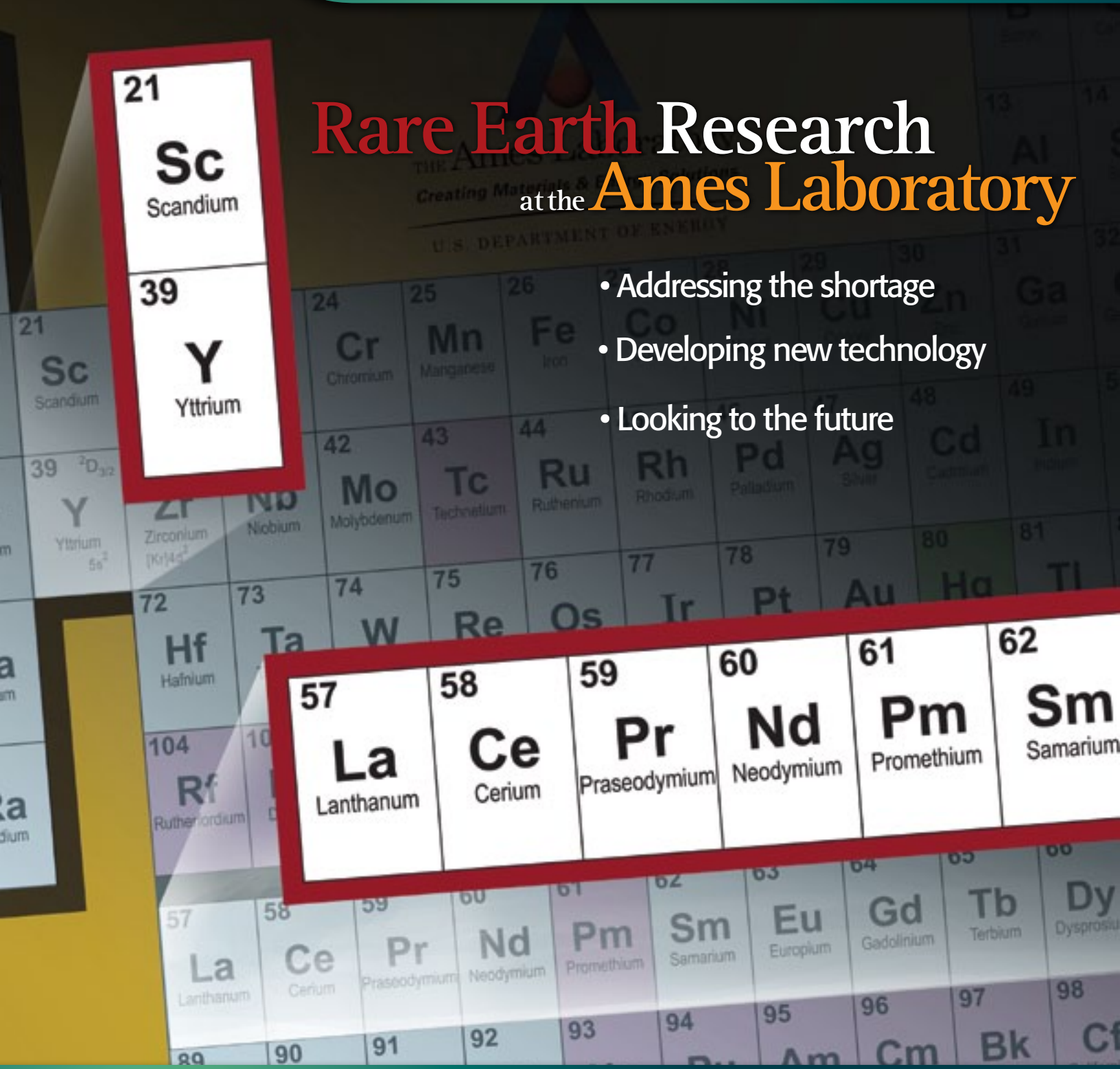
INQUIRY | 2010 ISSUE 2
SCIENCE & TECHNOLOGY AT THE AMES LABORATORY

Rare Earth Research at the Ames Laboratory

- Addressing the shortage
- Developing new technology
- Looking to the future



THE Ames Laboratory
Creating Materials & Energy Solutions
U.S. DEPARTMENT OF ENERGY

INQUIRY

The Ames Laboratory is a U.S. Department of Energy laboratory seeking solutions to energy-related problems through the exploration of chemical, engineering, materials and mathematical sciences, and physics. Established in the 1940s with the successful development of the most efficient process to produce high-purity uranium metal for atomic energy, Ames Lab now pursues much broader priorities than the materials research that has given the Lab international credibility. Responding to issues of national concern, Ames Laboratory scientists are actively involved in innovative research, science education programs, the development of applied technologies and the quick transfer of such technologies to industry. Uniquely integrated within a university environment, the Lab stimulates creative thought and encourages scientific discovery, providing solutions to complex problems and educating and training tomorrow's scientific talent.

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U.S. DEPARTMENT OF ENERGY | Office of Science

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Since its inception, the Ames Laboratory has been rooted in rare-earth research. The Lab's Materials Preparation Center is the world's leading supplier of research-grade, high-purity rare-earth samples. Take a look at what it takes to turn a rare-earth oxide into a top-quality sample.

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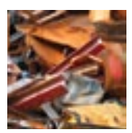

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Cover: *Rare-earth elements hold a special place on the periodic table*

From the Director

RARE EARTHS ARE SUDDENLY A BIG DEAL.

The Ames Laboratory has been a world leader in rare-earth science for most of its history, and our Materials Preparation Center has established itself as the preferred source of certified, research-grade, high-purity rare-earth samples to researchers around the world. The Ames Laboratory has maintained a capability in rare-earth science because of the unique properties of the rare earths, and it has delivered a steady stream of discoveries ranging from superconducting compounds, to alloys with special magnetic properties, and all the way to unique mechanical properties in intermetallic alloys.

Interest in any particular material is always cyclic, and it usually depends upon scientific discoveries or economic issues. The present interest in rare earths comes from a convergence of decades of scientific advances, emerging interest in green technologies and the economics of supply and demand.

The world's most powerful permanent magnets are now made from neodymium, iron and boron (sometimes with dysprosium, too), and these are used in wind turbines and the motors for hybrid and all-electric cars, along with smaller motors and transducers in a huge range of applications, including the microphones and speakers in our cell phones and other personal electronics. Efficient lighting, whether it comes from compact fluorescent lamps or light emitting diodes, depends on rare earths. LCD displays, light sensors, catalytic converters, advanced batteries and ultraviolet filtering glass all contain rare earths, too. A huge range of technologies that relate to renewable energy production or energy efficiency depends on the special properties of materials that contain rare-earth elements.

Rare earths are critical commodities in the effort to create a sustainable energy future, and the Ames Laboratory is a national resource in rare-earth science and technology.

If there is a green revolution going on out there, then one of its indicators is the demand for rare-earth materials. Big magnets in hybrid cars and huge ones in wind turbines are generating demands for tonnage amounts of neodymium that threaten to outstrip the world's available supply. The good news is that the world is building greater renewable power generating capacity and more hybrid vehicles. The bad news is that this may all be limited by the availability of rare earths. The rising price of neodymium tells you a lot about the world's progress toward sustainability, even though it is not the only commodity that is impacted by the shift toward green technologies.

Despite the name, rare earths are not actually all that rare in the crust of the earth, but they are hard to extract in an economic and environmentally appropriate manner. Richer ores make the task easier, and while demand and prices were low, the mining of rare earths became largely a monopoly of organizations that had access to higher concentrations and less severe environmental regulations. Almost all of the world's supply of rare earths now comes from China, but China does not have the capacity to meet the demand that is projected for the coming years. Prices are rising, and people are asking what can be done to allow the sustainability trend to proceed.

In some ways, we're the victim of our own success. The Ames Laboratory arguably helped to create this crisis by inventing some of the rare earth-based materials that are now in high demand, and also through assisting other labs in their work by providing them with rare earths to sustain their research. Now we are working on a range of projects that aim to increase the supply of rare earths, through improved extractive technologies and recycling, and to reduce the demand, by developing new magnetic materials that use less rare earths, or even none at all. Read on to find out how.

Alex King, Director

BRYDEN AND MCCORKLE WIN R&D 100 AWARD

The Ames Laboratory won a 2010 R&D 100 Award for osgBullet, a software package that creates 3-D, real-time computer simulations that can help engineers design complex systems, ranging from next-generation power plants to highly efficient cars and tomorrow's video games.

The R&D 100 Awards, sometimes called the "Oscars of invention," salute the 100 most technologically significant products introduced into the marketplace over the past year. The 2010 R&D 100 Award marks the 18th won by the Ames Laboratory. Lead scientists on the project are Mark Bryden, program director of Ames Laboratory's Simulation, Modeling and Decision Science research program and an associate professor of mechanical engineering at Iowa State University, and Doug McCorkle, associate scientist with both Ames Laboratory and ISU's Virtual Reality Applications Center. Co-developers of osgBullet sharing the R&D 100 Award include the U.S. Army Armament Research, Development and Engineering Center, Rock Island, Ill.; U.S. Department of Energy's National Energy Technology Laboratory, Morgantown, W. Va.; the U.S. Department of Energy's Idaho National Laboratory, Idaho Falls, Idaho; and Skew Matrix Software, Louisville, Colo.

The osgBullet software tool integrates highly detailed 3-D drawings with physics engines. This enables engineering to design in a real-time computed environment. According to Bryden and McCorkle, "osgBullet allows engineers to play 'what if?' games" during the design process – changing materials or trying different parts – all in a virtual environment, in precise detail and very quickly.

Mark Bryden

Doug McCorkle

AMES LABORATORY SCIENTISTS WIN NATIONAL TECHNOLOGY TRANSFER AWARDS

Three Ames Laboratory scientists received national Excellence in Technology Transfer Awards from the Federal Laboratory Consortium.

Iver Anderson, Ames Laboratory senior metallurgist, won for a lead-free solder alloy with wide industry acceptance. Mark Bryden, program director for Ames Laboratory's Simulation, Modeling and Decision Science program, and Doug McCorkle, Ames Laboratory associate scientist, along with scientists at the National Energy Technology Laboratory, won for VE-PSI, a virtual engineering process simulator software.

According to the FLC, the Excellence in Technology Transfer Award "recognizes science and technology employees in FLC laboratories who have accomplished outstanding work in the process of transferring federally developed technology. A panel of experts from industry, state and local government, academia, and the federal laboratory system judge the nominations."

Lead-free solder consists of a tin-silver-copper alloy that is a strong, durable, environmentally safe alternative to traditional tin-lead solder. This versatile, low-melting-point alloy is used for joining electronic microcircuits and electrical contacts and is Ames Lab's most successful technology to date. It is currently licensed to more than 50 companies worldwide and has generated more than $20 million in royalties.

Virtual Engineering Process Simulator Interface combines information about process simulation – data and models about chemical, physical and biological processes – with computer-aided design drawings and fluid dynamics data to create a comprehensive real-time graphic display of power plant designs. In the interactive virtual environment, engineers can analyze multiple aspects of a proposed power plant at the same time with the aim of optimizing the overall system.

In 2010, five Department of Energy technology transfer successes were selected for the national FLC award out of the 20 award winners selected from across all federal government research laboratories.

left to right: Iver Anderson, Mark Bryden and Doug McCorkle

"I am thrilled that our researchers have received national recognition from the FLC," says Deb Covey, Ames Laboratory's associate director for Sponsored Research Administration. "Having Ames Laboratory innovations as winners in two of the five of DOE's Excellence in Technology Transfer Awards is indicative of the Laboratory's commitment to the DOE and the U.S. taxpayer to provide new materials, techniques and instrumentation to help our economic growth, national defenses and the environment."

AMES LABORATORY NAMED AN INDUSTRY SAFETY LEADER

The Ames Laboratory has been named a 2010 Industry Leader Award winner by the National Safety Council. The Laboratory was one of only 81 organizations to receive the award for safety performance and the only DOE national laboratory on the list. The award represents the top 5 percent of members that have qualified for the National Safety Council 2010 Occupational Excellence Achievement Award, based on 2009 calendar year data.

"I'm pleased that the employees of the Ames Laboratory are being recognized by the National Safety Council for their safety efforts," says Tom Wessels, Ames Lab Environment, Safety, Health and Assurance manager. "We use continuous improvement efforts, documented processes, employee safety training, and a comprehensive assessment program to support our safety culture."

The NSC Industry Leader Award is one component of the NSC Occupational Award Program, which recognizes the outstanding safety achievements of NSC members. Winners are selected based on North American Industry Classification System code, lowest total incidence rate and employee work hours.

The Ames Laboratory was in the Professional, Scientific and Technical Services sector (NAICS code 54) that has between 100,000 and 999,999 employee hours. The actual number of employee hours without an incident at the Ames Laboratory for calendar year 2009 was 883,937.

The award was presented at the NSC Annual Awards Celebration that took place Oct. 5, 2010, in San Diego.

***Expert Driver Award** – Keith Schulke, property management delivery driver, received an Expert Driver Certificate from the National Safety Council. The certificate recognizes safe driving performance of those who drive an employer-owned vehicle as part of their regular daily work. Schulke was honored for "17 years of exceptional safe driving performance."*

HONG AWARDED FOUNDERS' MEDAL

Mei Hong, Ames Laboratory scientist and Iowa State University professor of chemistry, was awarded the 2010 Founders' Medal from the International Council on Magnetic Resonance in Biological Systems (ICMRBS). The medal was presented to Hong at the ICMRBS conference in Cairns, Australia, in August. The award carries a $3,000 honorarium.

Mei Hong

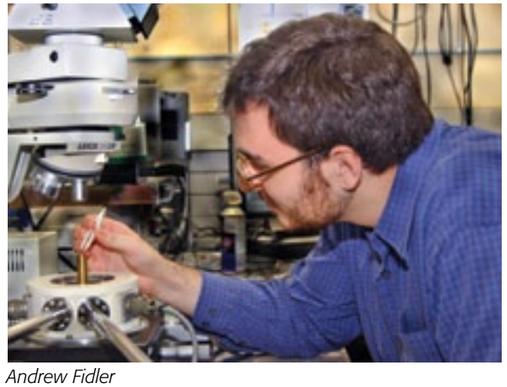
The Founders' Medal recognizes exceptional contributions by young scientists to the development and/or progress of the field of magnetic resonance in biological systems. ICMRBS noted Hong's outstanding achievements in solid-state nuclear magnetic resonance.

Matt Besser: Iowa State University Professional and Scientific Excellence Award
Iver Anderson: ISU Award for Achievement in Intellectual Property
Pat Thiel: ISU College of Liberal Arts and Sciences Institutional Service Award and ISU College of Liberal Arts and Sciences Master Teacher Award
Carol Streit: CYtation Award by the ISU Professional and Scientific Council
Charles Zaruba: ISU College of Liberal Arts and Sciences P&S Award for Excellence in Information Technology
Michael Schmidt: ISU College of Liberal Arts and Sciences P&S Research Award
Edward Yu: ISU College of Liberal Arts and Sciences Award for Mid-career Achievement in Research
Tom Barton: ISU Award for Achievement in Economic Development in Iowa
Bill Sears: DOE Cyber Security Award for Innovative Achievement in Collaboration

FORMER SULI STUDENT RECEIVES GRADUATE FELLOWSHIP

Andrew Fidler, a former student in the Ames Laboratory's Science Undergraduate Laboratory Internship (SULI) program, has been awarded a prestigious Department of Energy Office of Science Graduate Fellowship award. Fidler was one of only 150 students to receive the award, which provides $50,500 per year for up to three years to support tuition, living expenses, research materials and travel to research.

Fidler was an intern at the Ames Laboratory in 2007, where he worked under the guidance of mentor, Ames Lab physicist Ruslan Prozorov. Fidler's 10-week internship at Ames Lab resulted in a co-authored paper entitled, "Suprafroth in type-1 superconductors," which was published in the prestigious journal, *Nature Physics*. Following his internship at the Ames Lab, Fidler was accepted into graduate school at the University of Chicago, where he continues to pursue graduate studies in physical chemistry. Following his studies, he plans to pursue a tenure-track faculty position.


Andrew Fidler

Ames Laboratory's

"Mr. Rare Earth" Speaks Out

Karl Gschneidner's message is simple. If America is to retain its economic and strategic competitiveness, it must regain its leadership in rare-earth technologies.

BY MARK INGEBRETSEN

WHEN AMES LABORATORY SENIOR METALLURGIST Karl Gschneidner Jr. speaks, people listen – all the way up to the halls of the U.S. Congress. In March, Gschneidner took his message about the importance of rare-earth elements to the Investigations and Oversight Subcommittee of the House Committee on Science and Technology and helped ignite a whirlwind of publicity around an issue few Americans were even aware of beforehand.

Speaking to the committee alongside other U.S. rare-earth experts from industry and academia, the point of Gschneidner's testimony was both prescient and timely. In the coming decades, he said, virtually every technology vital to America's defense and economic well being will make use of rare-earth elements. That's because rare-earth elements are essential to everything from the magnets that power electric motors to the precision optics used for military lasers.

Losing an industry and the knowledge base that goes with it

Maintaining a leadership position in rare-earth technologies might not seem like much of a challenge when you learn that many rare-earth technologies were actually pioneered in this country and often at the Ames Laboratory itself. In fact, Ames Lab's expertise in processing exotic materials, such as rare earths, goes back to the facility's earliest days, during World War II. It was then that scientists, engineers, university students and others figured out how to refine tons of weapons-grade uranium, when previously only minute sample quantities had been refined.

But despite those early successes and many subsequent American improvements in the way rare earths were refined and utilized over the years, the industry, which Gschneidner estimates is worth more than $4 billion, shifted to China. Some cite the aggressive pricing policies by Chinese mining and processing operations for the industry's migration to that nation's shores. What is undisputable is that China today controls more than 95 percent of the rare-earth supplies and nearly all rare-earth refining.

And that fact has alarmed those concerned about America's national security and the environment. In the military, rare-earth elements are vital to precision-guided munitions, lasers, communication systems, radar systems, avionics, night vision equipment and satellites, according to a recent Government Accountability Office report. Moreover, rare earths are essential to the success of green technologies.

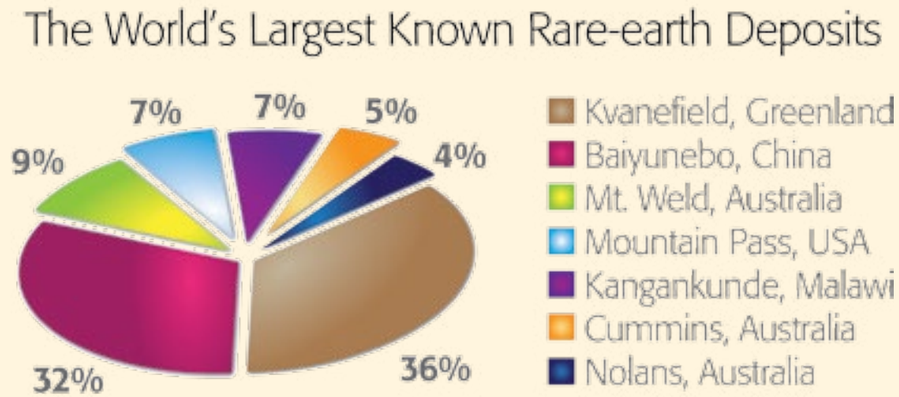
Gschneidner's Ames Lab colleague, senior metallurgist Iver Anderson, notes, for example, that a single new generation windmill capable of producing three megawatts of electricity requires 1,500 pounds of the rare-earth element neodymium. Similarly, each Toyota Prius hybrid car requires 6.5 pounds of neodymium for its electric motor.

Karl Gschneidner Jr.

In addition, many of today's prized consumer goods wouldn't exist without rare earths. Or as Ames Lab senior scientist Bill McCallum puts it, "Rare-earth materials are essential to life as the modern American teenager knows it, with applications in MP3 players, computers, cell phones and visual display technology."

Far more serious is the fact that because the U.S. rare-earth industry has been all but extinguished, many talented scientists and engineers have largely turned their attention elsewhere. The result is that "rare-earth research in the United States on mineral extraction, rare-earth separation, processing of the oxides into metallic alloys and other useful forms, substitution and recycling is virtually zero," Gschneidner told the House subcommittee. What is needed, he said, is a plan to develop and train a new generation of scientists and engineers adept at working with rare earths.

The message was especially well received, given the source. Gschneidner is one of the few scientists who steadfastly carried on with rare-earth research when others focused on other fields. Working with small groups of colleagues, he continued to pioneer advancements in rare-earth-dependent technologies. With help from fellow researcher Vitalij Pecharsky, a senior scientist at Ames Lab, for example, Gschneidner advanced one of the most promising uses of rare-earth materials, magnetic refrigeration, a green cooling method that relies on the magnetocaloric effect exhibited by the rare-earth element gadolinium and water instead of ozone-depleteing gases. Magnetic refrigeration if adopted could significantly reduce world energy consumption.



source: australianrareearths.com

The magnet that attracted the world's attention

To dramatize the critical importance of rare-earth technologies, Gschneidner showed House subcommittee members a quarter-sized permanent magnet containing neodymium that he and Ames Lab principal scientist emeritus Rick Schmidt developed.

While high-strength permanent magnets composed of neodymium, iron and boron ($Nd_2Fe_{14}B$) were simultaneously discovered nearly three decades ago by researchers at General Motors in the United States and at Sumitomo Special Metals. Co. Ltd. in Japan, Gschneidner and Schmidt recently devised a new process for creating the magnets that holds the promise of being cheaper and more environmentally benign than the methods currently used. The so-called Schmidt-Gschneidner process might even succeed in returning the permanent magnet industry back to the United States. Soon after Gschneidner's testimony, photos of the pair's matte-black magnet were published on blogs, technical magazines and other media outlets throughout the world (see page 14 for more details).

Gschneidner's ceaseless focus on new and innovative rare-earth research has prompted some to call him "Mr. Rare Earth," while a long list of publications heard his plea for more research in rare earths. In the weeks following his testimony, the Ames Lab scientist was interviewed by the *Wall Street Journal*, while the *New York Times, Popular Mechanics* and the *Huffington Post*, and many technical media outlets published his views.

Even the House subcommittee followed up Gschneidner's appearance with a list of additional questions. And thanks to the publicity he generated, bloggers worldwide soon weighed in on the subject. Some commentators equated America's dependence on China for rare earths to the nation's reliance on the Organization of Petroleum Exporting Countries (OPEC) for its petroleum. And virtually all appeared to agree with Gschneidner that some sort of plan or program was needed to ensure America had access to the rare-earth materials it needed and the knowledge to use them in efficient and innovative new ways.

As Gschneidner himself told the House subcommittee in a letter requested as a follow-up to his testimony: if the United States is to have a significant manufacturing role in the technologies and products that rely on rare earths, "it is essential that we play a leading role in the development of new techniques for the efficient production of rare-earth materials from the available resources and technologies, which maximize the benefit derived from the rare-earth content for a given application, and lead in the development of new rare-earth processes and applications."

BY KERRY GIBSON

THE ROOT OF Rare-earth RESEARCH

The Ames Laboratory's Materials Preparation Center is the source for research-grade samples

Rare-earth metals, oxide powder and fluoride crystal.

RARE-EARTH METALS PLAY A CRUCIAL, BUT LARGELY hidden, role in most of the technological breakthroughs of the past 30 years. You'll find them in all types of electronics and virtually anything with an electric motor, including electric-powered cars and the generators in wind turbines. They are also the "metal" in nickel-metal-hydride batteries found in hybrid cars and cordless power tools.

So just what are rare-earth metals? The name commonly applies to 17 elements on the periodic table that include scandium, yttrium and the lanthanides, as highlighted in the periodic table on *Inquiry's* back cover. None of these chemically similar elements exist naturally on their own, but are mined as comingled oxides in minerals, such as bastnasite and monazite.

Rare-earth metals are typically used in combination with other metals to create alloys with enhanced properties not found in the individual components. Neodymium, for example, when combined with iron and boron, creates an alloy with very strong magnetic properties.

At the research forefront

When it comes to studying and producing ultra-high purity rare-earth materials, the Ames Laboratory is the world-recognized leader. The work began in the 1940s when Frank H. Spedding and his colleagues developed the ion-exchange process, a technique that separates the "fraternal fifteen" plus yttrium and scandium.

That pioneering work and further rare-earth research efforts led to a constant demand for samples from the Ames Lab from research groups around the globe. To better serve the scientific community's demand for research materials, the Materials Preparation Center was formed. The MPC is a DOE, Office of Science, Office of Basic Energy Sciences, Division of Materials Sciences & Engineering specialized research center that's recognized throughout the worldwide research community for its unique capabilities in the preparation, purification, single crystal growth, and characterization of rare-earth metals, alkaline-earth metals, and refractory-metal materials. MPC operations are primarily funded by the DOE's Materials Discovery, Design, and Synthesis team's Synthesis and Processing Science core research activity.

Established in 1981, the MPC is a one-of-a-kind facility, which is acutely sensitive to the needs of researchers. Providing research and developmental quantities of high-purity materials and unique characterization services to scientists at university, industry and government facilities on a cost-recovery basis, the MPC allows access to novel materials as they are developed.

The MPC is renowned for its outstanding technical expertise in alloy design, creating materials that exhibit ultra-fine microstructures and high strength and high conductivity — properties of great potential value to American technology. The MPC also has established a reputation for close interaction with its clients, providing personalized service to meet each client's individual needs. Each year, the MPC satisfies hundreds of requests for customized materials and services that are unavailable from commercial suppliers and unmatched in quality anywhere else in the world.

Purity is key

In order for researchers to get an accurate picture of the properties of a particular alloy, it's essential to start with the best possible materials.

"Impurities can cause all kinds of problems," says Trevor Riedemann, an Ames Laboratory scientist and manager of the MPC's rare-earth materials section. "We've seen a number of cases where competing research groups have seen very disparate properties because the experimenters used different grades of rare-earth materials."

Producing such high-purity rare-earth metals on a research scale requires a multiple-step process that's basically unchanged from the 1940s. Using the best rare-earth oxides available, the oxides are first converted to their respective fluorides by exposing them to hydrogen-fluoride gas. These rare-earth "salts" are packed with purified calcium in tantalum crucibles. Tantalum is used to minimize contamination that would occur if ceramic crucibles, such as alumina or zirconia, were used. All the preparation steps take place in highly controlled environments, such as an argon gas-filled glove box, to prevent oxidation.

The reduction process is driven by an induction furnace. During the reduction process, when the rare-earth fluoride salts and calcium melt, from 1500 to 1800 degrees Celsius (2732 to 3272 degrees Fahrenheit), the calcium bonds with the fluoride, leaving the rare-earth metal. Depending on the specific rare-earth metal being refined, additional steps, such as vacuum casting, sublimation or distillation, are used to purify the metal.

"Gadolinium, terbium and lutetium are more difficult to refine," Riedemann says, "because they eat tantalum (the crucible material) for lunch. So we have to take additional steps to remove the tantalum that leaches from the crucible."

Once the materials are refined, they're stored in a controlled environment to prevent oxidation. Depending on what's needed, the MPC can provide the raw, rare-earth material, or produce specific alloys that researchers at the Ames Laboratory and other labs around the world might require. In the 2009 calendar year, the MPC provided research materials to clients throughout the United States, as well as Australia, Austria, Canada, Demark, France, Germany, Italy, Japan, Korea, the Netherlands, Singapore, Spain, South Africa, Switzerland, and the United Kingdom.

Ames Lab technician Ross Anderson prepares to refine lanthanum by packing a tantalum crucible with lanthanum fluoride crystals and purified calcium in an argon-filled glovebox.

The tanatlum crucible (left) is placed inside a second "heater can" crucible (right) that is wrapped with a graphite jacket. The assembly is then placed in an induction furnace.

The crucible assembly is placed inside a quartz tube that in turn is placed within an induction coil. Electrical current applied to the coil then heats the lanthanum and calcium.

As the temperature rises, the material inside the crucible begins to glow. Depending on the rare-earth metal being used, the rare-earth fluoride and calcium melt between 1500 and 1800 degrees Celsius, at which point the calcium bonds with the fluoride, leaving the purified rare-earth metal.

Calcium-fluoride salts (black crystals) formed during the reduction process are separated from the rare-earth metal.

Where Do We Go from Here?

Experts weigh in on current challenges and future opportunities for rare earths

BY BREEHAN GERLEMAN LUCCHESI

WHEN IT COMES TO RARE EARTHS, THE PROBLEM seems clear: the United States faces a shortage of materials that are important for many technologies. But a variety of perspectives and approaches — from both scientific institutions and industry — will likely be needed to address the challenges that lie ahead.

So, *Inquiry* invited senior scientists at the Ames Laboratory and the chief executive officer of Molycorp Minerals, an industry leader in rare earths, to weigh in on the current situation and their vision for the future.

WHY ARE RARE EARTHS IMPORTANT?

Alan Russell, Ames Laboratory associate scientist: The general public and even U.S. policy makers probably don't think of rare-earth materials as vital strategic materials. But, if they all suddenly vanished overnight, the loss would be devastating. Rare-earth elements are pervasive in modern engineering systems. They are essential to efficient operation of hybrid cars, computer hard disk drives, magnetic resonance imaging systems for medical diagnosis, audio and communications equipment, and in electric motors for manufacturing and transportation.

Bill McCallum, Ames Laboratory senior scientist: Rare earths really are in a lot of the technologies we enjoy today – things as everyday as cell phones and laptop computers and LED and compact fluorescent lights. And rare earths are important if we want to make progress in new technologies.

Mark Smith, chief executive officer of Molycorp Minerals: Yes, the list of rare-earth dependent technologies is long, more than most people understand. That is particularly true in green technologies. For example, the next generation of 3 megawatt wind turbines, which use permanent magnet generators, require about one ton of neodymium-iron-boron magnets. Hybrid electric, plug-in hybrid electric and all-electric vehicles require rare earths to work — and significant amounts at that. In general, hybrid vehicles use approximately 10-15 kilograms of rare earths each.

Another area that is getting increased attention in Washington, D.C., is the number of critical defense and homeland security technologies that don't work without rare earths. A recent report by the U.S. General Accounting Office highlighted three key findings that got a lot of attention in policymaking circles: a "wide variety of defense systems and components … are dependent on rare-earth materials for functionality"; rare earths in military technologies "would be difficult to replace without losing performance"; and several rare earths have "already caused some kind of weapon system production delay." Those findings certainly underscore the critical importance of rare earths for the future of our nation.

Karl Gschneidner Jr., Ames Laboratory senior scientist: Rare-earth magnets are in use in every computer system in the world. And every weapons system in the United States depends on computers. What happens if all our weapons systems are dependent upon a rare-earth supply from China? What will the future look like then?

From a scientific standpoint, rare earths are important because they are so unique. It's not as easy as just finding substitute materials for rare earths' uses. Rare earths' properties are hard to replicate or replace. For instance, europium was discovered many years ago, and people have been looking to replace it for 50 years and haven't been able to.

WHAT'S THE CURRENT STATUS OF RARE-EARTH RESEARCH AND PRODUCTION IN THE UNITED STATES?

Russell: Rare-earth research is ongoing, particularly here at Ames Laboratory, but there is a problem: no major funding source specifically focuses on research on these materials. This seems odd in light of the major push to develop alternative energy generation and utilization technologies. Rare-earth elements are vital to many of these technologies.

Smith: There is no question that we've allowed support in the United States for rare-earth research and production to deteriorate. And it is a situation that needs to be reversed, and soon.

When you consider how important and ubiquitous rare earths are in so many advanced technologies — from renewable power generation to hybrid and electric vehicles to advanced communications to military systems — the lack of rare-earth research and development is both surprising and disturbing. I have yet to find a single university in the U.S. that offers students an undergraduate or graduate level course specific to rare-earth development or application research — not a single one. In sharp contrast, China has thousands and thousands of scientists and researchers who focus on rare-earth research and development and applications deployment.

When Molycorp began looking five years ago for scientists and researchers with experience and background in rare earths, we could find virtually none. We had to hire bright, young scientists with no rare-earth experience and train them almost from scratch.

Essentially, we unleashed these bright young minds, let them experiment and investigate and think outside of the box for several years. Now, that investment turned out to be very much worthwhile, as our research and development team has come up with truly breakthrough technologies and processes that we are now implementing at our Mountain Pass Rare Earth Facility. But it was a sobering experience to learn how thin America's rare-earth research "bench" has become. [*Editor's note: Read about Ames Laboratory's efforts to educate a new generation of rare-earth experts on page 19.*]

Russell: I think the lack of emphasis on rare-earth research is partially the fault of scientists for failing to explain to policy makers the importance of the rare-earth elements in many technologies. For example, when one looks at a wind generator, the importance of the structural materials used for towers and blades is immediately obvious. Much less obvious is the

Iver Anderson, Ames Laboratory senior metallurgist and Iowa State University adjunct professor of Materials Science and Engineering

Karl Gschneidner Jr., Ames Laboratory senior materials scientist and Iowa State University Anson Marston Distinguished Professor, director of Ames Lab's Rare-earth Information Center from 1966 to 1996

Bill McCallum, Ames Laboratory senior scientist and Iowa Sate University adjunct professor of materials science and engineering, director of Ames Lab's Rare-earth Information Center from 1996 to 2002

Alan Russell, Ames Laboratory senior materials scientist and Iowa State University professor of materials science and engineering

Mark Smith, chief executive officer of Molycorp Minerals, a U.S. rare-earth producer and technology company

fact that each generator contains neodymium, and without the neodymium, the generator would be much heavier and less efficient. Similarly, discussions on hybrid cars tend to focus on the cars' fuel mileage, price, and performance while overlooking the fact that each Toyota Prius motor uses 1 kilogram of neodymium, and each battery requires 10 to 15 kilograms of lanthanum. And these numbers are expected to nearly double as newer, more fuel efficient versions of the car are introduced.

Smith: The good news is that I'm very optimistic that this trend of overlooking rare earths is about to reverse itself. Policy makers at the highest levels of our government are awakening to the critical role that rare earths play in our rapidly evolving "new energy economy" and to the fact that we have allowed ourselves to become much too dependent upon non-U.S. sources of rare-earth materials. Elected officials of both political parties are beginning to push policy initiatives across many areas of rare earths, and I think that this trend will result in increased support for rare-earth research and development in this country.

Gschneidner: I agree. Rare-earth research is picking up. Ames Laboratory probably does as much research on rare-earth materials as the rest of the United States put together. But rare earths are getting more attention lately, and our experience at Ames Lab is very beneficial to the discussion.

McCallum: For example, Ames Lab has scientists who are looking at the basic physics of rare-earth materials, and we have research in processing.

Iver Anderson, Ames Laboratory senior scientist: And I'd say that in the work of Larry Jones and the Ames Lab's Materials Preparation Center, we are working most on processing improvements and developing incrementally better ways to refine rare-earth oxides to produce the best metal. We're perfecting the steps in the process, but that still leaves the problem of whether there are some totally new routes to getting more efficiently to the end product. We have the potential to make that kind of breakthrough in the collapse of the processing steps, but that will need a dedicated study, not just the filling of a researcher's order. I think that the work of Rick Schmidt and Karl Gschneidner on new routes to rare-earth magnet alloys is a step in the right direction.

WHAT WOULD THE IDEAL FUTURE FOR RARE EARTHS IN THE UNITED STATES LOOK LIKE?

Gschneidner: Much more rare-earth research. I think one of the things we need in this country is a national rare-earth research center devoted to examining some of the critical scientific problems. This type of research would be applied, rather than basic. And it should include academic courses on rare-earth materials and separation processes. All types of rare-earth research might not be able to take place in one location. Instead, different laboratories and universities should focus on their strengths.

Russell: Yes, ideally the United States would establish a national center for both fundamental and applied research in the chemical, metallurgical, magnetic, optical and electronic properties of rare-earth elements. And the United States should restore its production capabilities for rare-earth elements.

Smith: In my view, the ideal future for rare earths in the U.S. involves three elements: alternative, non-Chinese sources of supply; a complete mine-to-magnets manufacturing supply chain on U.S. soil; and restoring the U.S. to a position of global leadership in rare-earth research, development and application innovation.

With regard to sources of supply, no entity should allow itself to become dependent on any single source. That is especially true of U.S. government agencies, such as the Defense Department. My hope is that we will eventually see several reliable sources of rare earths in North America. Molycorp may be the only U.S. producer of rare earths able to significantly ramp up production over the next several years. Our production will place the United States in a position of virtual rare-earth independence, given that our output will meet or exceed U.S. demand. But additional alternative sources of supply are going to be needed, particularly as the green technology revolution continues to grow.

We also need to deploy in this nation a complete mine-to-magnets manufacturing supply chain. Fortunately, Molycorp is on track to deliver this to the U.S. as well, and in only two years. The key to success in this regard is to keep processing and manufacturing costs low — at a level that can compete successfully against Chinese producers — and to partner or joint venture with those companies that have access to intellectual property related to rare-earth alloying and neodymium-iron-boron magnet manufacturing. Without such joint venture partnerships, no U.S. company will be able to make rare-earth alloys or magnets until at least 2014. Molycorp is positioned to succeed on both of these counts.

Anderson: I agree with Mark. We need to have a set of companies that are able to vertically integrate their operations from mining to final products, and this may take the form of

Rare-earth research is picking up. Ames Laboratory probably does as much research on rare-earth materials as the rest of the United States put together. But rare earths are getting more attention lately, and our experience at Ames Lab is very beneficial to the discussion. — *Karl Gschneidner, Ames Laboratory senior scientist*

several companies banding together into a partnership. It could be one company grabbing a hold of all the process steps. But I think it's going to be through vertical integration that we can get at least to the highest value-added stage that it becomes profitable. That's really what's going to be important. And we could follow that one step further to go from the magnets now and later, an exclusive deal with a motor manufacturer or an engine manufacturer. Those would be great. Can we vertically integrate to that step? It's certainly what the Chinese are trying to do. But we have all the technology here in the United States. The companies have to organize themselves. I think that makes the most sense to me.

McCallum: If we want to have the good jobs here manufacturing products that contain rare earths, we have to have our own supplies. As I understand it, a major problem at the current time is the cost of setting up a rare-earth operation where you are actually producing metal.

If we scientists can do research and increase the efficiency of things like separations, then the capital requirements go down and we have a better chance of getting where we need to be.

WHAT WILL IT TAKE TO ACHIEVE THE IDEAL FUTURE FOR RARE EARTHS IN THE UNITED STATES?

Smith: I would say four things are necessary to achieve an ideal future for rare earths in our nation. Three of those are areas on which Molycorp is focusing intensely. One, we need to establish alternative, non-Chinese sources of rare-earth supplies. Two, we need to establish a complete, domestic mining-to-magnets manufacturing supply chain that utilizes new technologies that can keep U.S. rare-earth materials costs competitive with any producer in the world. Three, we need to explore economic paths to rare-earth recycling. Four, we need to significantly ramp up support for basic and applied rare-earth research and development, including reestablishing rare-earth-specific curricula in our colleges and universities.

Molycorp is on track to deliver to the nation solutions on items one through three. Item four will require action by the U.S. Congress and the presidential administration and coordinated initiatives by the private sector, academia and research institutes. I am optimistic that the United States will succeed in achieving all four of these objectives.

Gschneidner: Mark's right. Rare-earth research and development at national laboratories and universities needs support. Money. Simple as that. And it's an investment that's vital to the United States. Only 5 percent of rare earths used today come from elsewhere than China. That's a real monopoly.

Russell: It has sometimes been said that Americans aren't particularly good at anticipating problems, but they are remarkably effective at responding to problems (think Pearl Harbor). If that is true, perhaps the impending shortages and price spikes in the global rare-earth marketplace will catalyze establishment of a national rare-earth research center. The United States already has many national targeted research centers. Perhaps the time will soon come to establish a national center for rare-earth research in the United States. It could serve to coordinate research on rare-earth production, recycling, fundamental science and technology development. China has had such a center for decades.

Anderson: If we organize a center here at Ames Laboratory or elsewhere that's a start. But what scientists would really like to have is some competition, somebody who has a slightly different viewpoint and a slightly different pathway. And you're trading results.

If we are going to retain a lot of our rare-earth knowledge here in the United States, we are better off with some peer groups that are capable of reviewing the work we're doing and maybe to have their own work going as well. I'd like to see at least a second center and maybe even a third rare-earth research center. So, now we're talking about some real money here, but that's a strategic investment by the country. I think science benefits from having competitive programs with different themes, and the study of rare earths is big enough and important enough that there's room for a lot of research.

DEVELOPING

Greener, Cheaper Magnets

BY MARK INGEBRETSEN

AMES LABORATORY SCIENTISTS HAVE COME UP WITH a new process to prepare neodymium-iron-boron ($Nd_2Fe_{14}B$) permanent magnets that has the potential to enable them to be produced economically in the United States. What's more, the Ames Laboratory process doesn't produce the environmentally unfriendly byproducts that result from traditional manufacturing methods.

"Neodymium-iron-boron magnets represent perhaps one of the most important uses of rare-earth elements," says Karl Gschneidner Jr., senior metallurgist at Ames Lab, who co-developed the process along with Rick Schmidt, principal scientist emeritus. "They're the most powerful magnets in the world." And they can be found in every computer and every hybrid and electric vehicle that rolls off an assembly line as well as a wide array of consumer, commercial and military products.

Little wonder. Permanent magnets make up a $4.1 billion global industry. Over the years, however, production of neodymium-based magnets has shifted to China and other low-cost-producing nations. The hope is that the new technology will help U.S.-based companies compete with these other nations on an economic basis.

The Schmidt-Gschneidner process leveraged know-how that had been amassed at the Ames Laboratory for more than half a century. Early lessons learned from the Lab's World War II role processing uranium were put to use by scientists researching rare earths. As breakthroughs at the Lab continued over the years, the scientific community began to view the Ames' facility as "one of the best places to be if you're researching rare earths," Gschneidner says. Now, fast forward to the early 1980s, when the discovery of $Nd_2Fe_{14}B$ magnets by U.S. and Japanese researchers set off a renewed flurry of related research at the Ames Lab and elsewhere.

Owing to their unique advantages of strength and durability, manufacturers began incorporating $Nd_2Fe_{14}B$ magnets into more and more products. The unfortunate tradeoff was an increase in the amount of unhealthy waste materials created as ever-larger amounts of neodymium for the magnets was being processed.

Indeed, the conventional refining process starts with the neodymium oxide, but goes through two steps in order to obtain the neodymium metal. Waste products are associated with both these steps, and they must be handled in an environmentally friendly manner.

In 2009, Ames Laboratory researchers began work on a greener process for refining neodymium. Instead of two steps, "it is a one-step process going from the neodymium oxide to the neodymium master alloy," Gschneidner explains, "and since the end-products are completely utilized, there are no waste materials to dispose of."

A green process with the potential to bring a greater share of the permanent magnet industry back to U.S. shores represents a major achievement in itself. But the greatest long-term benefit of the Ames Lab process may be yet to come. Gschneidner believes that "a modification of this process should enable us to prepare a lanthanum [element 57 on the periodic table] master alloy to produce lanthanum-nickel-metal hydride batteries, which are used in hybrid and electric vehicles."

A cheaper, greener battery for the world's growing fleet of hybrid vehicles could eliminate untold tons of carbon dioxide, and it's just the kind of industry needed to help ensure America's economic health for decades to come.

Karl Gschneidner Jr. , Ames Laboratory senior metallurgist, holds a neodymium-iron-boron magnet made using a new one-step refining process that eliminates waste products.

A cheaper, greener battery for the world's growing fleet of hybrid vehicles could eliminate untold tons of carbon dioxide.

Mining the Scrap Pile

BY BREEHAN GERLEMAN LUCCHESI

WHILE A SHORTAGE OF RAW RARE-EARTH materials available to the United States draws near, the number of rare-earth-containing products, such as cell phones and hybrid cars, appears to be ever growing. Scrap from the manufacturing of these consumer products contains some rare-earth material, and the products themselves are eventually discarded by their owners. So, could the United States create a new supply stream of rare earths by recycling them from industrial scrap and post-consumer products?

Perhaps. And scientists at the Ames Laboratory are working to improve rare-earth recycling processes.

"We'll be looking at questions of how you recover rare earths from a wide variety of mixed alloys, at the same time, at a reasonable price, without creating any additional hazardous waste," says Bill McCallum, a senior materials scientist at Ames Laboratory and part of a team evaluating rare-earth recycling.

The end goal may be developing an alternative to current rare-earth alloy separation processes, which start with an oxide form of rare-earth materials. Researchers will be looking to combine some processing steps so non-rare-earth elements can be separated from rare-earth elements in one continuous process.

"From a scientific standpoint, we look at the recycling problem and say it's something we ought to be able to do," McCallum adds. "Some of the economic factors are out of our control, but as scientists, we can examine and improve the processes. We can then determine their cost and have a starting point for improving economic viability of rare-earth recycling."

Ames Laboratory brings decades of previous rare-earth research to the challenges of rare-earth recycling. In fact, many rare-earth processing techniques currently in use all over the world were originally developed at Ames Lab.

"The Ames Laboratory has the ability to tap a considerable amount of knowledge that was gained in developing rare-earth processing," says McCallum. "We have reports, papers and records that other laboratories and researchers do not have access to. In addition, some personnel who are most familiar with the previous research are retired but are still available to consult. This will be true for a relatively narrow window in time. Thus, if we are going to address the rare-earth recycling challenge, the time is now."

The Ames Laboratory's research goals in the area of rare-earth recycling include developing a metallic flux process to recover rare earths in magnets, batteries and magnetic refrigerant; developing an efficient process for mixed materials not suitable for metallic flux processes; and modifying current processes to recover rare-earth elements from phosphors, lasers and optical materials.

Ames Laboratory brings decades of previous rare-earth research to challenges of rare-earth recycling. In fact, many rare-earth processing techniques currently in use all over the world were originally developed at Ames Lab.

"But, right now, regardless of whether materials come from discarded post-consumer items or industrial scrap, recycling rare earths faces some economic challenges," says McCallum.

For instance, in most consumer goods, like laptop computers or hybrid vehicles, the amount of rare earths in products is a relatively small part of the whole. So costs for dismantling a cell phone or a car are prohibitively high in comparison to the potential value of the salvaged rare earths.

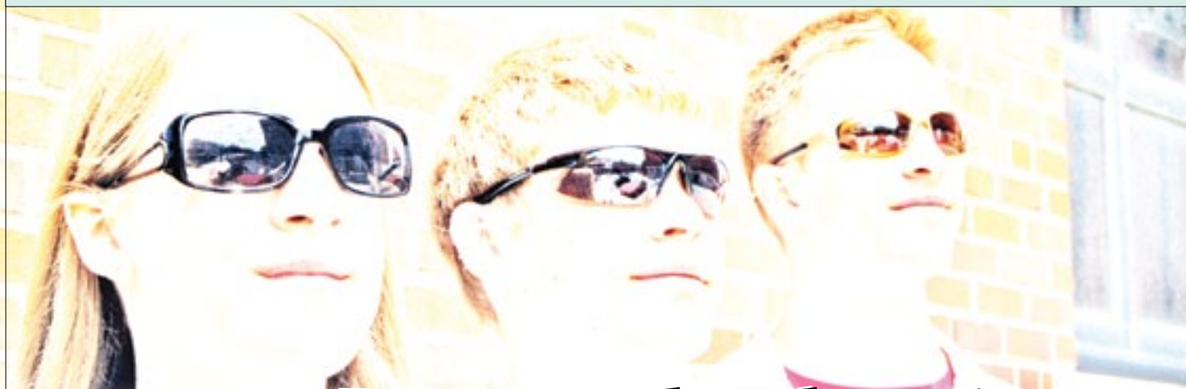
The relatively high cost of separating materials also holds true for manufacturing scrap created when rare-earth magnets are produced. Most current manufacturing processes result in some broken magnets and other scrap pieces, all of which contain alloys with high concentrations of rare-earth materials with some potential for recycling.

However, most magnet companies use the same production lines for many different grades of rare-earth magnets, which contain different concentrations of rare-earths. Manufacturers do not currently separate out scrap according to composition because it would introduce additional costs. The result is a mixture of scrap containing a fluctuating blend of alloys, making any potential recycling process difficult.

"Even if this mixed material is separated, the resulting material is not very usable in preparing new alloy because it is oxidized," said McCallum. "For now, it's cheaper to dump rare-earth manufacturing scrap in a landfill than to attempt to separate the scrap alloy, let alone attempt to separate out the rare-earth elements in the alloy for reuse."

But, as the volume of rare-earth materials in use in the United States and elsewhere grows and the supply of virgin rare earths dwindles, recycling discarded rare earths may become appealing and perhaps necessary.

"We know that if we can bring down the cost and increase the efficiency of rare-earth recycling, it will tip the balance toward increased recovery of rare earths," says McCallum.



The Future of Rare-earth Education Looks Bright

Students eager to become next generation of rare-earth scientists

BY STEVE KARSJEN

AMES LABORATORY HAS SEVERAL SCIENTISTS involved in rare-earth research. In fact, due to its large theoretical and experimental research base, the Lab probably does as much research on materials science and engineering, including rare-earths, as the rest of the United States put together, according to Karl Gschneidner Jr., Lab senior metallurgist and winner of the Frank Spedding Award, the top honor for researchers in the field of rare-earth science. So why would there be any concern about the future of rare-earth research and education at the Lab, or in the United States, for that matter? The answer has to do with longevity.

When you look at the Lab's leading rare-earth researchers right now, their average age is approximately 67 years old. That statistic is skewed somewhat by the ages of Gschneidner (79) and senior chemist and 2005 Spedding Award winner John Corbett (84). But even when not figuring in their ages, the average is around 61. Some scientists feel that's a statistic of mild concern.

"This is not a healthy situation for the long term," says 60-year old Alan Russell, Ames Laboratory associate and rare-earth scientist. Russell believes it's imperative there be a cadre of people at the Lab who understand the rare earths so that each time a new technology is under development, they can be called upon to answer key research questions. "Right now we have a fair number of people who can do this, but it's important that we support upcoming students to ensure that continues to be the case," Russell adds.

Russell supports one Ph.D. student who's involved in rare-earth research. Andrew Becker has been conducting research measuring the effect of elevated temperature on a yttrium-copper intermetallic compound. As an undergraduate in materials engineering, Becker says he found his niche at the Lab after listening first to one of Gschneidner's lectures on magnetic refrigeration and then by taking a class with Russell.

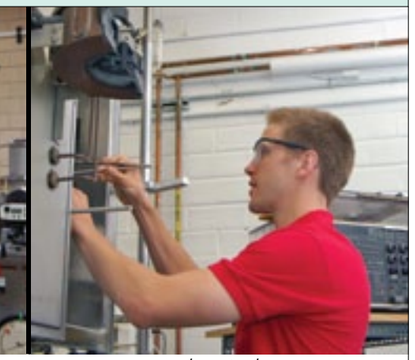
"Working with these two scientists, especially Dr. Gschneidner, who is so well known in the rare-earth field, has been a huge advantage," says Becker, who received his Ph.D. this summer and is continuing on at Iowa State University as a postdoctoral research associate. Following that, he hopes to find a position in academia that would potentially allow him to continue rare-earth research.

Most Ames Lab scientists agree the obvious key to attracting students is having outstanding projects upon which they can work. Their challenge has and always will be finding funding for research, whether it is fundamental or applied.

Karl Gschneidner

Katherine Ament

Nathaniel Oster



Andrew Becker

Alan Russell

The ebb and flow of rare-earth research funding is nothing new to Gschneidner, who has witnessed the ups and downs of the funding stream for most of the past 60 years.

Gschneidner was a graduate student at Ames Laboratory in 1952 and was mentored by none other than Frank Spedding, the Lab's first director and the person Gschneidner refers to as the "father" of rare earths. Spedding's rare-earth expertise was the catalyst for the creation of the uranium purification project at the Ames Lab for the Manhattan Project. Known as "Mr. Rare Earth" himself, Gschneidner earlier this year testified before Congress on the need for a national rare-earth research center in the United States that would cover most aspects of rare-earth research. The center would also be a catalyst for improving opportunities for student research on the rare earths.

That's good news to Katherine Ament, a Ph.D. student in Gschneidner's research group, who has spent the last year studying the magnetic properties of neodymium-iron-boron compounds in an effort to improve their strength. Upon graduation, she plans to take her rare-earth knowledge and use it to help find a job in industry. Like Becker, her introduction to rare earths was more of a chance happening. "I was looking for a 'different' type of project, and this one came up. It kind of fit, and I enjoy it," says Ament.

Ament believes the current national discussion on rare-earth research, production and education can only help lead to a greater number of student research opportunities at the Ames Laboratory and other DOE labs. "I don't think it's an obvious story yet, not in the classroom anyway, but there's certainly more interest than in previous years," she says. As a student, she also recognizes that the common denominator for future success hinges greatly upon government or private-sector funding available for both fundamental and applied rare-earth research.

Nathaniel Oster, a graduate student working with Ames Lab senior metallurgist Iver Anderson, hopes the current national discussion on rare earths will lead to a greater number of "practical research" opportunities, which has been his focus. Oster is currently studying rare-earth iron-boron magnets for applications in the auto industry, such as traction motors for hybrid or electric vehicles. "I'm "passionate" about having some type of impact on the energy sector," he says, and he believes more practical research opportunities will draw more students to rare-earth research. In addition to strong research opportunities, Oster believes students will also be drawn to opportunities to work with leading rare-earth researchers, such as those who work at the Ames Lab. Oster refers to the Lab's researchers as "the best rare-earth researchers in the world," and predicts their expertise and guidance eventually will help someone make a "huge" difference in the rare-earth research world.

Iver Anderson

"Students follow research opportunities," says Anderson. And in fact, he already sees new opportunities for student research that have been out of vogue for quite some time. "The extraction of rare earths was the focus of the Lab years ago, and I think we're now getting to the point in the development of rare-earth applications that it's time to take a second look at extraction and processing so we have the ability to reinvigorate that whole industry in this country."

Anderson goes on to mention numerous current rare-earth challenges, including the recovery and processing of used and scrap magnets. "I think there's a lot of room in the research angle of these subjects, and the key to interesting students is having researchers working on the problems," Anderson concludes.

Putting Their Experience to Work for Students

After a 15-year hiatus, the course, "Chemical and Physical Metallurgy of the Rare Earths" is once again being taught at Iowa State University, beginning in the 2010-2011 academic year. Ames Laboratory senior metallurgist Vitalij Pecharsky now teaches the course that was taught for many years by his colleague, Karl Gschneidner.

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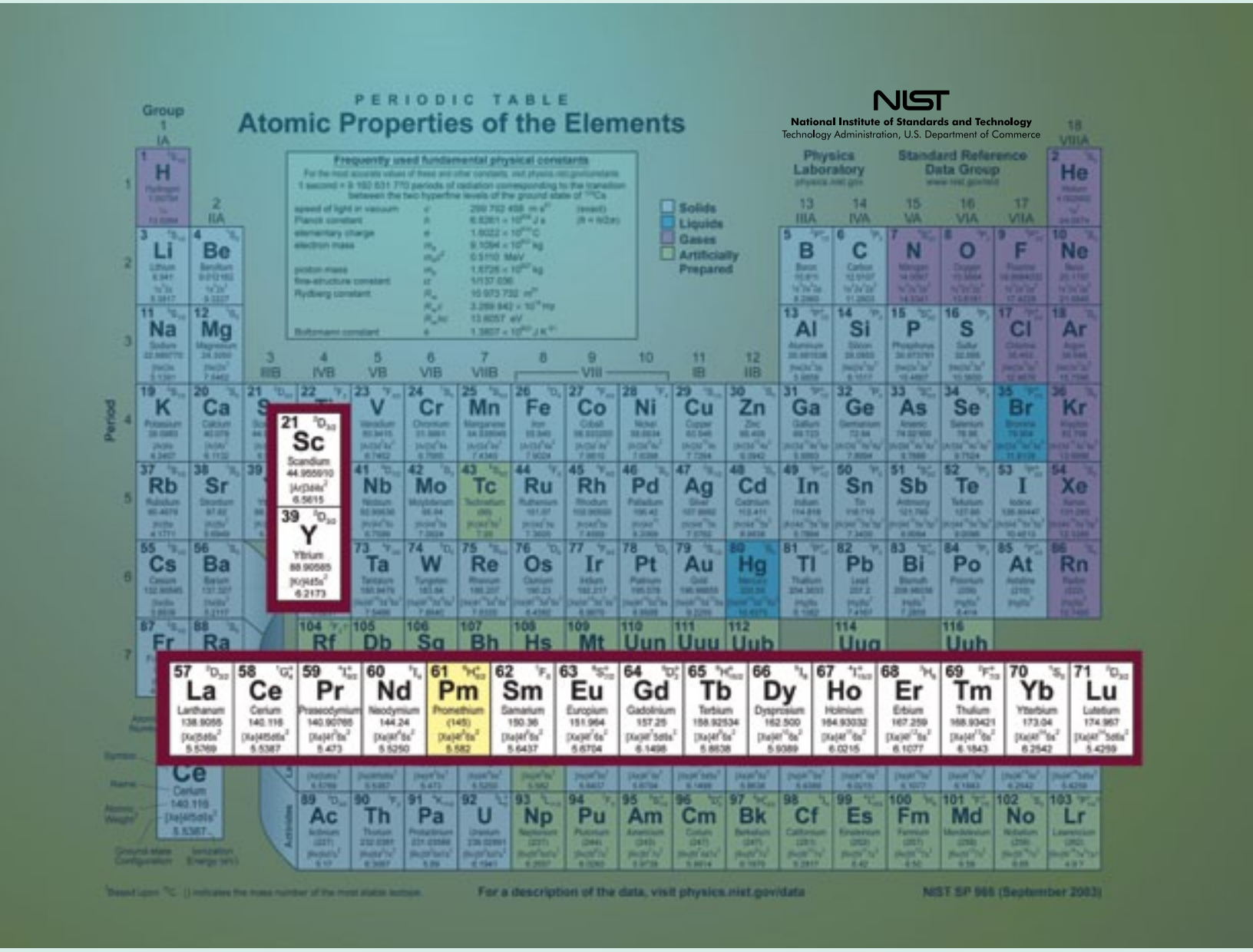

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