of aggregates and construction sand and gravel accounted for 38 percent. Consumption of natural aggregates was essentially unchanged from 2022; however, consumption decreased in residential housing because of interest rates increasing to the highest levels in 20 years, which was offset by increased demand for construction, energy and infrastructure projects as well as other manufacturing sectors. Changes in commercial and heavy-industrial construction activity, infrastructure funding, labor availability, new single-family housing unit starts, and weather affect natural aggregates production and consumption.

Cement was produced in 34 states and Puerto Rico with the four leading states (in descending order of production), Texas, Missouri, California and Florida, accounting for nearly 43 percent of U.S. production. Cement production accounted for 27 percent of the value of construction materials in 2023. Cement apparent consumption remained the same as in 2022. However, cement industry growth continued to be constrained by increased costs for energy, material and service inputs; labor and production shortages; and ongoing supply chain disruptions. Overall, the U.S. cement industry's growth continued to be constrained by closed or idle plants, underutilized capacity at others, production disruptions from plant upgrades, and relatively inexpensive imports. Regulators continued to implement measures designed to aid industry decarbonization efforts, such as green procurement strategies and research investments.

About 26 Mt of all varieties of clays, valued at about $1.7 billion, were mined in the United States. Not all clays are used in construction. Common clay, which was used mainly for brick, cement and lightweight aggregates, accounted for 50 percent of the tonnage of all clays. Kaolin accounted for 4.4 Mt, or 17 percent of the total clay tonnage. Fillers, extenders, and binders accounted for 52 percent of kaolin use.

Other industrial minerals. The United States produced several other industrial minerals that are not listed separately in any of these categories but are essential in abrasives, absorbents, catalysts, ceramics and glass, coatings, cryogenics, fillers and extenders, filtering agents, grinding and polishing materials, hydraulic fracturing, optoelectronics, pigments and refractories. ■

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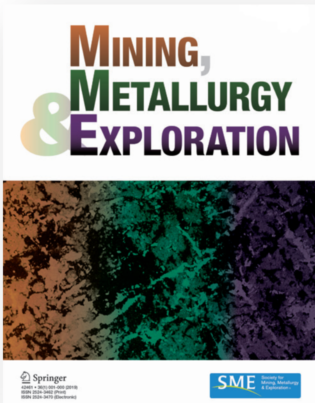

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Investigating the effects of reverse-osmosis treated water on the corrosion rate of armored-face-conveyor chains in longwall mining

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The chains of armored face conveyor (AFCs) are constantly in contact with water and wet coal, which results in a significant proportion of unplanned downtime experienced on longwall equipment due to corrosion. While reverse osmosis (RO) is one of the most prevalent water treatment methods for reducing salinity and dissolved solids in coal mining, its impact on the corrosion of the AFC chains has not been well studied. This work studies the direct effects of RO water on the corrosion of AFC chains. Immersion tests followed by surface micromorphology analysis and corrosion indices indicate that the RO water increased the corrosion rate of the AFC chains due to the reduced tendency of preventive films on the chains.

Introduction

Longwall mining is a prominent method for underground coal extraction globally, known for its high productivity [1]. Its mechanized system consists of hydraulic shields, shearers, AFCs and an automation system. However, significant downtime, up to about 40 to 60 percent worldwide [2], hampers its efficiency. Unplanned downtime, largely due to AFC chain failures, is a major contributor. Overloading and corrosion are primary reasons for premature AFC chain failure. Studies have focused on monitoring and simulation techniques to address overloading issues, but corrosion prevention remains underexplored.

The underground mining environment fosters highly corrosive conditions due to humidity, temperature and dust. Conventional methods like heat treatments and galvanizing have limitations in maintaining mechanical properties and effectiveness. Water, essential for dust suppression in longwall mining, exposes AFC chains to corrosion. The characteristics of groundwater vary by location, affecting corrosion rates. RO is a common water treatment method to reduce minerals and unnecessary substances, but its direct impact on metal corrosion in mining equipment is not well understood [3].

The current study has therefore been initiated to investigate the correlation between RO treated water and AFC chain corrosion, prompted by observed corrosion increases in a coal mine using RO treated water for more than five years. This study aims to provide insights into mitigating corrosion-related failures in longwall mining systems, crucial for enhancing operational efficiency and equipment longevity.

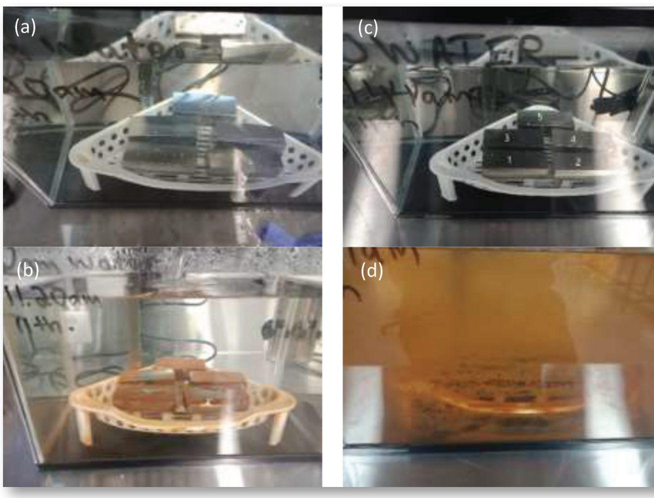

Fig. 1 Immersion test setup of AFC chain steel billets: (a) initial and (b) after 240 hours in dam water; and (c) initial and (d) after 240 hours in RO water.

Method

An immersion test was conducted at 25 °C using steel samples extracted from intact AFC chains submerged in two types of water: (1) dam water and (2) treated water from an RO plant at a coal mine in Queensland, Australia. Steel specimens were prepared according to ASTM standards, with precise dimensions and chamfered edges to prevent fractures. Immersion testing lasted 240 hours with continuous monitoring of the water temperature at 25 °C, as shown in Fig. 1. Water samples from the dam and RO plant underwent elemental analysis to determine total dissolved solids and critical elements for corrosion indices. Corrosion indices including Langelier Saturation Index (LSI), Ryznar Stability Index (RSI), Larson-Skold Index (LS) and Puckorius Scaling Index (PSI) were calculated based on the elemental analysis, pH and conductivity measurements. These indices provided insights into the corrosivity and scaling tendencies of the water samples. Surface micromorphology of the steel specimens post-immersion was examined using scanning electron microscopy (SEM) and atomic force microscopy (AFM). SEM imaging allowed observation of corrosion damage, while AFM was used to quantify surface roughness and measure the depth of pitting corrosion.

Results and discussions

The surface morphology analysis using SEM demonstrates notable differences between steel samples submerged in dam water and RO water. While the intact steel specimen shows minimal damage, SEM images reveal sparse localized damages in the dam water sample and more extensive corrosion in the RO water sample, with deeper and larger pitting corrosion observed, as shown in Figs. 2a-b. AFM analysis further confirms these findings, showing more severe corrosion damage on the steel surface immersed in RO water compared to dam water. The 3D AFM images indicate deeper pits on the RO water sample, suggesting increased corrosion tendencies (Figs. 2c-d).

The elemental analysis and corrosion indices presented in Table 1 provide insights into the underlying factors driving these differences. The corrosion indices suggest RO water is more corrosive than dam water, likely due to a complex interplay of various ions and alkalinity levels. Further investigation into the significance of parameters in corrosion indices reveals the importance of factors such as pH, total dissolved solids, calcium, alkalinity, chloride ions and sulfate ions. These parameters interact with each other, influencing the corrosivity of water. For instance, the LSI is heavily influenced by sulfate and chloride ions, with alkalinity levels mitigating corrosion tendencies. Similarly,

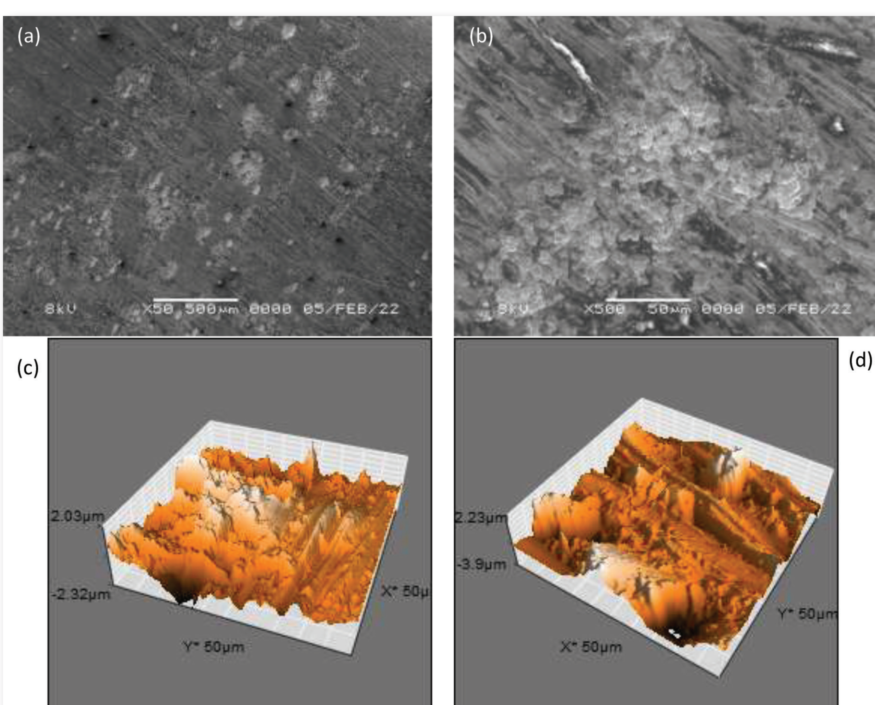

Fig. 2 SEM images of the specimens at ×50 magnification: (a) after the dam water immersion and (b) after the RO water immersion. AFM images of the steel samples in 3D: (c) immersed in the dam water and (d) immersed in the RO water.

the PSI highlights the delicate balance required between calcium and total alkalinity concentrations to prevent scale formation and corrosion [4,5].

Conclusions

The study highlights corrosion issues in AFC chains despite the use of water treated by RO. Elemental analysis shows reductions in corrosive substances like chloride and sulfate ions post-treatment. However, SEM and AFM observations reveal higher corrosivity in RO water. Three of four corrosion indices support this finding, except for LS, which suggests natural film formation for both waters. Nonetheless, RO water's higher LS indicates increased corrosivity. The study concludes that no single parameter or acid neutralization can minimize water corrosivity. Improper balance of ions in RO treatment may accelerate corrosion, necessitating careful management of bicarbonate, chloride, calcium and sulfate ions. ■

Table 1 — Results of elemental analysis and corrosion indices of the water samples at 25 °C.

Parameters and indices	Water source	
	Terminal dam water	RO treated water
pH	7.7	7.0
Total dissolved solids (mg/L)	342.0	159.0
Turbidity (NTU)	12.2	2.8
Electrical conductivity at 25 °C (µS/cm)	526.0	224.0
Total hardness as $CaCO_3$ (mg/L)	142.0	40.0
Bicarbonate alkalinity as $CaCO_3$ (mg/L)	160.7	59.0
Langelier Saturation Index (LSI)	0.26	–1.13
Ryznar Stability Index (RSI)	7.17	9.27
Larson-Skold Index (LS)	0.51	0.66
Puckorius Scaling Index (PSI)	7.10	9.13

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Fatal accident analysis and hazards identification in Turkish coal-extracting industry using analytic hierarchy process

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Keywords: Accident analysis, AHP, Fatal coal mine accidents, Hazards classification, Coal mine safety

The aim of this study is to present hazard classifications of location, type and causes of accidents in the Turkish coal-extracting industry using the analytic hierarchy process (AHP). In this study, fatal mine accidents were analyzed by pairwise comparison and weighting, and the most important hazards were identified by determining the effective main and sub-criteria among location, type and causes of accidents. For this purpose, first-, second- and third-level hazards consisting of location, type and causes of accident were determined by using the data of fatal mine accidents in underground and openpit coal mining in Turkey between 2010 and 2020.

Background

Coal mining has been accepted as one of the most dangerous workplaces due to the nature of the work in the world, where it is classified as the most dangerous sector in terms of occupational health and safety. Although it has become one of the safest sectors in some countries since the second half of the 20th century, many countries, including Turkey, are still struggling with the negative consequences of occupational accidents in coal mines. Coal mine accidents can occur as many different types, from firedamp and coal dust explosions to roof falls, mine floods and equipment-based accidents. These occupational accidents cause injury or loss of life as well as loss of resources and disruption of production.

Coal mine accidents are not only caused by a single factor risk, but also by the linkage between multifactorial risks. Therefore, investigating the mechanism of multifactorial risk and determining the linkage risk is important for the control of coal mine accidents. For this reason, this study analyzed coal mine accidents with the AHP method, which is one of the multicriteria decision-making (MCDM) techniques.

Methods

AHP, used as a decision analysis tool, is a mathematical method developed by Saaty in 1977 to analyze complex decisions involving many criteria. In the classical AHP, which allows simplification of complex problems by creating a hierarchical structure, the knowledge and experience of the decision-maker are included in the decision-making process. It is a method that allows the use of qualitative and quantitative criteria in the evaluation and selection of decision options. Problem solving with the AHP is based on three principles: (1) decomposition, (2) comparative evaluations and (3) synthesis of priorities.

In the AHP technique, a matrix is created as a result of pairwise comparisons, and criteria weights are obtained as a result of these calculations. It is also possible to determine the consistency ratio. The basis of the consistency ratio calculation is the comparison of the number of criteria and the coefficient called eigenvalue (base value, λ_{Max}). AHP calculates a consistency ratio (CR) that compares the consistency index (CI) of the matrix in question (with the judgment of the decision-maker) with the random consistency index (RI) of a random-similar matrix.

Results and discussion

In this study, the fatal accident data in Turkish coal mining between 2010 and 2020 were categorized and each category was prioritized using the AHP method. The most important hazards were determined by scoring both quantitative and qualitative data such as location, type and causes of accidents in the accident report prepared by the Chamber of Mining Engineers of Turkey, and expert opinions on accidents occurring in coal mining where uncertainty and complexity are high and where multifactorial risks are effective. When the results of the AHP analysis are compared with the accident statistics, there is an agreement between the statistical mortality rate and the accident types and accident causes determined by AHP. According to the accident statistics, the accidents with the highest number of fatalities in underground coal mining in these 10 years were firedamp explosions, roof falls and haulage-related accidents, and the death rates were 59.9, 19.8 and 4.9 percent, respectively. According to the AHP results, the weights of the type of accidents belonged to firedamp explosion (0.409), roof falls (0.229) and accidents by machinery used in haulage (0.113), respectively. In openpit coal mining, according to the accident statistics, the highest number of fatalities occurred in landslides at 20.3 percent, and truck and other accidents at 17.5 percent. According to the AHP results, the weight of landslides (0.429) and traffic accidents caused by trucks and other vehicles (0.385) are the top two with the highest scores. In this study, the results obtained with AHP are compatible with both the accident statistics and the results obtained from other studies on accident analysis.

Conclusions

The results obtained with AHP simplified the complex and multifactorial fatal accidents occurring in coal mining by making pairwise comparisons, and thus revealed with more clarity and in detail against which hazards more precautions should be taken. In previous studies on the analysis of occupational accidents, analyses were made by using only accident statistics, and evaluations were made based on numerical data, but the hazards were not categorized as in this study. Coal mining accidents are highly complex, and many factors can affect their occurrence. Coal mine accidents are not only caused by a single factor risk, but also by the linkage between multifactorial risks. Therefore, in this study, the MCDM technique was used to categorize and quantify these complex and multifactorial risks in coal mining and to determine which hazards are the most important. It is shown that the results obtained with MCDM in this study will contribute to the control of occupational accidents in coal mining in Turkey.

The detailed identification of the hazards that cause the most accidents and fatalities, together with their location, type and causes, using accident data, distinguishes this study from other studies, and it is expected to contribute to coal mining as the results are consistent with statistical data. Moreover, this study is expected to contribute to the reduction of accidents and fatalities by prioritizing the most important hazards and providing proactive measures. It provides safety, mining and practicing engineers with a new method of risk assessment that has not been applied so far. The usability of the AHP method instead of accident analysis and risk assessment methods in coal mining where different methodologies are used can be examined in future studies. ■

References

A list of all references is available in the full paper.

Are fatigue and sleepiness the same? A brief introduction to the differences and similarities, and their implications for work safety

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Keywords: Fatigue, Sleepiness, Mining, Countermeasures, Interventions

While not well established, there is evidence that the mining industry is encumbered by several work-related fatigue risk factors. Compared to other industries, mine workers are more likely to report inadequate sleep and work longer hours per day. Given these observations, there is a critical need to identify effective ways to intervene, manage, and mitigate mine worker fatigue and sleepiness when present. One barrier to this is confusion around the similarities and differences between fatigue and sleepiness, which can result in these terms being treated as interchangeable regardless of context and

make it difficult to assess and mitigate safety risk.

Fatigue and sleepiness differences and similarities

One way to define fatigue is as a state produced by a biological drive for recuperative rest, while sleepiness is defined as a sleep propensity or inclination to fall asleep. While defined differently, from a measurement perspective, neither sleepiness nor fatigue are directly measurable, and the observed effects of both look highly similar. As a result, indirect indicators are used, such as measuring a slower reaction time during a long shift. Distinguishing between fatigue and sleepiness requires examining the context in which the changes in these indicators occur. Thus, it is necessary to measure the risk factors that are co-occurring alongside these indicators and potentially leading to the observed changes.

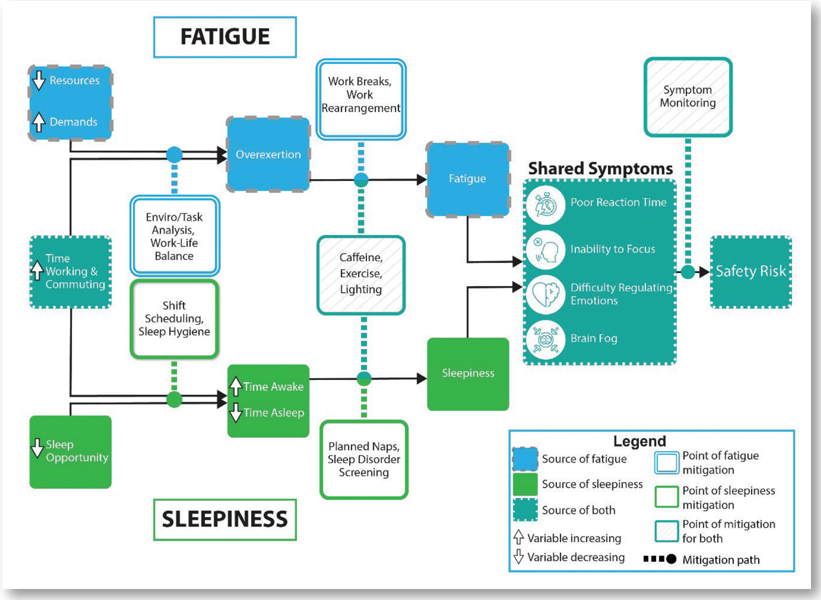

Fig. 1 The work safety visual model of fatigue and sleepiness.

Fatigue and sleepiness have a variety of distinct and shared risk factors that provide context for determining which state is most likely the dominant condition. Factors that can be measured and are relatively sensitive to fatigue, as opposed to sleep, include time on task, task complexity and workload. These risk factors are unique to fatigue as they primarily fall under the criteria within the job demands-resources model and are exertion-based risk factors. For example, job demands such as monotonous or complex tasks can lead to increased fatigue risk if a job resource such as work breaks are not utilized to balance out demands on the worker. There are distinct factors that predict sleepiness. These factors include poor sleep quality, an inadequate amount of sleep, wakefulness during time periods of peak biological drive for sleep (usually between 2 a.m. and 6 a.m.), or sleep disorders. Some of the shared risk factors between sleepiness and fatigue include work schedules, long commutes and long working hours. These shared factors can have a draining effect on workers while also potentially disrupting optimal sleep schedules. This contextual information can provide additional insight into which condition better accounts for symptoms such as slowed reaction time.

Although outcomes for fatigue and sleepiness are similar, interventions to address the two can be highly different. Treating fatigue and sleepiness as interchangeable can potentially result in misuse of interventions and the perception that the problem is being managed while it may persist unnoticed. It is therefore important to include considerations for both sleepiness and fatigue in a safety management system aimed at mitigating work-related fatigue risk for it to be more effective. As an example, if a worker is obtaining minimal sleep at night, focusing on job demands or task-based fatigue will likely have minimal impact. Likewise, after obtaining adequate sleep duration and quality, work factors such as extremely loud or hot work environments can still produce fatigue.

Visually modeling fatigue versus sleepiness

To depict the meaningful nuances between fatigue and sleepiness, and to aid workplace health and safety managers and workers alike, a visual model was developed. The following process was used to develop the model: (1) theoretical literature was reviewed to differentiate fatigue and sleepiness from each other, (2) specific literature on risk factors, measurement, and mitigation strategies for fatigue and sleepiness were reviewed and (3) an iterative approach to formulate a visual model representing the gathered information was taken until the current model, depicted in Fig. 1, was developed.

The aim of this model is to provide a visual representation of the relationship between fatigue and sleepiness that identifies general differences and how fatigue and sleepiness might be mitigated differently at different points. The top-left box illustrates that risk factors for work-related fatigue primarily fall into the category of excess demands and limited resources, which leads to a state of overexertion, while the bottom-left box presents decreased opportunity for sleep as a primary risk factor for sleepiness, which leads to increased time spent awake and decreased time spent asleep. Some shared risk factors between sleepiness and fatigue include long working hours and long commutes. More targeted interventions can be implemented for prevention at this level, such as assessing the balance of job demands and resources in the work environment for fatigue and increasing opportunities for restful sleep through efficient shift-scheduling practices for sleepiness. If not prevented, these risk factors can lead to increased sleepiness or fatigue but could potentially be mitigated by work breaks or work rearrangements (for fatigue), planned naps or sleep disorder screening (for sleepiness), or caffeine, exercise and adequate lighting (for both). Once fatigue and sleepiness occur, there are shared symptoms that manifest. From this point, symptom monitoring can be used to prevent potential safety incidents.

Conclusion

Fatigue and sleepiness are similar yet distinct in many ways, and in some instances, it may be difficult to decipher which state is exerting greater influence over observed performance decrements. However, understanding the nuanced differences and the visual aid in Fig. 1 can assist with the development of risk management plans and systems to mitigate work-related risk due to sleepiness and fatigue. ■

Disclaimer

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH.

References

A list of all references is available in the full paper.

Experimental and numerical investigation of methane flame propagation characteristics in a 30.5-m explosion reactor with obstacles

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Keywords: Methane explosion, Flame reactor, Computational fluid dynamics

Confined explosions are a major risk in underground coal mine operations. Depending on confinement, ignition location and obstacles in the flame path, methane explosions can transition to detonations. This research focuses on explosion experiments in a reactor with diameter of 71 cm and length of 30.5 m, along with developing the corresponding computational fluid dynamics (CFD) model that captures the observed flame behavior. The results show that the 2D and 3D CFD models are able predict the experimental flame front propagation velocity, but the 3D model shows more explicit conformity than the 2D model.

Fig. 1 Explosion reactor setup for large-scale experiments.

Introduction

Explosions in underground coal mine operations can be devastating, which can result in multiple casualties and destruction of mine infrastructure. Conducting experimental methane explosion research in a full-scale industrial setting is not practical due to cost and lack of available facilities worldwide. In recent years, CFD modeling has been used extensively to study the flame behavior and potential impact of an explosion in different industrial settings. CFD models that are capable of accurately predicting complex flame propagation behavior during an explosion scenario are highly sensitive to the chosen physical models (such as turbulence model), boundary conditions and initialization parameters. Thus, it is vital to acquire sufficient experimental data for validation to provide a reliable and robust model that is capable of simulating a methane gas explosion in an underground coal mine. The objective of this research is to investigate the impact of rock rubble obstacles on methane flame propagation velocities inside an explosion reactor that is 30.5 m long and 71 cm in diameter, and to validate and improve the predictive capabilities of a corresponding CFD methane explosion model.

Experimental and CFD modeling setup

In the large-scale experiments shown in Fig. 1, a methane (CH_4)-air gas mixture with a concentration of 7.5 volume percent of CH_4 is filled into a semiopen reactor with length of 30.5 m. The ignition of the explosive atmosphere happens 38 cm from the closed end of the reactor. Ion sensors protrude 10±1 cm radially into the reactor to record the flame front as it propagates toward the open end. The reactor consists of four sections, each 7.62 m in length, providing flexibility of testing different total reactor lengths and allowing varying CH_4-air mixtures to be confined to a specific zone. For the purpose of this research, three sections, approximately 23 m in total length, act as a reactive zone that includes the explosive mixture of 7.5 volume percent CH_4. The fourth section, located at the open end, is designated as a nonreactive zone and is filled with air. The local atmospheric pressure is 82 kPa, and temperatures range between 283 and 295 K (depending on the day of the test) prior to ignition. After the filling process, the reactor pressure is 86 ± 3.4 kPa. A plastic sheet barrier is installed between reactors 1 and 2 to separate the reactive zone from the nonreactive zone. This barrier is designed to break at approximately 156 kPa. For every test, the reactor's reactive zones are filled with approximately 27 m^3 of premixed CH_4-air mixtures, three times the volume of the reactive zone, from the closed end, while the ambient air initially inside the reactor prior to filling is allowed to bleed through valves through ports that are 0.47 m and 0.94 m from the gas barrier at the end of reactor 2.

The corresponding CFD models in 2D and 3D follow the same geometry and model initialization to replicate the experiments. The CFD models are ran in two stages, with the first stage including only the 23-m reactive zone with the gas barrier intact. The gas barrier is represented as a wall boundary condition. The second stage triggers with the burst of the gas barrier and simulates the full 30.5-m reactor length. As the barrier ruptures, the boundary condition switches from "wall" to "interface." A patch function is used to pass the initialization parameters to the nonreactive zone. The open end is treated as a "pressure outlet" boundary condition, and the simulation resumes.

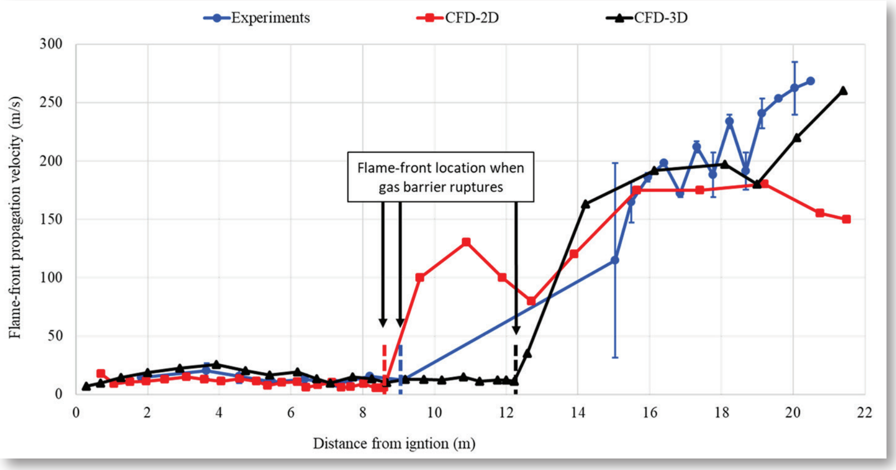

Fig. 2 Comparison of flame front propagation velocity over distance between experiments and CFD models.

Results and discussion

Figure 2 shows the comparison of flame front propagation velocity over distance from ignition location between experiments and CFD models.

Both 2D and 3D CFD models show similar flame propagation trends that compare well with the experimental results. The flame propagated slowly with the gas barrier intact, and flame velocity significantly increases once the barrier is opened. The 2D CFD model shows a good prediction initially but deviates past 18 m, predicting much smaller flame velocities where the experimental results show a continuous increase. The large error bars at a distance of 15 m from ignition indicate a large fluctuation of velocity and happen right after the gas barrier bursts. This can be related to a strong turbulent flame and pressure oscillations caused by the bursting of the barrier. Overall, the CFD models capture the effect of the gas barrier opening as observed in the experiments, with both models showing a significant increase in flame speed once the gas barrier bursts.

Conclusions and future work

This research presents a method for developing a flame propagation CFD model in a large-scale reactor and shows how coupling experiments with model development and validation can lead to improved modeling predictive capabilities. Key findings from this study include:

1. The 2D and 3D CFD models show good prediction of the flame behavior inside the empty reactor. Both models are able to capture the confinement effect of the gas barrier and the resulting flame acceleration after the barrier bursts. As expected, the 3D model shows improved agreement with the experimental results compared to the 2D model. However, considering the computational time required to run the simulation, 21 days for the 3D model to simulate 960 ms compared to five days for the 2D model, the 2D model provides an adequate alternative to the 3D model when relatively quick turnaround times are desired to capture general trends in flame propagation velocities. Both models used 4 × 36 cores and a combination of 192-GB and 384-GB RAMs.
2. The 2D model is sufficient in capturing the general trend of the flame propagation and predicts the flame propagation speed reasonably well. However, the 2D model underpredicted the resulting pressure. Pressure comparisons at 820 ms, as the gas barrier ruptures, show that the pressure of the 3D CFD model (approximately 113 kPa) is in good agreement with the experiment (approximately 103 kPa), compared to the 2D CFD model (approximately 56 kPa). Depending on the purpose of the study, such as explosion barrier design, a 3D model is necessary to more accurately simulate flame propagation speed and overpressures observed with the experiments. ■

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Investigating the impact of rock rubble on methane-air explosions: High-speed turbulent deflagrations and transition to detonations. Short-term innovative and exploratory research projects – follow up research Colorado School of Mines (Grant AFSTI14FO-69) https://www.alpha-foundation.org/outputs-and-impact/hsi-outputs/#ffs-tabbed-12|ffs-tabbed-31

Selected Abstracts

Valorization from waste: Combined reduction of chromite ore-processing tailings and subgrade manganese ore to produce 200 series stainless steel scrap

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Keywords: Low-grade ore, COPT, Nickel ore, Smelting, Stainless steel scrap, Submerged arc furnace

Chromite ore processing tailings and low-grade manganese ores are typically considered waste due to their limited or negligible utility, leading to environmental and storage concerns. Researchers globally have explored various methods to utilize or upgrade these wastes, particularly because dumping chromite ore has been linked to severe health issues through Cr(VI) leaching. Individually, these ores lack economic value, and there has not been research on simultaneously reducing both low-grade ores. In this study, the focus lies on smelting these ores together, aiming to create a precursor alloy for 200 series stainless steel scrap. Initial research indicates the potential for scrap formation, validated through laboratory experiments with varying coke rate, basicity and holding time. The investigation discovered that smelting this combination could yield a metal product consisting of 59 percent Fe, 24.93 percent Cr, 7.56 percent Mn, 0.62 percent Ni and 0.93 percent Si. The optimum basicity was found to be 0.6 with 80 percent recovery. Notably, this process eliminates intermediate steps in 200 series stainless steel production, potentially reducing overall carbon dioxide emissions. This proposed method represents a cleaner, sustainable approach to repurpose these two waste ores, projecting a net profit of US$330/t. ■

Collection in Honor of Dr. Patrick Taylor: All About Metallurgy

Nitric acid pretreatment applied to a refractory gold-tellurides ore

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Full-text paper:
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Keywords: Tellurides, Refractory gold ore, Nitric acid, Pretreatment, Cyanidation

This paper presents the results obtained by processing a gold and silver telluride mineral concentrate from a mine in Colombia. An acid wash, also known as acidification, was carried out, followed by oxidation with nitric acid as a form of pretreatment. Cyanidations of the pretreatment residues were carried out, and the results compared with results from cyanidations of base materials. The removal of carbonates in the acidification, a tellurium extraction close to 90 percent during pretreatment, and a 30 percent improvement in gold recovery compared to the conventional process were achieved. ■

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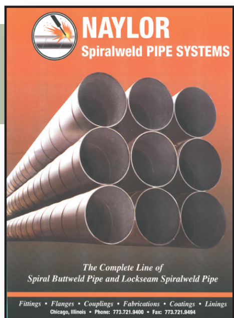

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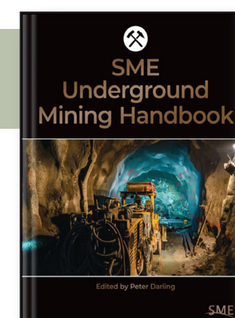

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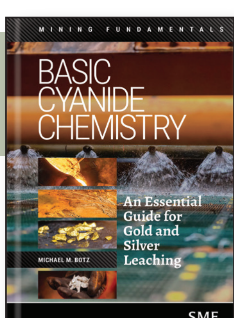

Basic Cyanide Chemistry: An Essential Guide for Gold and Silver Leaching

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Central Wyoming and Utah sections promote local community outreach in K-12 schools

by Greg Kruse, Central Wyoming Section and Abani Samal, Utah Section

Two sections, the Central Wyoming Section and Utah Section, have demonstrated outstanding efforts in mining outreach to K-12 schools, emphasizing the significance of minerals in everyday life. The sections are engaging with the K-12 schools in their communities through interactive classroom presentations and hands-on activities to teach students about the roles mining and minerals play in everyday life. You can join this outreach moving to K-12 schools in your community.

Greg Kruse speaking to students at Sagewood Elementary in Casper, WY.

Teaching students about the extraction industries in Wyoming — by Greg Kruse

As members of SME and the Minerals Education Coalition (MEC), we are committed to promoting the mining and extractive industries in a positive and professional manner.

Oftentimes, it is easy to get caught up in our day-to-day work and home lives and forget about other important things in our lives such as informing and educating our young generations about the importance of the mining and extractive industries we live in.

In January, I had an opportunity to speak to a group of fourth-graders at Sagewood Elementary in my hometown of Casper, WY. Many of you may know that Wyoming is the top producer of many extractive resources: trona, coal, bentonite and uranium. I enjoy speaking to classrooms in Wyoming as there are so many "fun facts" to educate students on the great benefits that mining does for them. For example, when I visit schools, there is always someone who is surprised that we mine these minerals in Wyoming — particularly trona and uranium.

During this time, I spoke to two fourth-grade classrooms (about 48 students) on the importance of Earth sciences, engineering and mining careers in Wyoming. We had more than two hours of nonstop fun. The classes were studying rocks, minerals, the rock cycle, landslides and volcanoes. We were able to tie everything together using Wyoming as the backdrop for every topic. The children asked great questions, like "Are there diamonds in Wyoming?"

During this classroom session, I discussed and distributed fact-based information on minerals and mining to the classroom participants and their teachers. Using the trona industry I work in as a backdrop, I was able to tell them about the impact the trona industry has on our local economy and also its impact on the world. I was also able to speak to the kids about Wyoming's mining industry and promoted the trona business by handing out trona samples. The session ended with me handing out "Little Debbie" snacks — the biggest highlight for them was knowing that there is trona in food.

(Continued on page 72)

Samples were handed out during the fun-filled event.

SME News Contents

A wrap-up of the 2023-2024

Metallic Student Design Competition

by Deniz Talan, assistant professor, West Virginia University and 2023-2024 Metallic Student Design Competition Chair

Thank you to all the teams who participated in the 4th Annual SME Metallic Student Design Competition sponsored by Rio Tinto. Congratulations to the six teams who made their way to the second phase and competed in the live presentation portion. They are, in no specific order:

- Missouri University of Science and Technology — Ore Enforcement Consulting.
- University of Arizona — Deep Rock Geologic.
- Universidad Nacional Mayor De San Marcos — MMPS Consulting.
- National University of San Agustin — Team Planning Mukis.
- University of Kentucky — Thoroughbred Mineral Extraction.
- Universidad Nacional de Ingeniera — UNI's Planners Team.

The Ore Enforcement Consulting team from Missouri University of Science and Technology, which included Gunnar Wurst, Santiago Reina Davila, Spenser Walchuk, Garrett Bell, Holli Finnell and Aidan Dumont and were led by Prof. Kwame Awuah-Offei, won the 2023-2024 competition.

The SME Metallic Design competition is designed as a cross-disciplinary adventure for teams to simulate project work revolving around mine planning, metallurgical processing, cost estimation, and environmental, social and governance considerations. If you are interested and have the influence to pull together a team, the competition is geared toward evaluating a hard-rock mineral deposit and developing an economically viable process flowsheet.

The competition evolves each year, bringing different deposit types and challenges to the students' attention. Since the inaugural competition in 2020, the problem statements have involved mine plans for copper, gold, lithium and boron. Next year's competition will continue to bring new challenges and twists.

Registration for 2024-2025 competition to start in September

Teams may consist of up to six undergraduate students with valid SME memberships from any program on campus including, but not limited to mining, chemical, metallurgical, geological, geotechnical engineering and any related sciences. Each participating team will have access to competition software and training, including Cost Mine, METSIM and HxGN MinePlan. In the first phase of the competition, each team member will be allowed up to 30 hours over 21 days to provide a full design report with the data provided. The submitted report will be reviewed by multiple well-respected industry experts who will provide comments and feedback.

The top six teams will then be asked to participate in an in-person, two-day event at the MINEXCHANGE 2025 SME Annual Conference & Expo in Denver, CO. In this phase, each team is provided with additional information to elaborate on their initial design and then asked to present to a live panel of judges, where they will be judged based on their presentation skills, the ability to answer questions and, of course, their technical response to the challenge posed.

Watch out for emails and announcements for this year's registration and competition information. You can also email your intent to register early to Mona Vandervoort at vandervoort@smenet.org or Deniz Talan at deniz.talan@mail.wvu.edu. Visit the competition website at https://www.smenet.org/Professional-Development/Awards-Competitions/METALLIC-Student-Design-Competition for more information.

We look forward to all teams joining and seeing who will come out on top in this year's challenge. ■

Summary of the M&E Division
Executive Committee meeting

by Katie Robertson (minutes) and Emily Rose (summary)

The Mining & Exploration (M&E) Division's annual meeting took place on Feb. 25, 2024, from 9 to 11:25 am during the MINEXCHANGE 2024 SME Annual Conference & Expo in Phoenix, AZ. There were 21 members in attendance at the meeting, including the executive board. After a safety share on safe lifting procedures and an introduction on attendees, the meeting commenced with a review of the 2024 executive committee reports and financials. Finances held within the M&E division remain steady and are used to fund donations to the foundation, awards and scholarships. In 2024, 11 scholarships were awarded with a total of $31,700 distributed to students, $3,000 more than in 2023. Overall conference attendance for MINEXCHANGE 2024 was nearly 7,000 people. The M&E Division membership has increased by 2 percent from 2023. M&E Division membership accounts for almost 30 percent of total SME membership, with more than 3,900 members associated with the division.

SME executive leadership provided a reminder on the importance of workforce and increasing interest in our industry. Marc LeVier indicated that mining education has heavily been influenced by the dissolution of the Bureau of Mines. Thank you, Marc, for your tenure as SME President in 2023.

The 2024 M&E technical program included 26 total sessions with 143 speakers. Program area managers (PAMs) responsible for the 2024 program included: Jennifer Baar, Geosciences, 10 sessions; Kat Tew, management, six sessions; Line-Audrey Nkule, innovation & technology, four sessions; and Clay McNeil, operations, six sessions. Thank you to the 2024 PAMs and 2024 program chair, Jenessa Haarala for developing an engaging technical program. The 2025 M&E program, presented in Denver, CO, will be managed by program chair Dan Rosenbach. PAMs include Maureen Moore, geosciences; Christine Linden, management; Josef Bourgeois, innovation & technology; and Michael Donkor, operations. Contact Rosenbach for more information on 2025 programming at daniel.rosenbach@gmail.com.

Two memorandum of understanding (MOU) documents continue between SME and the American Institute of Professional Geologists (AIPG) and American Rock Mechanics Association (ARMA), respectively. The MOU documents outline teaming opportunities for the two organizations in technical information sharing through conference technical sessions, webinars and short courses.

M&E Division Annual Luncheon in Phoenix, AZ.

The 2024 M&E Division Annual Luncheon had sponsorships provided by Hecla Mining Co., Berns & McDonnell, Hägglunds, WSP and Orla Mining. Thank you to the 2024 luncheon sponsors. The Jackling Award lecturer featured "Evolution of Rockburst Control Measures in the Coeur d'Alene District Over the Last 50 Years," presented by Mark Board, member of the Hecla Mining Co. board of directors. The 2024 silent auction featured many donations including antiques, coins, die-cast models, mineral samples and mining reference books. Thank you to all those who donated and participated in the silent auction.

Items that were discussed in the meeting included:

- MINEXCHANGE 2025 aligning with the 2025 World Gold conference.
- A donation of $10,000 to the SME Foundation for 2024.
- Update of the M&E bylaws to reflect updates to the Miner of the Year Award, Harry Parker Award and the dissolution clause.
- Success of the Boy Scout Jamboree.

Bob Washnock formally transitioned the roles and responsibilities of the silent action and Rock in the Box editor. Rosenbach took over the silent auction from Washnock. The M&E Division formally thanked Washnock for his tireless commitment to the division over the years at the M&E luncheon.

Additional committee updates provided during the discussion were for the SME Foundation, YLC, Finance Committee, SEG Partnership, Structure and Governance, and GPAC.

For more information on the M&E division, contact the Chair, Don Dwyer at Donald.Dwyer@orlamining.com. ■

Rock in the Box **serves as a forum for the presentation and discussion of facts, ideas and opinions pertaining to the interests and technology of the Mining & Exploration Division. Accordingly, all material published herein is signed and reflects the individual view of the authors. It is not an official position of SME or the division. Comments by readers will be referred to that division for response. The division chair in 2024 is Don Dwyer.**

Environmental Division scholarships
awarded at MINEXCHANGE 2024

by Emily Schlenker, project manager, Arcadis and Environmental Division Scholarship Committee Chair

The Environmental Division awarded three student scholarships at the division's annual luncheon during the MINEXCHANGE 2024 SME Annual Conference & Expo in Phoenix, AZ.

SME Environmental Division scholarships of $2,000 each were awarded to two students: Daniela Velasquez Vengas, from Universidad Nacional de Colombia, and Maxwell Bawa, from Oklahoma State University. An additional $2,000 scholarship was given by Veolia Water Technologies to Linda Mishell Jaramillo Urrego, from Southern Methodist University. Congratulations to these students.

Applications for the 2025 Environmental Division scholarships will open on Sept. 1 and close on Oct. 15, 2024. We encourage all students interested in mining and the environment to apply. To raise funds for these scholarships, the Environmental Division holds an annual silent auction at MINEXCHANGE. The 2024 silent auction included more than 40 items and raised $5,221. Thanks to all who participated in the event, especially those who donated items. ■

Veolia Water Technologies representative Jill Browning presenting the Veolia scholarship certificate to Linda Mishell Jaramillo Urrego at the Environmental Division Luncheon.

Green News **serves as a forum for the presentation and discussion of facts, ideas and opinions pertaining to the interests and technology of the Environmental Division. Accordingly, all material published herein is signed and reflects the individual view of the authors. It is not an official position of SME or the division. Comments by readers will be referred to that division for response. The division chair in 2024 is Annelia Tinklenberg.**

In Memoriam: Immo Heinz Redeker, 1930-2022

Immo Heinz Redeker, aged 92, of Asheville, NC passed away Sept. 6, 2022 in Palm Coast, FL. Redeker was born in Einbeck, Germany on April 21, 1930 to Heinz and Hilde Redeker. He was the oldest of four brothers, including Hartwig, Giselher and Heinz. While studying at the University of Mining in Leoben, Austria, he received a scholarship to Columbia University in New York City to further his education for a master's degree in mineral engineering. After graduation, he worked for two years for several mining companies in the United States for the experience. He then decided he wanted to get his U.S. citizenship.

Redeker was required to be out of the country in order to obtain an immigration visa. One of his classmates from Columbia, Kinnichi Matano, lived in Tokyo, Japan. Matano's family offered Redeker passage on one of their ships from the United States to Japan to stay with them to fulfill his requirement for the visa. This is where he met the love of his life, Kathleen Register, in 1957. She was working as a missionary teacher in Aoyama Gakuin University in Tokyo and was living with the Matano family at the same time. The two of them spent 63 years together, first in Jefferson City, TN, where he worked for the New Jersey Zinc Co. In 1962, they moved to Asheville, NC.

Redeker retired as director of the North Carolina State University's Minerals Research Laboratory after working for 30 years in industrial mineral processing. Since 1984 he was also visiting assistant professor in the university's Department of Materials Engineering. Redeker's applied research at the laboratory led to plant design or improvements in North Carolina's phosphate, feldspar, mica, spodumene, glass sand and olivine plants. He is the author of a number of papers on industrial minerals and mineral processing. He holds an M.Sc. in mineral engineering from Columbia University and a degree in mining engineering from Montan University, Leoben, Austria. Redeker worked for Allis Chalmers Manufacturing Co., Climax Molybdenum Co. and New Jersey Zinc Co. before joining North Carolina State University.

A member of SME since 1951, Redeker was the chairman of the Carolinas Section in 1972. He was a member of the German Association of Ore Miners and Metallurgists and the Mining and Metallurgical Society of America. He won the prestigious AIME Hal Williams Hardinge Award in 1991. His award citation reads: "For his own outstanding applied research and his management of industrial minerals research, which has led to the design and improvements in design of many processing facilities, and for the example and standard he has set for other process engineers."

(continued on page 71)

MEC rocks the 2024 NSTA

National Conference in Denver

by Akudo Nwokeukwu, Minerals Education Coalition Outreach Coordinator

The Minerals Education Coalition (MEC) made waves at the National Science Teaching Association (NSTA) National Conference on Science Education held in Denver, CO March 21-23, 2024. MEC volunteers led by Richard Schwering handed out more than 1,200 free rock and mineral kits to teachers to help educate students on the importance of mining and mined minerals. The excited teachers expressed gratitude for the opportunity to obtain the free kits and additional educational materials.

The MEC booth stood out as it displayed rocks and minerals important to the green energy transition. Teachers not only received a free kit each but also gained insights into the composition, properties and end-uses of these rocks and minerals, which ran the gamut from wind turbines and solar panels to electric vehicles and batteries. The rock and mineral samples on display at the MEC booth represented essential elements, minerals and metals required for sustainable energy solutions. These included lithium, copper, bauxite, molybdenum, silica, a polymetallic ore containing silver, zinc, and lead, gold ore, iron and graphite. To top it off, teachers received a hand lens each so that they and their students could more closely examine the samples they received.

By providing teachers with hands-on materials and educational tools, MEC is fostering a deeper understanding and appreciation of mining and the importance of mined minerals in daily life. Furthermore, MEC's initiative aligns seamlessly with the overarching goals of the NSTA, which is dedicated to promoting excellence and innovation in science teaching and learning. Through collaborative efforts such as these, MEC is paving the way for enhanced science education by providing teachers the necessary minerals resources and hands-on activities to inspire and engage their students.

"Chairing the MEC booth for the NSTA Denver Conference was a tremendously gratifying experience. I believe we were effective in communicating with teachers that mining is, and must be, an integral part of the transition to renewable energy," Schwering said.

Thank you to all of the committee members, volunteers, sponsors, and mineral specimen donors who were vital to the success of this conference over the last seven months.

Teachers receiving their free rock and mineral kits.

- Sponsors: Martin Marietta and the SME Colorado Section.
- Mineral sample donors: Albemarle, Hudbay Minerals Inc., SEMCOA, Climax Molybdenum (a Freeport-McMoRan Company), FTN Associates, Hecla Mining Co., Newmont, U.S. Steel and Northern Graphite Corp.
- Other supporters: Harrison Western and Hazen Research Inc.
- Denver team of volunteers: Richard Schwering, Dick Beach, Karen Jass, Laura Fletcher, Judy Colgan, Shun-Ping Chau, Sandra Labobar, Paul Chamberlin, Scott Hogan and Alan Cram.

To contribute to future NSTA conferences, MEC would appreciate your partnership, donations of rock and mineral samples, and service as volunteers to talk with teachers at these conferences. If you would like more information on how to get involved in this exciting event or contribute by way of sponsorship, please contact Akudo Nwokeukwu at nwokeukwu@smenet.org or 303-948-4221. ■

(continued from page 70)

In retirement, as Redeker and his wife were snowbirds, they split their time between North Carolina and Florida. Redeker joined the FernTrust cooperative in 1987. He raised tree fern and leatherleaf on the family homestead in Seville. He enjoyed spending time with his friends and family, all while traveling the world. Throughout his life, he was a devoted Christian. He always had an amazing smile on his face as he served faithfully as chauffeur and biggest fan for his wife, who was pastor for three little mountain churches. Redeker is survived by his wife Kathleen of North Carolina, his brothers Giselher (Elfriede) and Heinz (Martha), and his sister-in-law Ruthild of Germany, his brother-in-law James W. Register Jr. (Barbara) of Seville, his adopted children-in-Christ, Shivraj and Anita Mahendra, and his adopted granddaughter-in-Christ Smriti Mahendra of India, and many beloved nieces and nephews. He was preceded in death by his parents, his brother Hartwig, and his father and mother-in-law J.W. and Gene Register. His burial was at the Seville Cemetery. ■

MEC

(Continued from page 67)

Sagewood Elementary and Verda James Elementary received donations of science-related library books.

Science-related library books for schools, donated by Central Wyoming Section
— by Greg Kruse

In February, the SME Foundation (SMEF) Awards Committee presented awards to several organizations honoring their efforts in the mining industry. The SMEF selected the Central Wyoming Section in Casper, WY as the 2023 recipient of the MEC Organization Recognition Award. The recognition award includes a $250 monetary donation to be used for MEC-related expenses. In February, the award money was spent on books related to Earth sciences and engineering to be put into local school libraries. Sagewood Elementary and Verda James Elementary were the schools selected as the recipients of these books. Stickers were inserted into the inside covers acknowledging SME/MEC's contribution to this community effort.

Many school libraries are limited on this subject, and it is our intent to add books to these institutions — books that make these subjects fun and interesting. We encourage everyone to find these opportunities to educate kids on the importance of mining. You never know what kind of impact you will have on their future.

College Fair program of the American Preparatory Academy (APA)
— by Abani Samal

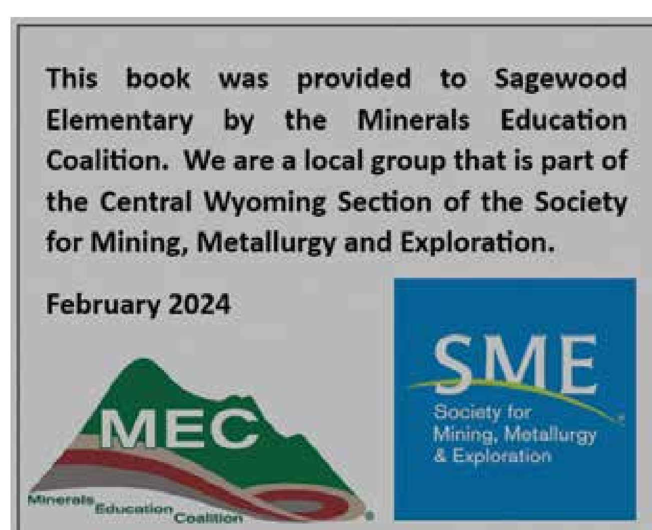
Toward the end of 2023, the American Preparatory Academy (APA), Draper, UT campus held its college fair for students in the third, fourth and fifth standards. The presenters were volunteer parents with professional degrees and working as a professional in his/her discipline; there were doctors, chiropractors, engineers and scientists in attendance.

Each parent presented for eight to 10 minutes three times to three different groups of students. Each time, students from two different classes joined. Each of them presented about their professions and how to be a professional like them.

I volunteered to discuss the mining industry and brought samples of copper and iron ore (collected from different parts of the world), samples of copper concentrates (from Asia) and various MEC-published materials to the class. I shared some of the materials including the Mineral Baby with teachers and students. Approximately 30 students attended in each of the three sessions. I answered many questions including job salaries in the industry and ways in which they can be part of the industry when they are older.

Many students asked me about how to become a geologist or another specialized professional in the industry. Both teachers and students enjoyed the interaction and learning more about the mining industry. ■

Samal interacting with children at the American Preparatory Academy while displaying a sample of copper concentrate.



This book was provided to Sagewood Elementary by the Minerals Education Coalition. We are a local group that is part of the Central Wyoming Section of the Society for Mining, Metallurgy and Exploration.

February 2024

Stickers were inserted into the inside covers of the donated books, acknowledging SME/MEC's contribution.

SMEF President's letter

by Tom Rauch, SME Foundation President

The global supply of minerals continues to be a headline for the news and around corporate and dinner tables alike. Whether it is due to geopolitics or Wall Street evaluations, the minerals that we need and the projects that produce them are not coming online fast enough. Global think tanks and consultancies suggest that it is already too late to keep up with the demand curves they are projecting, even in their most conservative case. Are these issues too large for any individual to have an impact? We think not.

The SME Foundation (SMEF) has been working hard to meet these challenges head on by engaging outreach and education to inspire the next generation to provide for the needs of a mineral-rich future. We believe that the materials and energy produced by our industry provide for a higher quality of life and are fundamental to the advancement of mankind. Sometimes, these are advanced materials for medical devices; other times, they are the building blocks for electricity, concrete or steel. Not everyone understands the direct connection between mining and a better future, but you can help them to see how this industry paves the way.

Around this time last year, we laid out a simple plan asking SME members to take an active role in supporting the SMEF's mission and vision. Since then, we have seen great successes with our programs and people — our reach has grown, and so has the passion behind our objectives. Whether it be talking to family and friends, presenting at a local school or community group, or advocating for permit reform and public education, among endless other possibilities, you can make a difference. The need for personal advocacy is only growing, but the power is in your hands.

Fortunately, you do not have to go it alone; you have access to the resources of the SME and the SMEF, like *Mining Engineering* magazine and the Minerals Education Coalition.

We want to empower you to advocate for our industry and the important mission that we serve. We want you to recruit to our industry. We want you to engage the public discourse about the need for mines and minerals. As before, please continue to inspire colleagues and coworkers to do their best work and engage in our communities. Keep up the great work.

Best,

Tom Rauch
SME Foundation President

Tom Rauch

Welcome new SME Foundation Trustees

by Lorie Laessig, SME Foundation Coordinator

The SME Foundation (SMEF) is pleased to welcome the new members of the SMEF Board of Trustees. They are Garland Davis, Michael Deal, Catherine "Cat" Joyner, Melissa Harmon, Marc LeVier, Jim Metsa and Jay Nopola. Cat Joyner will also serve as the Corporate Giving Committee Chair. We thank these individuals for their service to the SMEF in these new roles. ■

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Index of Display Advertisers - May 2024

What can you do for the mining industry?

William Gleason
Editor

On page 73 of this issue, Tom Rauch writes of the responsibility we all have in sharing the importance of our industry with friends, family members, local schools and community groups. This type of outreach is one of the cornerstones of the work of the SME Foundation (SMEF).

Rauch is President of the SMEF and he is clearly passionate about the mining industry. I first met him when he was active with the Young Leaders Committee of SME. A few short years later and he is steering the SMEF as the youngest person to ever hold that position.

In his column, Rauch writes about how the SMEF has chosen to face the challenges to the mining industry head on by engaging in outreach and education to inspire the next generation. These efforts include outreach to grade schools and middle schools so that students begin to learn about the importance of minerals in their daily lives. The goal is that by introducing the concepts early the students will carry the message forward. A positive view of the mining industry in the formative years might lead to more students pursuing the profession in college or may one day pay off with future decision-makers going to Capitol Hill with a better understanding of the importance of the mining industry.

The "SME News" section of *Mining Engineering* is often full of these kinds of efforts. In this issue, Akudo Nwokeukwu, Minerals Education Coalition (MEC) Outreach Coordinator, provides a summary of MEC's efforts at the National Science Teaching Association's National Conference that was held in Denver in March. Along with volunteers from the industry, MEC made very real connections with hundreds of educators. MEC volunteers, led by Richard Schwering handed out more than 1,200 rock and mineral kits. "By providing teachers with hands-on materials and educational tools, MEC is fostering a deeper understanding and appreciation of mining and the importance of mined minerals in daily lives," Nwokeukwu wrote.

At the MINEXCHANGE 2024 SME Annual Conference & Expo in Phoenix, MEC worked with the Arizona Science Center and the University of Arizona School of Mining & Mineral Resources to coordinate a program in which a group of local educators were invited to the conference. These educators walked the exhibit hall where they were able to see the technologies that are used every day in the mining industry. I hope they were able to see that mining is not a dirty and dangerous industry, but is in fact a highly technical industry in which safety of its employees and the environment is the highest priority.

This issue also includes short articles about the outreach efforts recently done by Abani Samal and Greg Kruse. Samal paid a visit to the American Preparatory Academy in Draper, UT where he brought samples of copper and iron ore from around the world, illustrating the global nature of the industry.

Kruse wrote about a similar visit to Sagewood Elementary in Casper, WY in which he spoke with nearly 50 students on the importance of the mining that takes place in the students' own state. He shares that the students were given "Little Debbie" snacks and told that the snacks contained trona that is mined in the southwestern part of the state.

Rauch, Samal and Kruse have all helped share the importance of mining in different ways and you can as well. I believe this issue can help. Each May, *Mining Engineering* publishes comprehensive reviews of critical minerals and mining generously supplied by the U.S. Geological Survey.

I would encourage you to take the time to dive into these reviews. They are full of fact-based information about the industry.

For example, we have all seen and heard that the United States is dangerously dependent on foreign sources for many minerals. On page 48 is a figure that lays out just how dire the situation is with the figure showing that the United States is 100 percent reliant on 15 minerals including 11 that are among the 50 mineral that the USGS has deemed to be critical minerals such as graphite and manganese.

The reviews also provide important talking points of which many Americans are likely unaware. For example, the estimated total value of nonfuel mineral production in the United States in 2023 was $105 billion: yes, billion with a "b." The estimated value of metals produced was $34.9 billion and the value of industrial minerals produced was $69.9 billion. These are pretty good talking points for those who might ask, "We still mine?" or wonder what value mining brings to the nation. ■

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