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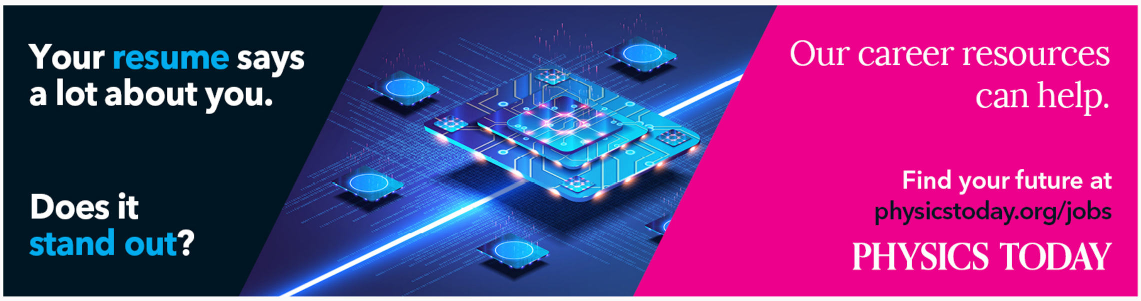

Wanted: Non-Chinese rare-earth elements

With few of its own hard-rock resources, the US may be forced to develop nontraditional sources of the essential metals.

The escalating US–China trade war and a newly enacted ban on defense acquisitions of high-performance permanent magnets made in China are underscoring US dependence on the Asian nation for rare-earth elements (REEs). Last month, the Trump administration backed away at the 11th hour from imposing steep tariffs on REEs from China, the source of nearly 90% of them, after appeals from US industrial consumers of the elements. The proposed duties, which would also have applied to some products that contain REEs, including some permanent magnets, catalysts, phosphors, and other chemicals, had been among the $200 billion worth of Chinese imports on which the White House had planned to levy duties at the border.

In addition to the 15 lanthanides—elements 57 through 71 in the periodic table—the REEs include scandium and yttrium because they occur with the lanthanides and exhibit similar properties. Despite their name, rare earths are relatively plentiful in Earth's crust. But they do not often occur in sufficient concentrations to be economically extractable, and they are difficult to separate from one another.

Low-atomic weight REEs, lanthanum and cerium, are used in petroleum-refining catalysts, automotive catalytic converters, and phosphors and as additives in glass for applications such as flat-panel displays, cell-phone screens, and camera lenses. Neodymium, another light REE, is alloyed with iron and boron to make the strongest-known permanent magnets. Other light REEs are used in steelmaking and alloying.

The heavy REE dysprosium is typically added to permanent-magnet alloys at a level of 1–3% to improve magnet operation at elevated temperatures. Terbium is used in green phosphors, which are found in electronics. However, magnet manufacturers are working to reduce or eliminate their use of heavy REEs. The next generation of wind turbines made by Siemens, for example, will have self-cooling magnets that won't require dysprosium. And the rapid switch from fluorescent to LED lighting has caused demand and prices for terbium and europium to decline significantly.

A provision in the National Defense Authorization Act signed into law in August will bar the Department of Defense after December from buying permanent rare-earth magnets made in China. The lightweight, strong magnets are used for motors and generators of varying sizes, computer hard drives, car window actuators, electric vehicle propulsion, robotics, and wind turbines. There is no domestic source of the magnets, however, and the measure will likely be a boon to Japanese manufacturers, the main producers outside China.

Few alternatives

The US consumed an estimated 11 000 tons of REEs last year, according to the US Geological Survey (USGS). The sole US REE mine, located at Mountain Pass, California, was acquired last year by a Chinese-affiliated consortium. Its output is being shipped to China for separation into individual rare-earth oxides, the product that is delivered to manufacturers.

"Given that there is currently no American-based alternative to China, it's unclear how tariffs would have offered the US any near-term upside or how they would have inflicted any pain on China, so it makes sense that following consultation with industry and end-users, the plan has been abandoned," says Ryan Castilloux, a rare-earth market analyst at Amsterdam-based Adamas Intelligence. Fear that China could restrict REE supply as the trade conflict continues may spur manufacturers to investigate other potential sources of supply. Before they commit to fund new mines or processing plants, though, developers will seek firm guarantees from end users to take the REEs. At the same time, the business case for a Japanese magnet producer to bring manufacturing to the US becomes more attractive. One producer, Daido Steel, had such plans a few years ago, but it abandoned them after REE prices collapsed as a result of China's short-lived curtailment of exports.

Castilloux predicts that China will actually become a net importer of REEs early in the next decade, as that nation's leaders prod industries to move up the value chain, from exporting raw materials to manufacturing finished products. At the same time, producers in Australia, Chile, and elsewhere will increase their market share.

Currently, the only sizable producer of REEs outside China is Lynas, an Australian mining and refining company

RESEARCHERS AT WEST VIRGINIA UNIVERSITY'S National Research Center for Coal and Energy use a series of mixer-settlers to extract rare-earth elements from acid mine drainage. The effort will help determine what combinations of organics and acids will work most efficiently and at the lowest cost. The research is sponsored by the National Energy Technology Laboratory.

that supplies around 12% of global output.

Coal is a dilute source

For the past four years, the Department of Energy's National Energy Technology Laboratory (NETL) has been funding R&D at a rate of $15 million annually to assess the potential use of coal-mining residues and postcombustion ash as REE sources. The work is performed at NETL's three facilities in Pittsburgh, Pennsylvania; Morgantown, West Virginia; and Albany, Oregon. It is also carried out by university and industry grantees. As PHYSICS TODAY went to press, appropriations bills for fiscal year 2019 proposed to increase funding to about $20 million.

But REE market watchers are skeptical that coal by-products could ever become an economically viable source, simply because vast quantities of the wastes have to be processed to extract meaningful amounts of the elements.

REEs are present at 60 ppm in coal, according to NETL. Clays and shales located above and below some coal seams can contain more than 200 ppm. Fly ash, a fine postcombustion waste, typically contains more than 400 ppm of REEs. Those levels are two orders of magnitude below the 40 000–100 000 ppm found in the hard-rock REEs mined in China and Australia.

Although much of the 75 million tons of fly ash produced annually in the US is recycled for concrete, fill material, and other uses, the American Coal Ash Association estimates that 2 billion tons of the ash and other coal-combustion products are disposed of in US landfills and sludge ponds.

But at coal's concentrations, "it will be a real challenge to [extract REEs] in a cost-effective manner," says Gareth Hatch, president of Canadian-based Innovation Metals. Hatch wouldn't dismiss coal residues entirely, however; he says it's possible that a more efficient extraction method can be developed to lower costs.

Castilloux also questions coal's economics. "You may have a similar concentration in your granite countertop," he says. But he notes that some of the costs incurred by having to chemically extract REEs from hard rock could be avoided with the coal by-products. He cautions that removing mixed rare-earth concentrates from coal wastes is only the first step in the production of high-purity individual REEs. "If [NETL] discovered an economically viable way to produce a mixed rare-earth carbonate or chemical concentrate, where does it go next?" he says. "Who is going to separate that material and at what cost?" Chinese and Australian companies refine REEs in-house; the US currently lacks large-scale capacity to do so.

A truckload per minute

Other experts offer more negative assessments of the NETL research. "The project cannot possibly succeed," says one researcher who declined to be named for fear of retribution. The chemistry of extracting REEs is trivial, he says, but at an REE concentration of 400 ppm, more than 2500 tons of material needs to be processed to yield 1 ton of REEs. Producing 800 tons of total rare-earth oxides per year—about what's necessary to meet US defense needs—would require processing fly ash at a rate of more than 8500 tons per day, assuming a very optimistic recovery rate of 95%, he says. That's equivalent to treating an 18-ton truckload of material every minute of an 8-hour workday for 250 working days a year. A similar volume of acid or alkaline extraction reagents also would be required. But those reagents would add to the huge quantities of waste left by the processing operation.

In coal's favor, few costs are incurred to obtain the coal by-products, notes Mary Anne Alvin, NETL's REE technology manager. And there are other valuable materials, such as zeolites, that processors could also recover from the coal wastes. "Their end products are going to determine their economics," she says. On viability, she adds, "I think the jury is out right now." As for wastes, the lab is developing processes to regenerate and reuse the reagents.

In July NETL announced a collaboration with West Virginia University to demonstrate the feasibility of extracting REEs from sludges generated during the treatment of acidic overflow water from abandoned coal mines. The university's opening of a rare-earth extraction facility is part of a $4.3 million effort in which the

PEGGY GREB, US DEPARTMENT OF AGRICULTURE

THESE RARE-EARTH OXIDES, clockwise from top center, are praseodymium, cerium, lanthanum, neodymium, samarium, and gadolinium.

collaboration is assessing extraction and separation processes for those wastes. The volume of that material in Pennsylvania and West Virginia alone could, in principle, generate up to 2700 tons of REEs per year, which is well above the US defense industry's needs.

Similar projects are under way to assess REE extraction from other coal wastes. In August NETL said it had begun investigating the clays that lie above and below coal seams. There, researchers are combining characterization methods used by the petroleum, coal, and mineral mining industries with spatial and statistical analyses of large data sets from the USGS and other sources.

Alvin says the lab and its academic research partners have proven the technical feasibility of extracting gram-level quantities of rare-earth concentrates from coal residues. She says that bench-scale projects on acid coal-mine drainage and lignite and pilot-scale studies on fly ash are currently under way. The goal is to produce an REE concentrate of 20 000 ppm. Follow-on projects will then strive to produce, by 2020, 4.5 kg a day of at least three 90–99% pure rare-earth oxides.

Rare-earth deposits with concentrations as low as 500 ppm are being mined in southern China from deposits known as ion-adsorption clays. The elements in those deposits are more easily extracted than from hard-rock ores. Moreover, the clays contain the most valuable heavy REEs, such as dysprosium and terbium, and not the more common mix, rich in light elements, found in hard rock. China is currently the only source of dysprosium and several other heavy elements, although the Browns Range mine in Australia and the BioLantanidos mine in Chile are just beginning to produce them. Alvin says the content of coal by-products is rich in heavy REEs.

Incomplete supply chain

A handful of US and Canadian companies are developing REE separation capabilities. However, the economic viability of those processes is untested and will depend on whether the companies can obtain long-term, stable arrangements both with the suppliers of concentrates and with customers for the rare-earth oxides.

Rare Earth Salts, located in Nebraska, last month began producing 99.9% pure rare-earth oxides, at a rate of 18 tons per month, by separating concentrates taken from recycled fluorescent light bulbs. The company has acquired other light and heavy concentrates from a non-Chinese source in Asia, says CEO Cameron Davies. It also has contracted with BioLantanidos to supply 500 tons a month of concentrates beginning next year. And Medallion Resources, a Canadian company that plans to extract REEs from monazite sands, a by-product of mining heavy mineral sands, will be providing other concentrates.

Heavy mineral sands deposits are most often found in beach environments, where REEs and other elements are naturally concentrated according to their specific gravity. Davies says his company has a capacity to produce 430 tons of oxides annually and plans to expand that to 3500 tons by the end of 2019.

Ucore Rare Metals, another Canadian-based company, proposes to build a rare-earth separations plant in Ketchikan, Alaska. Mark McDonald, vice president for business development, says the company is evaluating four potential non-Chinese sources of concentrates. Ucore president Jim McKenzie said in a June press release that he had met with officials in Washington, DC, to discuss US dependence on Chinese critical materials. The discussions included the possible development of REEs from Appalachian coal resources. McDonald wouldn't identify the US officials who met with McKenzie, but a source says that Senator Lisa Murkowski (R-AK) supports the Alaska project.

The Critical Materials Institute at DOE's Ames Laboratory has produced rare-earth magnets sourced entirely in the US from rare-earth ores from the Mountain Pass mine. National labs and industrial firms performed the refining and manufacturing. But there is no domestic industrial capacity covering the entire supply chain.

David Kramer