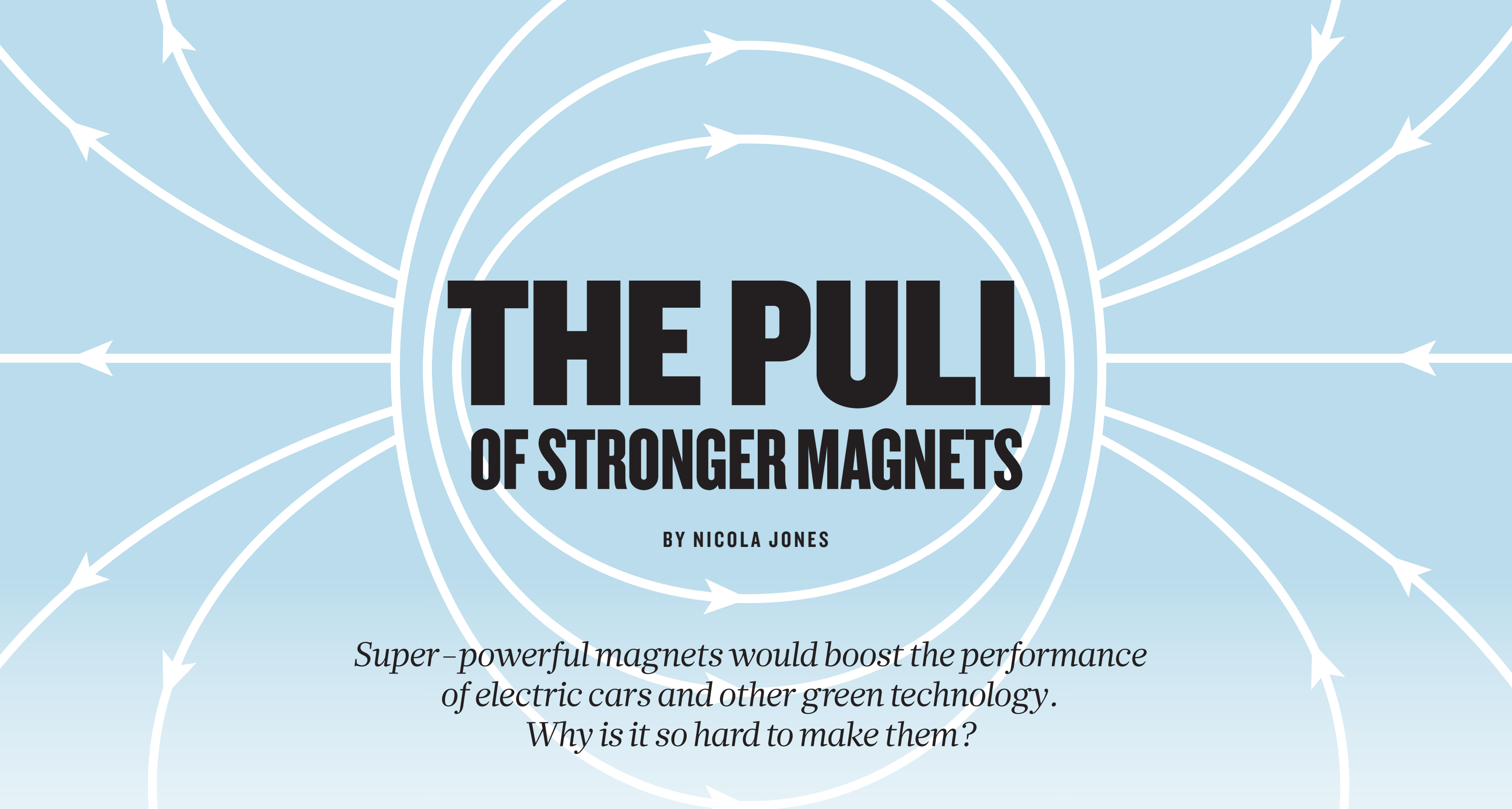

THE PULL
OF STRONGER MAGNETS

BY NICOLA JONES

Super-powerful magnets would boost the performance of electric cars and other green technology. Why is it so hard to make them?

For Christmas, magnetics researcher William McCallum got one of the latest cool toys: 'Buckyballs: The Amazing Magnetic Desktoy You Can't Put Down!' The magnets are state-of-the-art — strong enough that, if they were cubes rather than spheres, you wouldn't be able to pry them apart. But if McCallum has his way, his team will make them look like weaklings.

McCallum, a materials scientist at Iowa State University in Ames, is tackling two big problems at the same time: magnet strength and cost. For most of the twentieth century, the strength of available magnets doubled every decade or two, but it stalled in the 1990s. The limit has hampered efforts to make high-tech products such as electric cars more efficient. And in the past two years, the cost of the rare-earth elements that are essential to advanced magnets has shot up. The price of neodymium oxide jumped from US$17 a kilogram to $85 a kilogram in 2010 alone.

Despite their name, rare-earth elements such as neodymium aren't truly rare geologically, but they are expensive to mine and process. China, which provides about 95% of the 96,000 tonnes currently produced worldwide every year, has put increasingly stringent caps on exports, even as the need for the elements is booming. Magnets made with them are at the heart of modern technology from mobile phones and laptops to high-efficiency washing machines. And many devices that are part of the green economy require substantial amounts: an electric car carries a few kilograms of rare-earth elements, and a 3-megawatt wind turbine uses about 1.5 tonnes. Demand leapt from 30,000 tonnes in the 1980s to 120,000 tonnes in 2010 (which was met in part by depletion of national stockpiles), and is predicted to hit 200,000 tonnes by 2015, says Gareth Hatch, founder of the Technology Metals Research consultancy in Carpentersville, Illinois (see 'Market forces').

Fortunately, the leading idea for how to make 'next-generation' magnets could solve both problems at once. It involves combining nanoparticles of rare-earth magnets with nanoparticles of cheaper magnetic materials — creating super-strong end-products with far less of the expensive ingredients. Governments keen to invest in energy-efficient technology, and scared by a global crunch in the rare-earth market, have started to pay attention to magnetics research.

In the United States, an infusion of funds has come from the Department of Energy, home of the Advanced Research Projects Agency — Energy (ARPA-E), which was established in 2009 to bring high-risk, potentially 'transformative' technologies to the market. ARPA-E has allocated $6.6 million to research on next-generation magnets — a shot in the arm for the field. "We're long overdue" for the next magnet revolution, says George Hadjipanayis, a physicist at the University of Delaware in Newark, who is head of a $4.4-million ARPA-E consortium of which McCallum is part. "We need to do it."

Permanent magnets get their pulling power from the orbits and spins of unpaired electrons, which tend to align with an external magnetic field and stay that way when that field is taken away. These magnets are ranked by their 'energy product' in kilojoules per cubic metre (kJ m^{-3}) — a combination of how much they respond to an applied magnetic field (their magnetization) and how well they resist being demagnetized. These properties don't always go hand in hand. Iron–cobalt alloy has the highest potential magnetization known, but its energy product is effectively zero because it is easily demagnetized: it has a symmetrical cubic crystal structure, with nothing to keep its electron spins pointing in any one direction, so they can be jolted out of alignment by a bump or a nearby magnetic field.

SPINS IN SYNC

Newer magnetic materials have a complex crystalline structure that helps to keep the spins pointing one way. In the 1950s, the best of such magnets, made of an alloy of iron, aluminium, nickel and cobalt called Alnico, achieved an energy product of 40 kJ m^{-3} (see 'Stalled progress'). The 1960s brought the first generation of rare-earth magnets, made of samarium and cobalt, which eventually enabled energy products to exceed 250 kJ m^{-3}. In the 1980s, researchers devised neodymium–iron–boron (NIB) magnets, which hold the record at about 470 kJ m^{-3}. If the magnets have to work at high temperatures — such as in a car engine — the rare-earth element dysprosium is added to the mix.

The dream is to unite the magnetic punch of something like iron–cobalt with the stability of, for example, a NIB magnet. That should be possible by combining nanoparticles of the two, packed so closely that neighbouring electrons influence each other and keep their spins aligned. In theory, a nanocomposite could reach an energy product of a whopping 960 kJ m^{-3}, with rare earths making up just 5% of its weight, compared with 27% in a normal NIB magnet (R. Skomski and J. M. D. Coey *Phys. Rev. B* **48,** 15812–15816; 1993). But making such a composite is extremely difficult.

The grains in a successful nanocomposite must be small (10 nanometres or less); have the right crystal structure; have aligned magnetic directions; and be tightly packed. Achieving all of these at once is an engineering nightmare. On top of that, rare-earth nanoparticles aren't stable — they love to react with oxygen, which ruins their magnetic properties.

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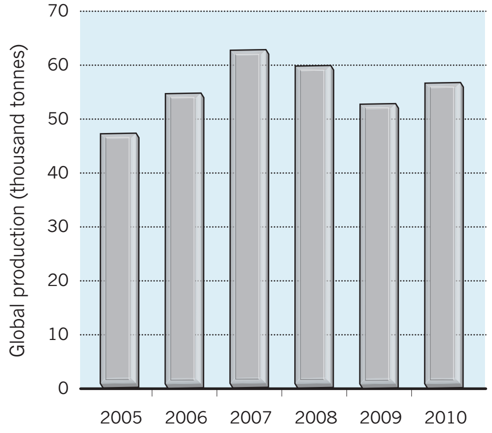
MARKET FORCES

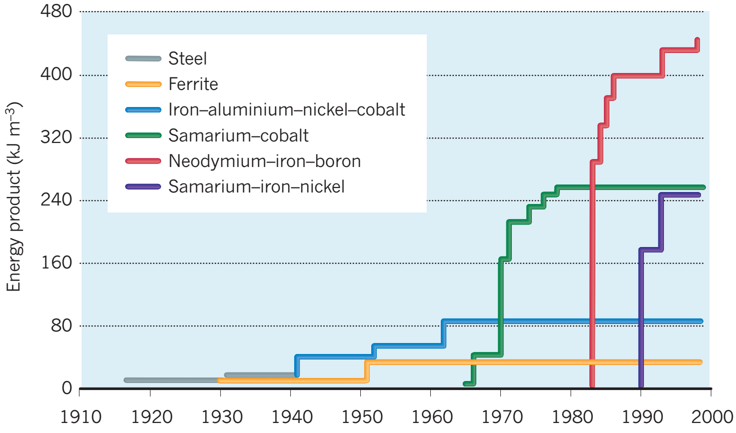
Sharply rising demand for neodymium–iron–boron magnets drove production up rapidly until 2007, but the global economic crisis caused a brief downturn.



SOURCE: W. T. BENECKI, T. K. CLAGETT & S. R. TROUT *PERMANENT MAGNETS 2010–2020* (2010)

STALLED PROGRESS

For most of the twentieth century, the strength of magnets jumped up every decade or so, with the introduction of new materials. The improvement has now slowed, but researchers hope to make the next leap soon.



SOURCE: O. GUTFLEISCH *ET AL. ADV. MATER.* **23**, 821–842 (2011)

In 2006, a team led by Ping Liu, a physicist at the University of Texas at Arlington, pioneered a manufacturing method that used steel balls to grind up magnetic material with the desired crystalline structure in a solution containing detergents. “I had postdocs working for years on this before we got a publication,” says Liu. “They hated me.” The soap lets the team produce nano-sized grains that don’t adhere to each other but do keep their magnetic properties. Hadjipanayis is using the same technique, and says that in the past year he has made grains as small as 2.7 nanometres.

Even more difficult is making a bulk magnet out of these grains. One standard technique — pressing the grains together and heating them to 800–1,000 °C — causes them to diffuse into each other, so they become too big to create the cooperative nanocomposite effect. Another method — using polymer glues to bind the grains — dilutes the magnetic material.

There are alternatives. Hadjipanayis plans to charge one set of nanoparticles positively and the other negatively, so that electrostatic attraction binds them together. Liu’s group squeezes about half a gram of the nano-grains in a press for 30 minutes instead of the standard half a minute. He also adds a bit of warmth (about 500 °C) to help them deform, but not so much as to ruin them. Using this method, Liu has managed to make relatively strong, dense magnets, but the grains aren’t magnetically aligned, so the magnets are still weaker than a standard NIB one.

> “YES, IT IS AMBITIOUS, BUT THAT’S EXACTLY WHY WE NEED TO BE DOING IT.”

Alignment is the final hurdle. Liu’s group is trying to clear it by putting material through a second slow- compaction process, but is having limited success. The researchers are fiddling with the details, trying to hit on a recipe that works. “I hope it can be done before my retirement,” says Liu.

CORPORATE COMPETITION

Liu could be beaten by his competition before he reaches that deadline. The technology firm General Electric, headquartered in Fairfield, Connecticut, has been given a $2.2-million ARPA-E grant to pursue nanocomposites, and has beefed up its magnetics research team. The company, which started its experimental work in January, told *Nature* that it has a good way to make crystalline grains, but it wouldn’t give details.

Last December, the US Department of Energy released its *Critical Materials Strategy*, which outlines a three-part mission to deal with shortages in rare-earth elements: secure new supplies, promote recycling and conduct research into alternatives, such as next-generation magnets. This push toward stronger magnets is a welcome change with potentially big pay-offs, says Liu. According to his calculations, doubling the strength of a magnet in an electric car should improve the motor’s efficiency by about 70% — although that number could vary wildly depending on the design of the magnet and engine.

Although the United States seems to be making the most concerted push towards creating the strongest magnets, other nations have invested more money in general magnetics research, says Liu. China’s 5-year economic plan for 2011–15 includes a big boost — reportedly more than 4 trillion renminbi (US$610 billion) — for spending in seven ‘strategic emerging industries’, including energy systems, clean cars and new materials. Observers such as Hatch and Liu expect great things from the investment. Japan has invested heavily in magnet research for its high-tech industry, and has strong government–industry collaborations — although one of its largest centres for magnetics research is Tohoku University in Sendai, which was hit hard by the earthquake and tsunami in March (see *Nature* **471,** 420; 2011).

Last year, the European Union’s research-funding framework put out a €4-million (US$6.3-million) call for proposals from groups working to develop novel materials, with the goal of totally replacing rare earths. But most researchers say that this is massively overreaching. “This is a joke, scientifically,” says Liu of the quest to remove rare earths from strong magnets. Several major labs have had proposals rejected because they aimed simply to reduce the quantities of rare earths used in magnets, says Dominique Givord, a magnetics researcher at the Louis Néel Laboratory in Grenoble, France.

Researchers’ target of building next-generation nanocomposite magnets is, most admit, a long shot. “I know that this activity is becoming popular in the United States, but I feel that their goal is a bit too ambitious,” says Kazuhiro Hono, a magnetics researcher at the National Institute for Materials Science in Tsukuba, Japan. Givord agrees. “It is extraordinarily challenging,” he says. More realistic, he says, are attempts to make existing magnets a bit stronger and cheaper by altering their microstructures. In Japan, such efforts have helped to reduce dysprosium demand.

But Hatch, who has worked in the field for nearly two decades, says that next-generation magnets are worth the battle. “Yes, it is ambitious, but that’s exactly why we need to be doing it,” he says. “It’s time to put money behind it.” ■

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