Sparing the rare earths

Potential shortages of useful metals inspire scientists to seek alternatives for magnet technologies

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August 27th, 2011; Vol.180 #5 (p. 18)

Text Size

A potential shortage of several rare earth metals (some shown) has spurred research into technologies that don’t require them.Images-of-elements.com

The Toyota Prius isn’t exactly a muscle car. But the magnets under the hood certainly pack a punch.

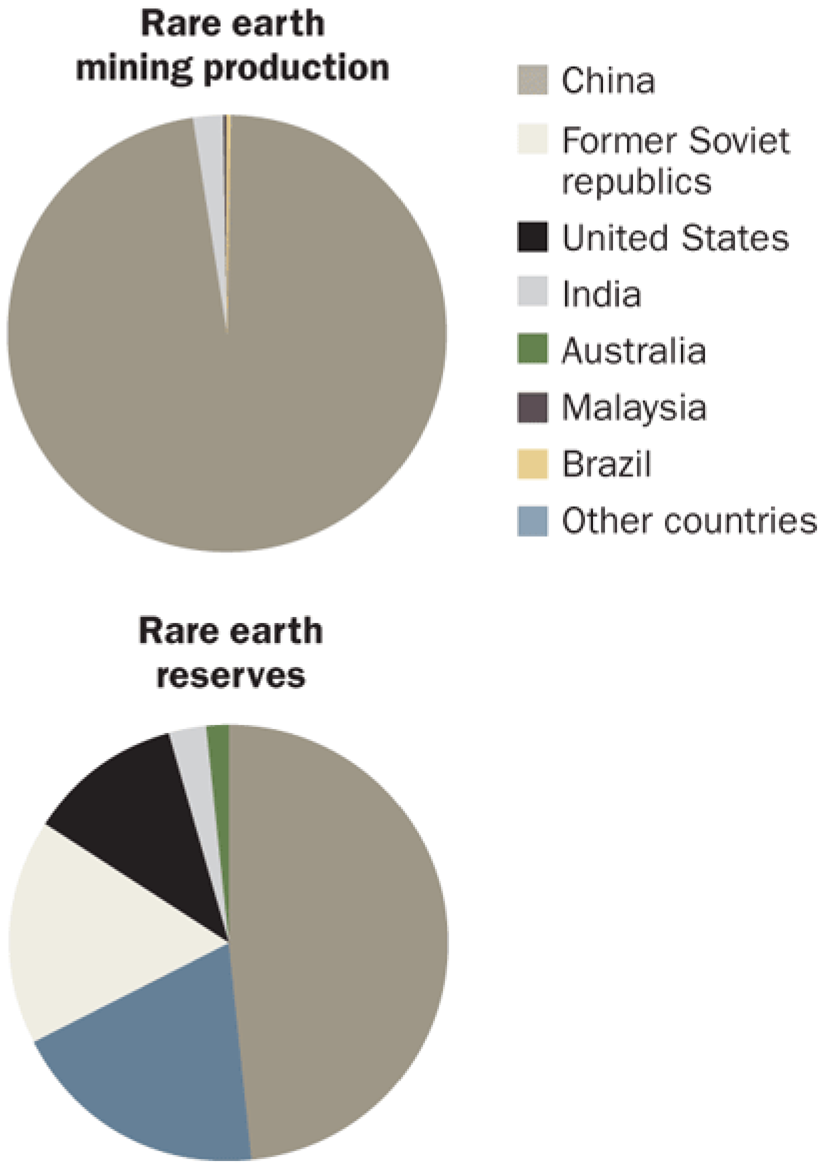
Pound for pound, these permanent magnets are some of the most powerful on the planet. They generate fields 10 times stronger than those of typical refrigerator magnets, helping the hybrid car’s motor and generator to turn the wheels and charge the battery. The secret to the magnets’ intense fields? About three pounds of alloy made with rare earth elements.

Rare earths, 17 chemical elements found mostly in an appendage to the periodic table, have long been the darlings of solid-state physics and the electronics industry. Without these materials, hard drives wouldn’t be able to store so much information and smartphones wouldn’t be so pocket-friendly.

“Take away the small rare earth magnets inside the earbuds for your iPod, and you’re back to traditional-looking over-the-ear headphones,” says Alex King, director of the U.S. Department of Energy’s Ames Laboratory in Iowa.

But some people, particularly in the United States and Japan, have begun to worry about potential shortages in the supply of rare earths. Although the elements are not rare in themselves, they are concentrated in just a few locations. Last year, China produced about 97 percent of the rare earths mined on the planet. In recent years that country has been cutting back on the amount of rare earths it exports, reducing quotas by almost 40 percent in 2010.

Rising prices and a looming potential shortage have now ignited searches for alternatives to magnet technologies that chew up large amounts of rare earths.



Rare indeedChina contains about half the world’s reserves of rare earth elements,and it far outstrips other countries in producing them from mining operations. SOURCE: USGSJanel Kiley

For some applications, rare earth elements may be simply irreplaceable. The phosphors used in color televisions and other displays with cathode-ray tubes get their brilliant reds from europium compounds. This rare earth’s electrons jump between energy levels and emit light in ways that can’t be mimicked by any other element in the periodic table.

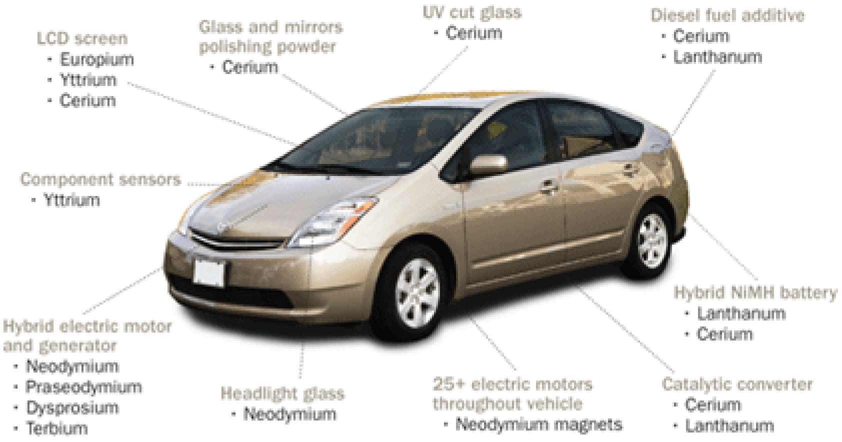
Magnets, which account for about one-fifth of global rare earth consumption, may be a different story. With DOE funding, materials scientists in the United States are reviving the study of magnets, a field that hasn’t seen a major breakthrough in nearly three decades. Meanwhile, Japan — second only to China in global magnet production — has dedicated more than $150 million of its 2011 budget to research that would reduce its need for rare earths.

Some scientists plan to make the strongest rare earth magnets stronger with blends that use less of these materials. Others hope to ditch the elements in favor of common metals that might be good enough to get the job done.

“A lot of old problems in permanent magnetism are being revisited with new tools,” says Oliver Gutfleisch, a materials scientist who studies magnets at the Leibniz Institute for Solid State and Materials Research in Dresden, Germany. “We have to produce a next-generation magnet.”

Revisiting the iron age

The strength of a magnet — its ability to tug on iron — starts with its electrons. Every electron spins around its axis, like a planet or a figure skater. In most substances, electrons pair off, spinning in opposite directions. But some elements have unpaired electrons that spin in a way that makes their atoms into tiny bar magnets, with a north and a south pole. Expose a group of these atoms briefly to a magnetic field, and they line up with one another straight as soldiers, working together to make one big magnet.



HYBRID VIGOR | A vehicle such as the Toyota Prius contains rare earth elements throughout its various advanced technologies, including more than 20 pounds of lanthanum in the battery pack.© Owaki/Kulla/Corbis

Iron is one of the most magnetizable materials on Earth, but there’s a good reason why magnets aren’t usually made of pure iron. At the slightest provocation, such as a tiny electric field or change in temperature, iron’s atoms break rank and swing out of alignment, ruining the magnet. Iron is thus considered magnetically soft.

Metallurgist Iver Anderson, who spent years purifying rare earth metals in the crucibles of the Ames Laboratory, now hopes to harden soft iron alloys to create a magnet free of rare earths. The goal isn't to make something that can rival today's best magnets, just something with a better bottom line.

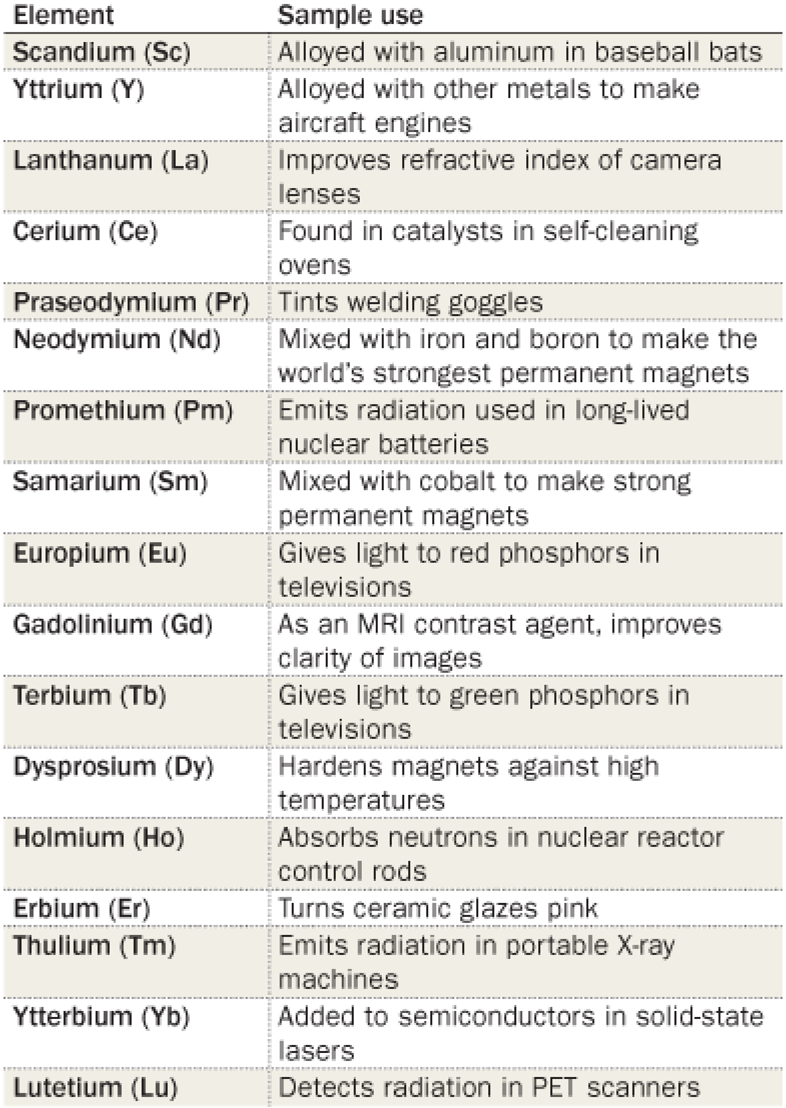
"For many applications, we don't have to reach the same magnetic strength levels as rare earth magnets," he says. "For hybrid cars, we need something maybe 50 percent or so as strong."

Anderson and his colleagues plan to harden a blend of iron and cobalt by changing the shape of its crystal structure. The cube-shaped atomic lattices that make up iron cobalt give atoms too much freedom to wiggle around. Other crystal structures, such as hexagons and tetrahedrons, are better at keeping atoms in line, so "we're trying to figure out a way to distort the cubic structure and make it tetrahedral," says Anderson. Computer simulations he presented at an Energy Department meeting in May suggest that this goal could be achieved by peppering the usual iron cobalt recipe with other atoms: tungsten, maybe, or nitrogen.

The Ames team is also dusting off "alnico" magnets, commercialized in the 1940s. Made mostly of aluminum, nickel, cobalt and iron, these magnets are reasonably hard but only about one-fifth as strong as the best rare earth magnets. Tweaking the structure of these magnets to line up the iron cobalt grains might up the oomph.

"We're at least a year away from knowing whether this will work," Anderson says. "Whether it makes sense from an economic standpoint is another step beyond that."

What rare earth elements are good for



Element	Sample use
Scandium (Sc)	Alloyed with aluminum in baseball bats
Yttrium (Y)	Alloyed with other metals to make aircraft engines
Lanthanum (La)	Improves refractive index of camera lenses
Cerium (Ce)	Found in catalysts in self-cleaning ovens
Praseodymium (Pr)	Tints welding goggles
Neodymium (Nd)	Mixed with iron and boron to make the world's strongest permanent magnets
Promethium (Pm)	Emits radiation used in long-lived nuclear batteries
Samarium (Sm)	Mixed with cobalt to make strong permanent magnets
Europium (Eu)	Gives light to red phosphors in televisions
Gadolinium (Gd)	As an MRI contrast agent, improves clarity of images
Terbium (Tb)	Gives light to green phosphors in televisions
Dysprosium (Dy)	Hardens magnets against high temperatures
Holmium (Ho)	Absorbs neutrons in nuclear reactor control rods
Erbium (Er)	Turns ceramic glazes pink
Thulium (Tm)	Emits radiation in portable X-ray machines
Ytterbium (Yb)	Added to semiconductors in solid-state lasers
Lutetium (Lu)	Detects radiation in PET scanners

Another scientist who wants to work with magnets from the iron age is Migaku Takahashi of Tohoku University in Japan. He is experimenting with combinations of iron and nitrogen because thin films made out of these elements are the most magnetizable material known. In March, Takahashi's collaboration announced a method to create powders that retain this property, though they still lack the hardness needed to be useful for rare earth–free magnets. Like Anderson, Takahashi is taking the long view; he doesn't expect to be able to make a commercial magnet out of this material until at least 2023.

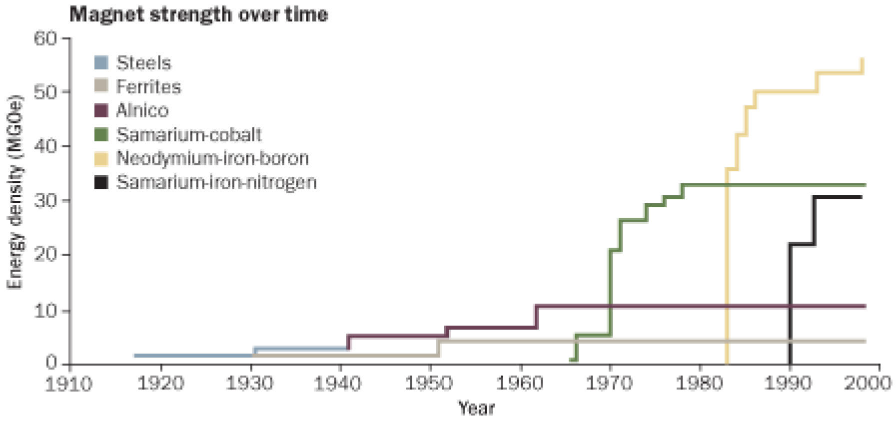
Rare attraction

Uncertain that these well-explored traditional materials will yield new surprises anytime soon, Ames scientists and other groups are trying to reinvent rare earth magnets from the bottom up.

The best rare earth magnets used today date to 1983, when scientists at General Motors and the Sumitomo Special Metals Co. in Japan independently created the first alloy of iron, boron and the rare earth metal neodymium. This breakthrough was driven by economics; the best magnets at the time were made of cobalt and the rare earth samarium, and the price of cobalt was rising rapidly.

Adding neodymium atoms smothers some of the iron’s magnetic strength but greatly improves its ability to resist demagnetization. Neodymium magnets can achieve about 56 megagauss-oersteds, or MGOe, a unit of magnetic field strength. That compares with more than 10 MGOe for the best non–rare earth magnets, and less than 5 MGOe for the stuff used in refrigerator magnets.

“It’s hard to imagine making a more perfect magnetic material than neodymium-boron-iron,” says George Hadjipanayis, a materials scientist at the University of Delaware in Newark, whose research was crucial to the invention of the first neodymium magnets.



| Magnets containing rare earth elements, such as neodymium and samarium, achieve far higher measures of magnetic field strength than older magnets based on iron alloys.O. Gutfleisch et al/Advanced Materials 2011

Confident that no single material could do a better job, Hadjipanayis and his colleagues have turned to composite neodymium magnets. The researchers are grinding magnetically hard and soft materials into pellets and trying to bind them like candies stuck in a ball. The soft stuff, perhaps iron cobalt, should boost the magnet’s pull. The hard stuff, rare earth compounds, should preserve the strength.

For the materials to play well together, though, these pellets must be extremely small, small enough to qualify as a “nanocomposite” material. When hard chunks and soft chunks are arranged in a kind of patchwork quilt, the hard bits stay connected over distance by the equivalent of magnetic springs. If stretched too far over the soft bits, the springs snap, and the nanocomposite stops behaving as a single material.

A magnet structured as a nanocomposite could achieve some 120 MGOe — more than twice as strong as anything on the market today, according to calculations published in 1993 by Ralph Skomski and Michael Coey of Trinity College Dublin. It would also use significantly less rare earth material.

"Nanocomposite magnets are the holy grail for rare earth magnets," says John Burba, executive vice president and chief technology officer at Molycorp Minerals in Greenwood Village, Colo.

New teamwork

Thanks to advances in nanotechnology in the years since nanocomposites were first proposed, Hadjipanayis' team can now create suitably tiny and uniform bits of hard and soft magnetic materials — while also preventing oxygen from damaging their surfaces, a key problem in making nanocomposite magnets. So can a team at General Electric's Global Research Center in Niskayuna, N.Y.

GE is pursuing nanocomposite magnets because it's the largest manufacturer of wind turbines in the United States. New turbine designs incorporate huge magnets that can better handle fluctuations in wind speed and provide more torque than older designs. But a turbine capable of powering about 2,400 homes uses as much as a ton and a half of rare earth permanent magnets.

Last year, in response to a steep increase in the price of the metal rhenium (which is not a rare earth), GE scientists made a very strong replacement "superalloy" out of very small grains of nickel. Using techniques similar to those developed for that and other work, the researchers now aim to improve the strength of rare earth magnets by about 40 percent while decreasing the amount of rare earths in the magnets by 80 percent. What these magnets will be made of, though, is still anyone's guess.

"We're exploring several different hard and soft materials but haven't selected a specific chemistry yet," says materials scientist Frank Johnson of GE.

Choosing the right stuff for a nanocomposite isn't easy. In 2002, physicist Ping Liu, now at the University of Texas at Arlington, and colleagues published a paper in *Nature* describing experiments that mixed magnetically hard and soft particles made of iron and platinum. His team fused the particles, and the resulting magnetic fields were more than 50 percent stronger than the hard material on its own.

But Liu hasn't figured out how to get all of the grains lined up before fusing, which would allow the nanocomposite to reach its full potential. And the platinum may make this approach too expensive to be viable for everyday magnets.

Dyspros and cons

If they ever live up to their promise, nanocomposite magnets should reduce the demand for both neodymium and for another rare earth element called dysprosium.

Dysprosium hardens magnets against heat by reshaping their magnetic fields. Every neodymium magnet intended for a hybrid car, a wind turbine or another application in which temperatures soar to hundreds of degrees must be spiked with a bit of the pricey dysprosium. It costs more than seven times as much as neodymium and is currently mined in only one place in the world: clays in southern China. So some researchers are exploring pragmatic ways to cut down on its use.

Changing the microstructures of magnets could help, as neodymium magnets made of smaller grains are naturally more resistant to demagnetization. Working with the magnet company Intermetallics, materials scientist Satoshi Sugimoto of Tohoku University and colleagues recently developed fine-grained magnets that require 40 percent less dysprosium.

The best fine-grained magnets completely free of dysprosium may belong to Kazuhiro Hono, a researcher at the National Institute for Materials Science in Tsukuba, Japan, and colleagues. These magnets, to be described in September in *Scripta Materialia*, are 60 percent more resistant to demagnetization than commercial neodymium magnets that lack dysprosium. But Hono's magnets are still not quite good enough for cars and wind turbines.

Despite recent advances, neither Japan nor the United States appears to be counting on magnet breakthroughs anytime soon. Geologists from the University of Tokyo and their colleagues recently proposed dredging the Pacific Ocean for rare earths (*SN: 8/13/11, p. 14*). Several Japanese companies have also started "urban mining" programs meant to reclaim the rare earths buried in cell phones and other devices. Hitachi is working to reclaim 80 percent of the rare earths from the magnets of discarded hard drives and air conditioners.

In the United States, Molycorp Minerals has reopened a mine on the edge of California's Mojave Desert that was once a profitable source of europium and cerium. Last year, the company began processing previously mined ore for rare earths, including neodymium.

But these efforts to dig out of a difficult situation may not prove economical, and the combined creativity of scientists on both sides of the Pacific may fall short. So Toyota has launched a program to rid its cars altogether of permanent magnets — rare earth or not — by developing a new motor that would run on electromagnets, which generate fields by passing current through coils of wires and have traditionally been considered too bulky for hybrid and electric cars.

If Toyota engineers succeed, these new motors could push forward the next generation of hybrid vehicles without the need for any rare earths.