RARE-EARTH PREP In China, rare-earth chemistry research thrives. This recent photo shows Peking University's Haoshuai Wu (left) and Xiaoquan Min preparing reagents for analysis of rare-earth compounds.

CHUN-HUA YAN

SECURING THE SUPPLY OF RARE EARTHS

Green-energy and high-tech industries grow anxious over China's monopoly on these valuable resources

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CLUSTERED AT THE BOTTOM of the periodic table like a chemical afterthought, the rare-earth family is a collection of tough-to-pronounce elements that tend to go largely unnoticed in most chemistry classes. But don't misjudge the rare earths. Their low classroom popularity belies the critical role they play in many high-tech applications and their enormous commercial value.

Likewise, their family name is misleading. Several rare-earth minerals and metals are in fact abundant. Yet due primarily to economic reasons, the supply of these important materials, which overall are not rare in nature, is becoming increasingly tough to secure in the U.S.

"The situation is nothing short of a crisis," says Karl A. Gschneidner Jr., a senior metallurgist at Iowa State University's Ames Laboratory who has been studying rare-earth materials there since the 1960s. "There is nearly zero rare-earth mining, processing, and research going on now in the U.S.," Gschneidner says. And in large part, the U.S. no longer manufactures rare-earth products, he adds. A small number of U.S. labs, however, and some research institutions outside of the U.S. are working to improve industrial methods for processing and recycling rare-earth minerals, and they're also searching for substitute materials.

The problem with the low level of activity in this field, especially in the U.S., is that the rare-earth family, which includes 15 lanthanides plus scandium and yttrium, is central to numerous technologies in the computer, electronics, transportation, energy, and defense industries. For example, the powerful permanent magnets found in today's computer disc drives, as well as the motors and motor generators that are crucial to the performance of hybrid automobiles, electricity-generating windmills, and other "clean" technologies, are made from a neodymium iron boron compound, $Nd_2Fe_{14}B$.

Driven by an enormous number of applications, the global market for purified rare-earth starting materials is in the billion-dollar range. Dudley J. Kingsnorth, executive director of Industrial Minerals Company of Australia, based in Mount Claremont, reports that worldwide demand for rare-earth oxides in 2007 was on the order of 124,000 metric tons and valued at $1.3 billion.

Even more valuable are the products made from these compounds. For example, the rare-earth magnet market is estimated to be worth $9 billion. Yet the world's supplies of neodymium and other rare-earth materials are provided almost exclusively by manufacturers in China.

"Today, nearly 100% of the world's rare-earth metals and more than 94% of rare-earth oxides come from China," says Peter C. Dent, vice president for business development at Electron Energy, in Landisville, Penn. Electron Energy designs and manufactures high-performance rare-earth magnets and magnet assemblies, specializing in samarium cobalt products.

"In 1970, we were one of the first companies in the world to produce rare-earth magnets," Dent says. By the late 1980s and early 1990s, the American magnet industry reached its peak, with more than 20 companies manufacturing a large variety of magnets. But then the 1990s witnessed a decline and eventually a wholesale migration of this industry to China, according to Dent. "Now we find ourselves to be the last rare-earth magnet maker in the U.S.," he says.

According to industry watchers such as James Kennedy, owner and president of Wings Enterprises' iron ore mine in Sullivan, Mo., China has maneuvered effectively since the mid-1980s to establish a worldwide monopoly on rare-earth resources. Aiding its effort to corner the market is China's tremendous rare-earth mineral wealth. U.S. Geological Survey reports indicate that China possesses roughly 52% of the world's known rare-earth reserves. By comparison, the U.S. is believed to have the second-largest share, at about 13%. Russia and Australia each have 5–6% of the known reserves. India, Canada, Greenland, and a few other countries also have appreciable quantities of rare-earth minerals.

In the 1990s, China's low production costs rapidly deflated rare-earth prices, driving many non-Chinese mining and processing operations out of business. Molycorp, owner of the largest U.S. rare-earth mine—Mountain Pass in southern California—mothballed its mining operations in 2002. In 2005, prices started to rise as China began limiting production and imposing export tariffs on some rare-earth products. Then China began restricting rare-earth exports in 2006 and further tightened export quotas in the first half of 2010.

The rare-earth news from China continues. Just last month, China's Ministry of Commerce announced plans to further cut export quotas by 72% for the second half of 2010. That move caps foreign shipments at 7,976 metric tons, down from 28,417 tons for the same period last year. And earlier this month, two of China's largest state-owned rare-earth mining companies announced plans to launch "a new unified pricing system," a move that will likely give China even greater control over the availability and supply of rare-earth compounds. No doubt the action will drive up prices of these valuable resources around the world.

NOT SURPRISINGLY, the news from China this summer is making Electron Energy and other U.S. companies jittery. "We've seen rare-earth prices increase steadily in recent years," Dent says, "but until now, we have been able to get the supplies we need. We're very concerned now about the long-term availability of these materials."

So is Molycorp CEO Mark A. Smith. "China is doing what it feels it must in order to maximize the value of its resources," Smith says. By cutting back on exports yet again, China is securing the supplies it needs to further develop its own high-tech industries and protect Chinese manufacturing jobs. But in Smith's view, that protection is "clearly troubling" and could lead to near-term rare-earth shortages.

The view from China is somewhat different. "China's new policy is beneficial to rare-earth industries across the world" in that it will force other countries to develop alternative sources of rare-earth materials, says Chun-Hua Yan, a professor of inorganic chemistry at Peking University. Yan also heads the State Key Laboratory of Rare Earth Materials Chemistry & Applications, the country's premier research facility in the field.

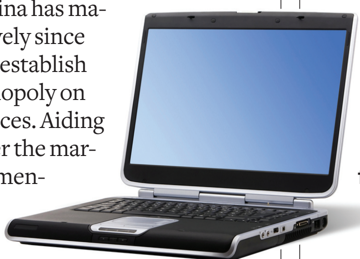
Yan describes China's near monopoly in rare-earth production as "an unreasonable

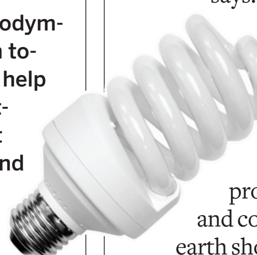
Common Chemicals

Contrary to their name, rare-earth minerals are common. Many products that depend on their unique properties are also common.

Hybrid-electric cars typically contain about 10 kg of lanthanum in the form of nickel-metal hydride batteries and smaller amounts of neodymium, praseodymium, dysprosium, and terbium in electric motors and generators. Cerium is used to polish automobile glass and is found together with zirconium in catalytic converters.

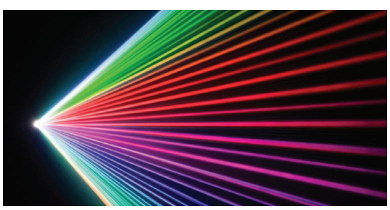
Electricity-generating windmills depend on magnets that weigh 1 ton or more and contain hundreds of pounds of neodymium.





Lightweight and strong neodymium-iron-boron magnets in today's computer disc drives help keep laptops small, and flat-panel displays and compact fluorescent light bulbs depend on europium and other rare-earth phosphors for color contrast.

Rare earths also play key roles in lasers, radar equipment, precision-guided munitions, and other weapons systems.



SHUTTERSTOCK (ALL)

and unhealthy situation that needs to be changed." He sees the combination of tight export caps and high world demand for rare-earth compounds as the impetus that can drive that change.

Yan adds that beginning in the late 1980s, when China became the world's largest producer of rare-earth materials, it almost single-handedly drove down rare-earth prices by as much as 90%. Much of that rapid price drop, according to Yan, was a result of unlicensed factories that pump toxic waste into rivers to reduce their operating costs. "It is unfair for the rest of the world to be using cheap, Chinese-made rare-earth materials at a prohibitive cost to China's natural environment," he says. "In the end, it's part of the world's environment too."

While Chinese officials have been considering the environmental cost of poor mining practices and drafting stringent regulations to curb those activities, industry representatives in the U.S. have been trying to draw lawmakers' attention to China's monopoly and the impending effects of this monopoly on U.S. science, technology, and commerce.

"The news from China should serve as a huge red flag for U.S. government officials," says Edward Richardson, president of US Magnetic Materials Association (USMMA), a trade group representing U.S. producers of high-performance magnets. Richardson, who is also vice president of Thomas & Skinner, an Indianapolis-based manufacturer of aluminum-nickel-cobalt alloy (Alnico) magnets, adds that "if the United States is to become a leader in clean-energy technology, it needs a reliable domestic rare-earths supply chain."

Several groups have been working recently to spread the word and impress upon legislators the critical nature of the problem. According to Jeffery A. Green, president of J.A. Green & Co., an advocacy group working with USMMA, the groups' efforts are starting to pay off. "We're now seeing a lot of political momentum surrounding this issue," Green says.

For example, at a Washington, D.C., rare-earth conference in March, the Department of Energy's David B. Sandalow, assistant secretary of energy for policy and international affairs, announced DOE's intention to develop its first-ever strategic plan for addressing the role of rare-earth and other strategic materials in clean-energy technologies. "There's no reason to panic," Sandalow said, "but every reason to be smart and serious as we plan for growing global demand for products that contain rare-earth metals." DOE later released a public request for information to help develop that plan.

AT AROUND THE SAME TIME, the Government Accountability Office, the investigative arm of Congress, prepared a report on rare-earth materials in the defense supply chain and presented it to the Armed Services Committees of the Senate and House of Representatives. The GAO report affirmed that rare-earth materials play important roles in numerous defense technologies, including radar, missile-guidance systems, lasers, and night vision equipment. The Department of Defense is now conducting an internal assessment and is expected to devise strategies to protect against rare-earth supply interruptions. The report is scheduled to be completed next month.

In addition to the DOE and DOD activities, the House Committee on Science & Technology convened a hearing in March at which rare-earth experts including Gschneidner of Ames Lab and Smith of Molycorp testified about the threat of a rare-earth supply shortage in the U.S. After the hearing, Rep. Mike Coffman (R-Colo.) introduced the Rare Earths Supply-Chain Technology & Resource Transformation (RESTART) Act, which aims to revitalize the U.S. rare-earth industry. Sen. Lisa Murkowski (R-Alaska) later introduced similar legislation in the Senate.

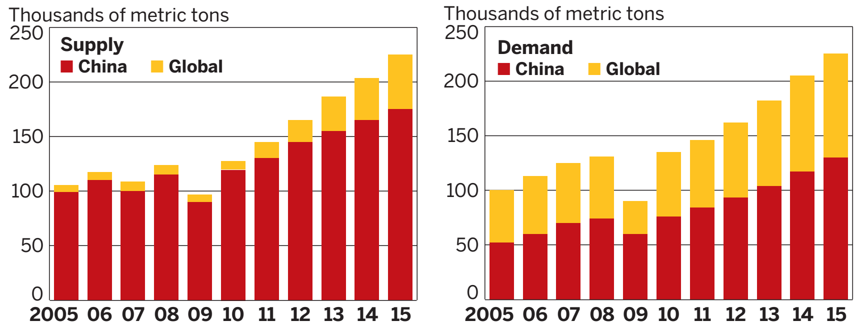
A key piece of the plan to revitalize rare-earth activities in the U.S. centers on restarting operations at Molycorp's Mountain Pass mine. The company is now raising funds necessary to bring the level of production at the California mine back into high gear—and to do so quickly.

James T. Sims, Molycorp's director of public affairs, says the company has an ambitious plan to begin producing some 20,000 metric tons of rare-earth oxides annually by 2012. But that's not all. In addition to resuming mining and milling operations and producing high-purity oxides at the now mostly dormant mine, Molycorp aims to reduce the oxides to metals, convert the metals to rare-earth alloys, and produce high-end permanent magnets. All in all, he says, the plan is to completely shore up the "mining-to-magnets manufacturing supply chain."

"Mostly dormant" describes the state of affairs at Mountain Pass since 2002. Mining and processing operations were put on hold at that time, but not long thereafter, company scientists and engineers began retooling their processing techniques with an eye toward eventually reopening a new and improved mining facility. The aim was to reduce production costs, cut back on

RARE-EARTH SUPPLY AND DEMAND

China's increasing demand for its own rare-earth materials is predicted to drive production abroad



SOURCE: Dudley Kingsnorth/IMCOA

"Today, nearly 100% of the world's rare-earth metals and more than 94% of rare-earth oxides come from China."

waste output, and boost the efficiency of rare-earth extractions, separations, and other processing steps.

"Historically, Molycorp used a whole collection of acids and bases to process rare earths, which generated a complex mixture of salts in the wastewater," says John L. Burba, Molycorp's executive vice president and chief technology officer. Sulfuric acid, nitric acid, hydrochloric acid, ammonia, sodium hydroxide, and other reagents all played important roles in extracting purified compounds from the Mountain Pass ore—which in terms of its rare-earth content is composed of cerium (49%), lanthanum (33%), neodymium (12.5%), praseodymium (4%), samarium (1%), and heavier rare-earth elements.

"We needed to simplify our chemistry," Burba says, to reduce the enormous volumes of intake and wastewater. The challenge there is that the ore body consists mainly of bastnasite, a rare-earth fluorocarbonate mineral, and monazite, a rare-earth phosphate. "But rare-earth fluorides and phosphates are profoundly insoluble," he stresses.

Nonetheless, Molycorp has developed chemical methods that depend strictly on hydrochloric acid and sodium hydroxide, Burba says. That simplification enables the company to install a chlor-alkali plant on-site to recycle the sodium chloride by-product. The well-established technology converts saltwater to NaOH, hydrogen, and chlorine, which in turn are used to produce sodium hypochlorite (which can be sold to make bleach) and hydrochloric acid, which is recycled into the mineral-processing loop.

"We're turning this site into a near-zero wastewater-discharge facility," Burba says. In addition to the environmental benefits of recycling and reusing water and reagents, the new plans, he adds, significantly reduce the company's operating expenses. Additional cost savings will come from generating electricity on-site via a highly efficient natural gas-fueled cogeneration plant.

Precisely how Molycorp reduced the number of key reagents needed for its new processing methods is a closely guarded trade secret and has not been patented, according to Burba. The reason is that the advances depend on new technologies for which patent protection is challenging to ensure.

A separate challenge for Molycorp and organizations such as Ames Lab, which remain interested in this area of research, is finding scientists with rare-earth expertise. "We need help in that regard," Smith told Congress in March. "I have 17 engineers and scientists competing with over 6,000 scientists in China."

Quite a few of those Chinese scientists conduct research under Yan's direction at Peking University and the State Key rare-earth lab. Yan's group has focused on a number of research challenges, including refining a key solvent-extraction process. The traditional method, devised in the 1970s, used organic phosphonic acids to extract rare-earth ions before capturing them with stronger inorganic acids in a process called stripping. Yan's team developed a simplified system that decreases the consumption of chemicals.

Yan is keeping quiet about the details. But he estimates that the new procedure reduces the costs of acids and bases needed for processing rare earths by 30–50% relative to traditional methods. His team has also developed methods specifically directed at separating heavy rare-earth elements such as thulium, ytterbium, and lutetium.

Back in the U.S., Gschneidner and coworkers at Ames Lab report that they have devised a way to make neodymium-iron-boron magnets less expensively and without generating the hazardous by-products formed by today's standard manufacturing methods. They, too, are keeping the details under wraps.

Elsewhere at Ames, senior metallurgist Iver E. Andersen heads a group searching for non-rare-earth substitutes for permanent magnets. One of his team's focus areas is the Alnico iron-alloy family. By customizing the alloy's composition, it may be possible to tailor-make a suitably powerful magnet, Anderson says. Other groups are focusing on iron-cobalt-based alloys and nanostructured compounds made from combinations of rare-earth elements and transition metals.

Basic rare-earth science has not been a focus of most U.S. research centers for quite a long time, "but suddenly it has come roaring back," Ames Lab director Alex King says.

From an industrial perspective, Molycorp scientists hope that rare-earth mining and processing in Mountain Pass will soon be back in full swing. At the same time, Chinese scientists are under pressure to drastically improve resource usage and environmental practices. Forthcoming regulations in China are likely to be strict. They may take two to three years to implement, Yan says. But the hope for the Chinese rare-earth industry is that those regulations will usher in an era of environmental responsibility that will help ensure that a reliable supply of rare-earth materials remains readily available for many years to come. ■

MOLYCORP

EARTHY VIEW Nighttime view of Molycorp's rare-earth mining facility in Mountain Pass, Calif., which the company aims to reopen in 2012.