COLORADO SCHOOL OF MINES

RESEARCH

2018–19

MATERIAL MASTERY

By collaborating across disciplines, Mines scientists and engineers are developing solutions throughout the full spectrum of materials research, including discovery, extraction and characterization, on Earth and beyond.

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

Stefanie Tompkins is Mines' vice president for research and technology transfer. Prior to joining Mines in February 2018, she was acting deputy director of the U.S. Defense Advanced Research Projects Agency, where she spent the last decade in leadership and program management roles.

Developing solutions across the life cycle of resources

One extraordinary aspect of research at Mines is that it spans the full life cycle of many natural resources, be they mineral, water or energy, in any combination. This issue of our research magazine explores a range of research topics as they relate to that full life cycle—starting with discovery and characterization in the Earth's subsurface, to extraction, to transformation into useful materials and ultimately to reuse or recy[illegible] back to the earth. In each of these areas, our faculty and students are developing solutions to challenging global problems, such as:

- **Discovery of mineral resources:** Mines has been selected by the National Science Foundation to lead a new industry-university cooperative research center. The Center for Advanced Subsurface Earth Resources Models will develop tools to create three-dimensional subsurface geologic models of mineral deposits.

- **Safer, more effective mineral extraction:** Automation has immense potential to both enhance mine safety and increase mining efficiency. Researchers in mechanical engineering, computer science, mining engineering and other disciplines are combining advances in communications networks, artificial intelligence and human-robot interaction to map, navigate and someday extract ore with minimal risk. And, as important as safety and efficiency is the need to reduce the public health and environmental impacts of resource extraction. Mines faculty are working with researchers in Colombia, Peru and across Colorado to develop new techniques to improve the safety and sustainability of artisanal gold mining around the world.

- **Sourcing space:** Mines is bringing its traditional strengths to bear on the final frontier, working toward an infrastructure that will extract water and other resources from the moon, asteroids and more and allow us to expand our range in the universe.
- **Measuring the properties of materials:** Our modern world is entirely dependent on the materials (transformed from minerals) that make up everything from buildings to automobiles to electronics. Creating and characterizing new materials, across multiple length scales, is a critical and unique capability of Mines' newest research building, the CoorsTek Center for Applied Science and Engineering.

To close the circle on the life cycle of materials, at least from a technology perspective, Mines is working closely with our neighbors at the National Renewable Energy Laboratory to bring together world-renowned scientists and policy makers to explore technical challenges and solutions in getting to a "zero waste" economy, where all materials are fully recycled.

Our faculty and students continue to excel in many fields linked to this issue's theme and beyond, and we celebrate many of them throughout the magazine. Several new research awards illustrate the continued growth of Mines research in biological sciences and engineering. Mines' dominance in energy- and manufacturing-related research continues unabated, and several stories feature new projects in those areas (and in one case, both at once). This issue also details research related to software, to dissolving rocks and to the intersection of gender and mining with respect to Western coal.

The research portfolio at Mines is extraordinary, and in this issue of our research magazine, my first as vice president for research and technology transfer, I hope we convey even just a fraction of its diversity, depth and potential impact on the world.

Dr. Paul C. Johnson
President

Dr. Stefanie Tompkins
Vice President for Research and Technology Transfer

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Managing Editor
Mark Ramirez

Editor, *Mines Magazine*
Ashley Spurgeon

Contributing Writers
Joe DelNero
Electa Draper
Jenn Fields
Teresa Meek
Emilie Rusch

Photography
Agata Bogucka
Joe DelNero

Graphic Design
Wendy Kent
WKent Designs

Colorado School of Mines
1500 Illinois Street
Golden, CO 80401

303-273-3000 or 800-446-9488

research.mines.edu
mines.edu/news

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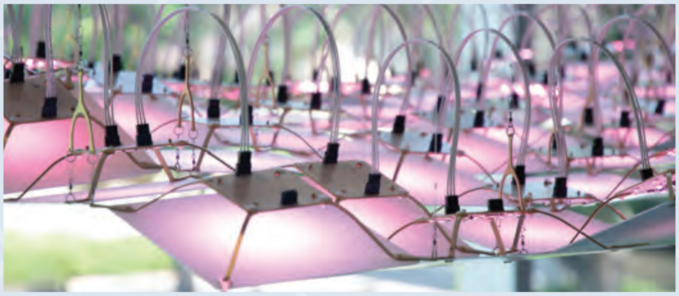
Bastnaesite, bottom, a rare earth fluorocarbonate mineral, is one of the predominant ore minerals in carbonatite-related deposits. At left is a rare earth oxide powder, an intermediate compound produced from bastnaesite ore via calcination and separation. Rare earth elements are found in the phosphorescent compounds that coat the inside of compact fluorescent lightbulbs. Mines researchers are working on advancements in each of these phases, from discovery and extraction to characterization and manufacturing, and more.

Special thanks to Cynthia Howell and Mandi Hutchinson of the Critical Materials Institute, geological engineering student Justin Lewis and the Colorado School of Mines Geology Museum.

FEATURES



Alexis Navarre-Sitchler

A new look at how rocks wear away

It's a discrepancy that has dogged geochemists for years—when researchers bring rocks back to the lab and measure how quickly they dissolve, the numbers don't match what they can see happening in the field.

In fact, it's an order of magnitude of six—rocks dissolve one million times faster in the lab than they do in the natural environment, said Alexis Navarre-Sitchler, associate professor of geology and geological engineering at Mines.

"My current working hypothesis is that when we take rocks from the field, we crush them up and put them in a beaker, so all of the surface area of the mineral is exposed. You don't have the same pore structure as you would in the field and the mineral is being bathed in water that's constantly being refreshed," Navarre-Sitchler said. "Think about it like a block of salt—if you want to dissolve all the salt, you'll be able to do it much faster if you crush it up than if you just put the whole block into the water."

"How the water actually flows through the rocks and that heterogeneity, the way the water gets through the rock, what those paths look like, how fast the water is moving might be responsible for this long-standing discrepancy between what we do in the lab and what we see in the field," she said.

Navarre-Sitchler has been awarded just shy of $600,000 in funding from the U.S. Department of Energy's Office of Basic Energy Sciences to take a new approach to that question. With the help of fellow Mines professors Jeff Squier and Brian Gorman, Navarre-Sitchler will use femtosecond lasers to develop small-scale experimental devices where researchers can gain understanding—on the individual pore level—of the flow of water and dissolution of minerals in rocks.

"We can't go to a watershed and map all of the pores, where all the water is going. We don't have X-ray glasses to do that or any technique that would allow us to go in and probe where the solutes are being formed and how fast," Navarre-Sitchler said. "What we want to try to do is gain information about how this works in small-scale systems where we can see it, then we can take that information and project it out to large-scale systems where we can't see it."

How small is small scale? The thin wafers of rock will be just one centimeter by two centimeters in size, and the channels etched into the surface tens of micrometers wide.

Imaging will be done in a couple of ways, with normal light microscopes and a fluorescence technique that will allow researchers to map the chemistry of the water and how fast the water moves through the device via time-lapse photos.

"Rock weathering is part of the engine that drives the rock cycle. Weathering breaks rocks down so that soil can form and sediments or nutrients can be transported to the oceans," Navarre-Sitchler said. "Knowing more about this important process helps us understand how Earth's near-surface environments evolve and how they will respond to perturbations in the future."

Turning algae into a fuel source

A Mines professor is part of a team that has been awarded $8 million over five years by the U.S. Department of Energy to engineer a particular strain of alga to produce renewable biofuel.

Nanette Boyle, assistant professor of chemical and biological engineering, will receive $616,000 over the next five years for her part in the project, which is to create a genome-scale metabolic model of the algae—*Chromochloris zofingiensis*—and use it to predict how carbon is directed through its metabolism and what genetic changes will lead to increased production of lipids, which can then be extracted and converted into biodiesel.

"I will also be performing isotope-assisted metabolic flux analysis to quantify carbon fluxes in the cell for both growth on glucose and carbon dioxide," Boyle said. "This will validate or help to iteratively improve the predictions made using the metabolic model and identify any bottlenecks or undesired side products that can then be targeted using genetic engineering techniques."

There are two main challenges in developing high-yielding algae strains, Boyle said. "First, our understanding of genetic regulation and cellular physiology lags behind other model organisms like E. coli and yeast," Boyle said. "Second, we don't have sophisticated genetic tools to introduce the desired changes."

In addition to Boyle's work, the team will collect data on a large scale to gain insight into genetic elements that control metabolic shifts responsible for lipid accumulation. This information will then be used to develop synthetic biology tools to enable fast and efficient engineering of the algae's cells.

The project, "Systems analysis and engineering of biofuel production in Chromochloris zofingiensis, an emerging model green alga," is led by Krishna Niyogi of the University of California, Berkeley. Investigators include Crysten Blaby, Brookhaven National Laboratory; Mary Lipton, Pacific Northwest National Laboratory; Sabeeha Merchant, UCLA; and Trent Northen, Lawrence Berkeley National Laboratory.

The grant is administered by the Genomic Science Program in the Energy Department's Office of Biological and Environmental Research.

» Read about Nanette Boyle's DOE Early Career Research Program award on page 38.

A mathematical model of blood coagulation

Applied Mathematics and Statistics Assistant Professor Karin Leiderman is part of a team of researchers that has been awarded nearly $500,000 by the Army Research Office's Mathematical Sciences Division to study blood coagulation.

A break in a blood vessel triggers blood coagulation, a complex network of biochemical reactions where dozens of proteins act collectively to form a gel and seal the injury.

Leiderman and her colleagues will use a combined mathematical, statistical and experimental bottom-up approach to develop and experimentally validate a mathematical model of blood coagulation. Their approach will employ global uncertainty and sensitivity analysis to account for and quantify experimental noise, uncertainty in protein levels and kinetic rate constants, as well as determine missing or incorrect kinetic schemes.

The project seeks to establish an accurate, predictive model that will complement existing experimental assays in risk prediction and therapeutics development.

"Our model is expected to have a positive impact," Leiderman said. "It will seamlessly and accurately probe the coagulation network and thus provide a more detailed analysis of the pathways and rate constants leading to thrombin generation. It could also be used to inform anticoagulant treatment strategies and speed the development of prohemostatic agents by helping to find optimal biochemical targets or combinations of synergistic targets that treat or prevent bleeding."

The project is a collaboration with Dougald Monroe from the University of North Carolina, Chapel Hill, and Suzanne Sindi from the University of California, Merced.

Karin Leiderman

Making small-scale mining safer for workers and the environment

A five-year, $4 million National Science Foundation grant will put Mines at the center of efforts to tackle the public health and environmental challenges posed by artisanal and small-scale gold mining.

About 30 percent of gold produced worldwide—for use in jewelry, electronics, currency and more—comes from artisanal and small-scale mining operations, a broad categorization that ranges from subsistence miners with a shovel and gold pan to small outfits equipped with basic machinery.

The practice, which provides a livelihood for an estimated 100 million people directly and indirectly, also comes at a cost: large-scale deforestation, air and water contamination and chronic human diseases, particularly from the mercury used to process the gold ore.

"Artisanal and small-scale mining is the No. 1 anthropogenic cause of mercury pollution in the world, but most people don't pay attention to it," said Juan Lucena, professor of engineering, design and society and director of the Mines Humanitarian Engineering Program. "It's invisible to the minds of most people, because it's hidden in the mountains and jungles of Latin America."

Since January, a multidisciplinary team of researchers led by Lucena have been working hand in hand with mining communities and universities in Colombia and Peru to develop not simply improved techniques and technologies but social organizations that make artisanal and small-scale gold mining (ASGM) cleaner, safer and more sustainable.

"Existing efforts to introduce sustainable practices, primarily through mercury-free processing technologies, have not achieved long-term sustainability because they are believed by miners to be inefficient or uneconomical. And many well-intentioned technical experts in this area lack the training to know how to work with and engage ASGM communities," Lucena said. "This project will break the trend by educating U.S. engineers to co-design, implement and evaluate sustainable and culturally appropriate ASGM technologies and practices with miners and affected communities in Colombia and Peru."

The Mines-led project was one of 14 nationwide to receive Partnerships for International Research and Education awards from the NSF, funding collaborative research with international partners in 24 countries. Established in 2005, PIRE leverages and supports international relationships to address critical science and engineering questions and to develop a cadre of U.S. scientists and engineers with a global outlook capable of working across cultures.

Professor Juan Lucena, right, speaks with miners and the owner of an artisanal mine in Bajo Cauca, Colombia.

Mines researchers are collaborating with faculty and students at four universities in Colombia and Peru—Facultad de Minas of the Universidad Nacional de Colombia, Corporación Universitaria Minuto de Dios, Pontificia Universidad Catolica de Peru and Peru's University of Technology and Engineering—as well as the U.S. Air Force Academy and University of Colorado closer to home.

"The crux of the grant is working with artisanal miners and affected people to design technology and social practices that are more sustainable—you can't do that if you don't understand the local context," said Jessica Smith, associate professor of engineering, design and society and one of four co-principal investigators on the project.

The technologies, practices and social organization of artisanal and small-scale mining can vary greatly site to site and miner to miner, said Nicole Smith, a cultural anthropologist and assistant professor in mining engineering. Smith, a co-principal investigator on the project, has studied ASGM in Africa and South America throughout her career, including two separate State Department-funded projects in Peru to implement cleaner and safer ore-processing technologies.

"Even within Peru, there are many people doing all different kinds of things—there's the real small-scale guy and then there's the larger-scale guy who has lots of equipment. There are women and there are youth playing different roles in the gold supply chain," Nicole Smith said. "What we're trying to do is get a site-specific understanding of these systems—where they're mining, why they're mining, questions related to geology, how miners decide where to mine. We'll use that data to inform the interventions."

Small-scale gold miners around the world have been using mercury to process ore for centuries, including here in the U.S. during the days of the Gold Rush, said Elizabeth Holley, assistant professor of mining engineering and a co-principal investigator on the project.

Mercury amalgamates with gold—add it to gold-containing ore and the mercury will bind to the gold, leaving everything else behind. Miners then burn the mercury off, often over an open fire, to obtain the gold.

"The problem is, mercury is very persistent when it enters the environment. It's reactive. It doesn't degrade, and it bioaccumulates in the food chain," Holley said.

Holley, who specializes in ore deposits and the geochemistry of mine wastes like mercury, is analyzing the geological and geochemical characteristics of the various sites in Peru and Colombia. Geology plays a major role in how individual deposits are mined, what techniques are used and how damage spreads into the broader environment, she said.

Researchers are also studying environmental monitoring and remediation, applying an approach that relies less on data and modeling and more on local knowledge to address mercury pollution, said Kate Smits, assistant professor of civil and environmental engineering and co-principal investigator.

"Many remediation strategies have been developed to remove or trap mercury in soil and water, but the implementation of such strategies is often limited by cost, material availability, and the knowledge and skill sets of the local communities," Smits said.

The grant will support five undergraduate researchers and six graduate students every year, with the goal of graduating at least three PhD candidates over the five-year program.

"We're really trying to focus on educating engineers about the concepts related to human-centered design," Nicole Smith said. "What does that mean? It means getting into the field and interacting with the people who will be using these designs."

Large-scale mining companies are in need of employees who understand the complexities of artisanal and small-scale mining, said Jessica Smith, an anthropologist who also teaches courses on corporate social responsibility and participatory fieldwork methods at Mines. In many countries, ASGM and large-scale mining happen in close proximity and often on the same land, leading to potential conflict.

"This is the biggest challenge facing hard-rock mining not just in South America but Africa and other parts of the developing world," Jessica Smith said. "This is an opportunity to help large-scale companies think about how they can most effectively engage that challenge while creating shared social, environmental and economic value with the communities closest to their operations."

Miners use high-pressure water hoses to access a gold vein deep in the jungle in Bajo Cauca, Colombia.

Protonic ceramic fuel cell research wins Rath Award

Conducting the longest study published to date on the durability and fuel flexibility of protonic ceramic fuel cells required no small amount of commitment from Chuancheng Duan PhD '18.

He spent almost two full years baby-sitting the custom test rig that could simultaneously test seven cells using different fuels for thousands of hours. He finally shut down the experiment in May 2017—before his wedding and honeymoon.

"The longest test was 8,000 hours, which is almost a whole year," Duan said. "If there was a power outage in the campus, I had to drive back to the lab as soon as I could to reboot the system and stations—no matter where I was. I will never forget that period but I also enjoyed it."

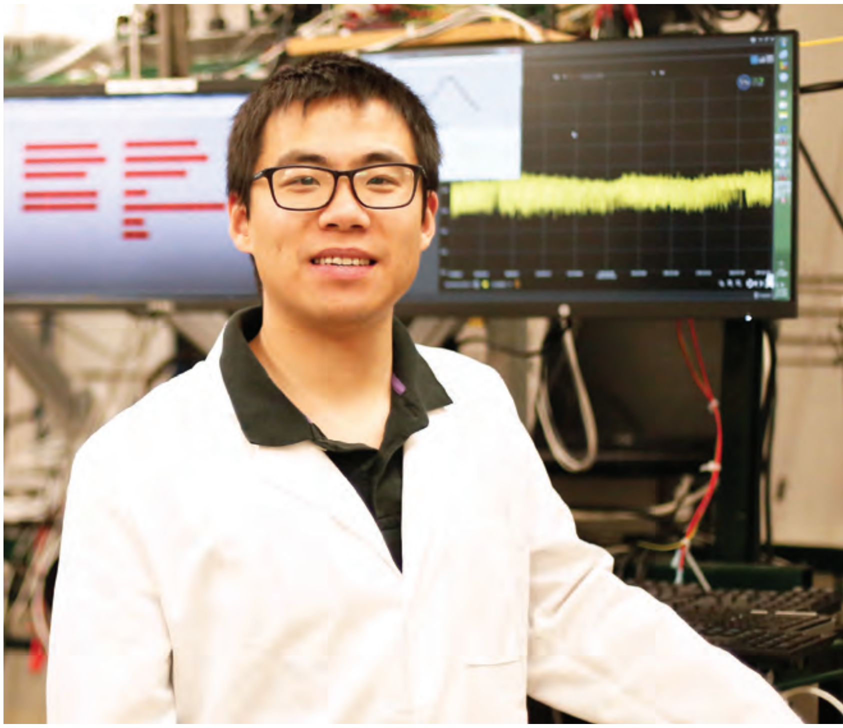
The results of his work, "Highly durable, coking and sulfur tolerant, fuel-flexible protonic ceramic fuel cells," was published in the journal *Nature* in May, just one day before Duan graduated with a doctoral degree in materials science.

At the ceremony, Duan was honored with the Spring 2018 Dr. Bhakta Rath and Sushama Rath Research Award, which recognizes the Mines doctoral graduate whose thesis demonstrates the greatest potential for societal impact. Duan's thesis was titled "Ceramic Electrochemical Cells for Power Generation and Fuel Production."

"Chuancheng is one of the most motivated and driven PhD students I've ever seen—he just works so hard, 80 hours a week, week in and week out. He's exceptionally dedicated, he's a self-starter and always has really good ideas and is really enthusiastic," said advisor Ryan O'Hayre, professor of metallurgical and materials engineering and co-author of the *Nature* paper. "His work on protonic ceramic fuel cells could lead to commercial products for emergency or remote off-grid power applications and someday may even provide a new, greener way to power our homes and schools."

Duan came to Mines after meeting O'Hayre in China, where Duan was a student in the city where O'Hayre was taking his sabbatical. Duan reached out to O'Hayre and began working at the Dalian Institute of Chemical Physics under his direction. When O'Hayre returned to Golden, he convinced Duan to apply to Mines' graduate program.

"I worked on protonic ceramic fuel cells for five years at Mines and really enjoyed the process of designing electrodes, developing devices, measuring fuel cell performance and investigating their stability," Duan said. "After two years of research, I realized it was critical to develop one highly durable fuel cell technology that could directly use natural gas and hydrocarbons in order to be commercially viable. In addition, the fabrication method needed to be cost-effective."



Chuancheng Duan received the Dr. Bhakta Rath and Sushama Rath Research Award for his work showing the commercial viability of protonic ceramic fuel cells.

Protonic ceramics are a relative newcomer in the fuel cell world, the material having only been discovered in Japan in 1980. It wasn't until the late 1980s and early 1990s, though, that the technology began to gain acceptance, and in just the last eight or so years, researchers have made major inroads in addressing stability issues and how to make the dense membranes necessary to power a device, O'Hayre said.

During his time at Mines, Duan was also the lead author on another paper on PCFCs published in *Science*. The 2015 paper, "Readily processed protonic ceramic fuel cells with high performance at low temperatures," reported a cost-effective PCFC fabrication method and established the basis for the research later published in *Nature*.

In the *Nature* paper, Duan and colleagues showed for the first time that PCFCs exhibit both the long-term durability and fuel flexibility needed to become a viable commercial alternative to other existing fuel cell technologies. In all, researchers tested 11 different fuels—hydrogen, methane, domestic natural gas (with and without hydrogen sulfide), propane, n-butane, i-butane, iso-octane, methanol, ethanol and ammonia—demonstrating excellent performance and exceptional durability across all fuel types over thousands of hours of operation.

The research was funded through the U.S. Department of Energy's Advanced Research Projects Agency-Energy and its Reliable Electricity Based on Electrochemical Systems program.

"Based on our current work and achievements, it is time to collaborate with an industrial partner to make commercial products," Duan said. "In three years, there will be a 500-watt direct-natural gas PCFC stack developed based on our technology. In less than 10 years, there will be a 1-kilowatt PCFC stack that could serve as a house power supply, the backup power supply for offices or mobile base stations."

Preventing plugged pipelines with advanced coatings

A Mines professor has been awarded $1.5 million in funding from the U.S. Department of Energy for advanced technology solutions for unconventional oil and gas development.

Carolyn Koh, William K. Coors Distinguished Chair of Chemical and Biological Engineering and director of the Center for Hydrate Research, is the lead investigator on the three-year project, one of six nationwide to receive funding through the Office of Fossil Energy program.

"The grant allows us to look at robust coatings for pipeline plugging prevention," Koh said.

Koh's research team will collaborate with Oceanit, a Honolulu-based science and engineering company, to develop a coating that can be applied to pipelines in situ. The coating will be designed to mitigate hydrate deposit formation along pipeline walls, which in turn will prevent critical blockage of the pipes.

Not unlike arterial clogging in the human body, gas hydrates are problematic for flow assurance programs in the oil and gas industry. Given proper thermodynamic and flow conditions, these crystalline solids of water and light hydrocarbons can form in pipelines and, in particular, accumulate at the inner wall of pipes. If enough hydrates form, they can completely block the flow, potentially damaging the pipeline.

Finding a coating that can be applied in situ could mean large savings on operating expenditures for oil and gas companies, Koh said. Since the coatings work even on already-corroded pipelines, companies would not have to spend money on pipeline replacement.

The project builds on work funded by an earlier DOE grant in which Koh's team was able to show that coatings from Oceanit worked to prevent hydrate formation. That work was conducted at the lab-bench scale; the end goal of this newly funded research, however, is to transition into a multiphase-pilot scale and eventually a field-scale study.

Koh's research team is implementing a "flow loop" in the Center for Hydrate Research to simulate a flowing system. Marshall Pickarts, a first-year PhD student in chemical engineering, is working with the flow loop. The team, with the help of Mike Stadick, laboratory coordinator for the Chemical and Biological Engineering Department, recently added an extension to the loop to help amplify the pressure drop throughout the system.

Ahmad Majid, a postdoctoral researcher who completed his PhD in the Center for Hydrate Research and was awarded the Best Doctoral Thesis in Flow Assurance award at the 2017 International Conference on Gas Hydrates, helped with the design of the flow loop. Hao Qin, a fourth-year PhD student, is developing a mathematical model to aid in the understanding of how hydrates form on the pipe wall. The model will be coupled with OLGA, a dynamic multiphase flow simulator that is commonly used in the oil and gas industry.

Professor Carolyn Koh is developing an advanced coating to prevent hydrate deposits in pipelines.

Mines, NREL researchers improve perovskite solar cells

Researchers from the Mines Chemistry Department and the National Renewable Energy Laboratory have developed a perovskite solar cell that retains its efficiency after 1,000 hours of continuous use, with their findings published in *Nature Energy*.

Associate Professor Alan Sellinger, graduate student Tracy Schloemer and former Mines postdoc Jonathan Tinkham are co-authors of the paper, titled "Tailored interfaces of unencapsulated perovskite solar cells for >1,000 hour operational stability." The project was led by NREL's Joseph Luther and Joseph Berry and also included Jeffrey Christians, Philip Schulz, Steven Harvey and Bertrand Tremolet de Villers.

Over the past decade, perovskites have rapidly evolved into a promising technology, now with the ability to convert about 23 percent of sunlight into electricity. But work is still needed to make the devices durable enough for long-term use.

According to the researchers, their new cell was able to generate power even after 1,000 straight hours of testing. While more testing is needed to prove the cells could survive for 20 years or more in the field—the typical lifetime of solar panels—the study represented an important benchmark for determining that perovskite solar cells are more stable than previously thought.

A new molecule developed by Sellinger, nicknamed EH44, was used to replace an organic molecule called spiro-OMeTAD that is typically used in perovskite solar cells. Solar cells that use spiro-OMeTAD experience an almost immediate 20 percent drop in efficiency, which continues to steadily decline as it becomes more unstable.

The researchers theorized that replacing the layer of spiro-OMeTAD could stop the initial drop in efficiency in the cell. The lithium ions within the spiro-OMeTAD film move uncontrollably throughout the device and absorb water. The free movement of the ions and the presence of water causes the cells to degrade. EH44 was incorporated as a replacement because it repels water and doesn't contain lithium.

The use of EH44 as the top layer resolved the later more gradual degradation but did not solve the initial fast decreases that were seen in the cell's efficiency. The researchers tried another approach, this time swapping the cell's bottom layer of titanium dioxide (TiO_2) for one with tin oxide (SnO_2). With both EH44 and SnO_2 in place, as well as stable replacements to the perovskite material and metal electrodes, the solar cell efficiency remained steady. The experiment found that the new SnO_2 layer resolved the chemical makeup issues seen in the perovskite layer when deposited onto the original TiO_2 film.

"This study reveals how to make the devices far more stable," Luther said. "It shows us that each of the layers in the cell can play an important role in degradation, not just the active perovskite layer."

Funding for the research came from the U.S. Department of Energy Solar Energy Technologies Office.

Mines and NREL researchers have developed a perovskite solar cell that remains efficient after 1,000 hours of continuous use.

Courtesy Dennis Schroeder / National Renewable Energy Laboratory

A cheaper, greener way to purify natural gas

Fundamental researchers at Mines have proposed a novel two-part system for separating impurities from natural gas in the *Journal of Renewable and Sustainable Energy,* from AIP Publishing.

Natural gas primarily contains methane, but impurities in the gaseous mixture need to be removed before the methane can be put into the pipeline. The newly proposed purification system combines two separation methods and, in principle, promises to improve performance, reduce costs and diminish ecological side effects compared to benchmark technologies.

Natural gas processing typically relies on high-temperature techniques that incur high operating costs. "We propose an integrated process consisting of gas hydrates and membranes, to make the overall process of purifying natural gas potentially more economical without high-temperature driven processes," said co-author Moises Carreon, an expert in membrane separating technologies and associate professor of chemical and biological engineering.

Membrane technology applies different types of material to filter out carbon dioxide and nitrogen from raw natural gas. Propane and hydrogen sulfide are also often present and can negatively affect membrane performance. A possible solution to this problem emerged when Carreon began talking with Carolyn Koh, an expert in hydrates and William K. Coors Distinguished Professor in Chemical and Biological Engineering at Mines, and Pramod Warrier, a postdoctoral researcher.

"Hydrates form hydrogen-bonded water cages that trap the gases you want to separate," Koh said. "It's a potentially very selective way of trapping those gases."

Carolyn Koh

Moises Carreon

Different pressure and temperature conditions are required for impurity hydrates to form compared to methane hydrates. The engineers decided to introduce selective hydrate formation as a preliminary step to the membrane separation process.

"In this integrated system, we first remove all of the nasty chemicals present in natural gas using gas hydrates to produce a purer mixture," Carreon said. The purer mixture of gases is easier to separate using membrane technology.

Hydrate formation is not only energy-efficient but also environmentally friendly. Water is the only additional material required for gas hydrate formation, and it effectively sequesters hazardous gases like hydrogen sulfide into the solid hydrate form, which prevents its release into the environment. There are some other contaminants that need to be removed separately, but this newly proposed system reduces environmental impact from the current industrial processes.

~~This September, Carreon and Koh were awarded $300,000 by the National Science Foundation to design the membrane.~~

– AIP Publishing

A closer look at 3D-printed alloys

A Mines associate professor will be studying the properties, defects and instabilities in metallic alloys produced via additive manufacturing in a project funded by the Office of Naval Research's Multidisciplinary University Research Initiatives Program.

Amy J. Clarke, associate professor of metallurgical and materials engineering, joins a team that includes researchers from Iowa State University, University of California Santa Barbara and Virginia Tech and is led by the University of Tennessee's Suresh Babu. An Australian team, with scientists from the University of Sydney and University of South Wales, is also working on the project.

The award is for about $1.5 million over three years, with the possibility of a two-year extension. Mines' share could total up to $1.25 million over the duration of the project.

The team will examine the physical processes that impact additively manufactured metallic alloy parts, such as solidification and solid-state phase conditions under highly transient conditions.

At Mines, Clarke will lead an effort focused on the multiscale characterization of phase transitions and microstructural evolution. This work will include the use of novel tools and unique probes available at national user facilities and in the laboratory to watch phase transitions in real-time.

Additive manufacturing and nuclear science: A powerful combination

Mines is combining its strengths in nuclear engineering and additive manufacturing in a research project to determine how 3D-printed metals perform in a reactor.

Metallurgical and Materials Engineering Associate Professor Jeffrey King, a core faculty member of Mines' Nuclear Science and Engineering Program, is the principal investigator on the $2.5 million project, funded through several Department of Energy nuclear programs.

The project recently reached a critical point, with 288 samples of stainless steel and Inconel alloys, manufactured using five different 3D printing methods, inserted into the Advanced Test Reactor at Idaho National Laboratory earlier this year.

"It's the first major reactor experiment that Mines has performed," King said. "It's a big deal for both the Nuclear Science and Engineering Center (NuSEC) and the Alliance for the Development of Additive Processing Technologies (ADAPT)."

The reactor cycle started June 6, with some samples subject to the neutron field for 80 days and others for 160 days.

The 250-megawatt Advanced Test Reactor is the highest-power research and testing reactor in the United States. It has anywhere from a tenth to a quarter of the power of most commercial nuclear plants, but 10 times their neutron flux. The effects of that flux are what King and his colleagues hope to observe.

"It is well known that being bombarded with neutrons causes physical changes in metals—it makes them harder and more brittle," King said. "How are additively manufactured parts going to perform in a reactor environment? Will they be as good as conventional parts, or better? Will they meet performance requirements?"

Additive manufacturing is of interest to the nuclear industry for several reasons. The new techniques could allow innovative geometries for filters, fuel elements and other components that improve the performance of nuclear reactors. Another is that most current nuclear plants are 50 to 60 years old. "There are whole inventories of parts that they don't make anymore, such as valves, that are very expensive to replace," King said. Additive manufacturing could allow the relatively cheap manufacture of single replacements.

While nuclear power is not as popular in the U.S. as it has been in the past, two new plants are under construction and one came online a couple of years ago. "It depends on where you are," King said. Lowering the high operating costs could help make nuclear energy more attractive.

"Worldwide, we're actually seeing a lot more interest," King said. "China is building a lot, the United Arab Emirates is about to start up four of them, Russia is still active. It's still a necessary component if we're really serious about carbon reduction."

King said early evidence suggests that 3D-printed metals will perform at least as well as conventionally manufactured materials. "And there are tantalizing hints out there that we may actually have the ability to do better," he said.

"At the heart of it, it's a materials science project with a tie to the nuclear world," said Ryan Collette, a Mines PhD student who has worked on the project for a little over a year and one of three PhD candidates attached to the project. The bulk of the work so far has been designing and otherwise preparing the samples for machining, a pre-irradiation report on their basic microstructures and then conducting testing on samples that won't be irradiated.

Researchers already know that additive manufacturing techniques lead to very different microstructures. And while the physics in a nuclear reactor are fairly well understood at the atomic level, scaling those up to physical properties is harder to predict, making this an active area of research.

Charlie Becquet, an engineering physics major with plans to pursue a master's in nuclear engineering, is working on the project through the NextGen Fellowship, awarded by ADAPT founding partner Citrine Informatics.

Associate Professor Jeff King, left, and students Ryan Collette and Charlie Becquet conduct materials testing in the lab.

Technicians at Idaho National Laboratory insert Mines' experiment, comprising 288 samples of stainless steel and Inconel alloys, into the Advanced Test Reactor.

Citrine combines artificial intelligence with the world's largest materials database to help bring new products to market faster.

"My role is to apply the data we obtain from the irradiation experiment to the Citrine database and look for trends in our data that can provide useful information toward the viability of additively manufactured materials for nuclear-specific applications," Becquet said.

"I've always looked forward to working in the nuclear industry," Becquet said. "This project is the first major step toward making my dream a reality."

Collette also sees the project as a benefit to his job prospects. "I find additive manufacturing to be a really interesting niche, and one that moves quite a bit faster than the nuclear industry, so I feel it will provide me with some additional career options when I graduate," he said.

King said Mines is uniquely positioned to play in this area, with its strong materials background, its interdisciplinary nuclear program and the work of its NuSEC and ADAPT research centers. "DOE is very interested in this project," he said. "We're out there playing with the big kids in the nuclear field—it's a big win."

Book on coal mining and gender recognized for contributions to social sciences

Jessica Smith

Jessica Smith, associate professor of engineering, design and society and co-director of the Humanitarian Engineering Program, has received the 2018 Western Social Science Association Distinguished Book Award for "Mining Coal and Undermining Gender: Rhythms of Work and Family in the American West."

She was honored during the WSSA Annual Conference in San Antonio in April. The award recognizes cutting-edge research and substantial contributions to the social sciences.

"The book committee believes that Dr. Smith seamlessly integrated deep ethnography with academic scholarship and in-depth analysis and insights. We find her work compelling, well researched and supported, and believe this piece contributes to a variety of disciplines and a range of literature, including economics, labor relations, communications, women's studies, masculinities studies, sociology, anthropology and linguistics," said Michele Companion, immediate past president of the Western Social Science Association.

The book, funded by a fellowship from the National Endowment for the Humanities and a research grant from the National Science Foundation, was published by Rutgers University Press in 2014. It investigates gender and mining from the perspective of Wyoming's Powder River Basin, where Smith grew up and drove haul trucks in the mines for summer employment during college.

Since publishing the book, Smith has turned her attention to studying engineers and social responsibility in the mining and energy industries. She is currently writing her second book, based on her ongoing NSF-funded research on corporate social responsibility, and contributing her expertise to Mines' new $4 million NSF-funded project on artisanal gold mining in Colombia and Peru.

Smith, who joined Mines in 2012, holds a PhD in anthropology and a certificate in women's studies from the University of Michigan and bachelor's degrees in international studies, anthropology and Latin American studies from Macalester College.

Resolving scalability issues in computing

Bo Wu

Computer Science Assistant Professor Bo Wu is contributing to a collaborative research project that aims to pinpoint and resolve scalability issues in the software stack of multi-core and many-core hardware.

Wu will receive $499,891 in funding from the National Science Foundation's Scalable Parallelism in the Extreme (SPX) program for his part of the collaborative effort with the University of Texas San Antonio.

Unlike previous research that focused on application code to identify hidden scalability issues, the Mines and UTSA team will consider the whole software stack, including the memory allocator, third-party runtime libraries and the operating system. The project's goal is to develop analyzers to automatically pinpoint the root causes of bottlenecks and then fix them via a runtime optimizer—all without intervention from a programmer.

"The proposed techniques will greatly reduce manual effort spent on identifying scalability problems hidden in various layers of the software stack, which is expected to achieve better scalability than existing techniques in many domains, such as high-performance computing, big-data analytics and machine learning," Wu said. "The improved program performance will eventually lead to accelerated scientific discoveries and energy saving."

At Mines, Wu's specific focus will be developing instrumentation tools, designing runtime adaptation methods and experimenting with heterogeneous systems that consist of both central processing units and graphics processing units.

The NSF SPX program aims to support research addressing the challenges of increasing performance in the modern era of parallel computing, which will require a collaborative effort among researchers in multiple areas, from services and applications down to micro-architecture. All projects funded through the program are collaborative in nature.

» Read about Bo Wu's NSF CAREER Award on page 41.

The link between blood clots and The Pill

Keith Neeves

Nanette Boyle

Birth control pills are the most popular form of contraception in the U.S., used by an estimated 9.7 million women nationwide. But nearly 60 years after "The Pill" first came on the market, scientists still don't understand exactly why oral contraceptives cause a heightened risk for blood clots.

Two Mines professors hope to unravel that medical mystery with help from a five-year $3.4 million grant from the National Institutes of Health.

Keith Neeves, associate professor of chemical and biological engineering, and Nanette Boyle, assistant professor of chemical and biological engineering, are the co-lead investigators on a National Heart, Lung and Blood Institute project to identify the mechanisms by which sex hormones—the effective ingredients in oral contraceptives—modulate platelets, a key agent in the formation of a type of clotting disorder called venous thromboembolism, or VTE.

Together with a team of hematologists and gynecologists at CU Denver, Children's Hospital of Colorado and the National Cancer Center in Aviano, Italy, the two Mines professors will take a systems biology approach to the question, looking at how coagulation and platelets work together to form clots.

"There's been a long-known relationship between oral contraception and venous thromboembolism, a type of thrombosis, but how that relationship actually works is a little up in the air," Neeves said. "We're bringing a different skill set to the table. This approach is called systems biology, and the idea is that it's not so reductionist, where you're always trying to break things down. You're essentially trying to put things back together to understand how things work across an entire system."

To do that, researchers will follow a cohort of premenopausal women prior to and for two years after the start of oral contraceptives, doing extensive blood workups every four to six months. At Mines, Neeves and Boyle will use a combination of computer modeling and laboratory experiments to create predictive tools to better understand their risk of clots.

"What Nanette and I do is build computer models of systems to make predictions. We can take out some of the empiricism and correlative nature of this field—if we know X, Y and Z about somebody, we can make some predictions on how they will respond to estrogen or progesterone or some other drug," Neeves said.

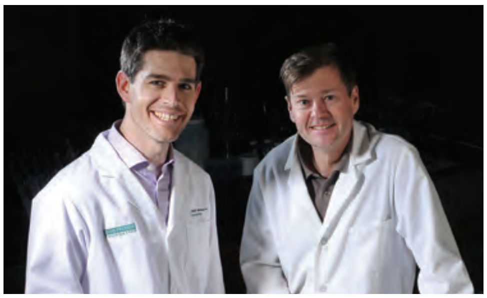
Neeves is an expert in platelet physiology, while Boyle specializes in metabolism. Boyle's research will focus on measuring how metabolism changes in response to estrogen, as well as modeling those changes.

"There are some known hormones that affect the clotting process that come from metabolism, namely lipids and fatty acids," Boyle said. "We want to see how metabolism plays a role in clotting and if certain responses make the platelets more sticky and likely to clot."

The ultimate goal is to identify specific genetic traits or other factors that may increase the risk of women developing clots while on oral contraceptives. In one relevant case study, a common genetic mutation among people with Northern European ancestry was shown to increase the risk of developing a VTE some eightyfold.

"What we want to do is be able to identify who are those people who are at higher risk," Neeves said. "Right now, we blanket it—everyone who is on oral contraceptives gets this warning that you may be at a higher risk for clotting, but ideally you'd be able to identify those people a priori and either not put them on oral contraceptives in the first place or have them be monitored a little more closely."

Using microbots to tackle small-vessel strokes



Keith Neeves, left, and David Marr

Strokes are the fifth leading cause of death in the United States, and a team of researchers at Mines is working on a new treatment for blockages that occur in vessels too small to be accessed by traditional catheters.

And not just any treatment—tiny bots that are designed to deliver a potentially life-saving medication straight to the problem area in the brain.

"If you have a stroke right now, there are two approaches to mitigating it. One is a catheter— you feed a catheter up there with the idea of physically removing the blockage. That works pretty well for larger vessels, the big ones in your brain where catheters actually fit. But about 20 percent of strokes are small-vessel strokes, lacunar strokes where catheters won't work," said David Marr, professor of chemical and biological engineering.

"Another approach is using a clot-busting drug called tissue plasminogen activator, or tPA. tPA can also work, but it has a very limited therapeutic window—the drug has to be given to you intravenously within the first three hours of when the stroke begins or there are just too many complications."

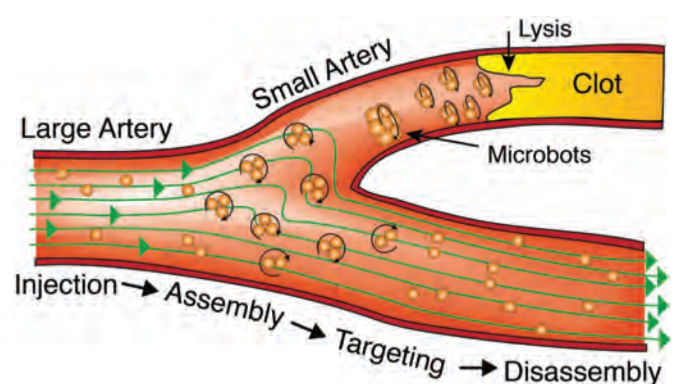
Led by Marr and Keith Neeves, associate professor of chemical and biological engineering, the team has been awarded $2.6 million by the National Institutes of Health's National Institute of Neurological Disorders and Stroke to further develop magnetically powered blood cell-sized microwheels, or microbots, capable of delivering tPA more quickly and directly to treat small-vessel strokes.

Specifically, researchers will develop better ways to navigate the microbots through the body, improve how quickly the bots can dissolve clots and determine just how much functional benefit they can provide in animals. The new funding will allow them to test the technology in physical models of increasing complexity and scale, starting with zebrafish larvae and moving to mice and life-size human replicas.

"The idea is microbot particles can be injected into the body, assembled in place with a magnetic field and then they're small enough to get to these small vessels where strokes occur but where catheters can't reach," Neeves said. "The big advantage is we can drive them to the point of blockage and then we can deliver the clot-busting drug on the particles. Instead of waiting for the drug to be diffused through the body, we can drive them to the site."

Once those microbots have completed their job, the magnetic field can be turned off and the bots will break down into individual particles again.

Also working on the project are Mechanical Engineering Assistant Professor Andrew Petruska and collaborators at University of Colorado Anschutz Medical Campus and University of Michigan.



Once the microbots have completed their task, the magnetic field that holds them together can be turned off, leaving them in tiny particles that can be removed by the body's white blood cells.

The Office of Technology Transfer

Professors David Marr and Keith Neeves' project to develop microbots for vascular health was one of five chosen to receive $35,000 grants from the Office of Technology Transfer's Proof of Concept Advisory Board.

It's one of several ways the office serves the citizens of Colorado and the United States and fulfills its mission of protecting and commercializing the inventions of Mines researchers. The office:

- Engages with inventors, communicating next steps to bring products to market
- Finds the right partners, connecting with industry leaders, venture capitalists, entrepreneurs and more
- Enhances the academic mission, showcasing Mines' world-class researchers and providing learning opportunities for students
- Ensures fair return on taxpayer and university investment

To learn more about commercializing Mines intellectual properties, contact William Vaughan, director of technology transfer, at wvaughan@mines.edu or 303-384-2555.

Mines ventures into health technology

Expanding its presence in the health-tech sector and Denver, Mines will join Catalyst HTI, a first-of-its-kind health care innovation hub that will bring together startups, established health care entities, nonprofits and academic organizations to spur collaboration and innovation.

Mines plans to open a 1,700-square-foot office inside Catalyst HTI in early fall. The space will have an open workshop and classroom that will be home to Capstone Design projects, career fairs, technology information sessions and a gallery showcasing student and faculty work.

"The biotech and health care industries offer great employment opportunities for Mines students and great collaborative opportunities for our faculty who are working on the cutting edge of tissue engineering, computational systems biology, medical device development and more," said Mines President Paul C. Johnson. "We're excited to join the Catalyst HTI venture, increasing our visibility in this vital, growing field of health technology at a local level and accelerating our progress toward establishing Mines as an innovative partner for the industry."

Artist rendering of the Catalyst HTI facility on Brighton Boulevard in Denver's River North District.

Catalyst HTI is the first facility of its kind in the U.S., designed to bring together stakeholders from across the health care market to foster collaboration and accelerate innovation. Mines is one of three academic institutions that have committed to join the health-tech integrator, along with other national organizations and startups.

"If we want to create a long-term health-tech innovation ecosystem in Denver, we have to have a talent pipeline," said Catalyst HTI President Mike Biselli. "There's no better way to make that happen than by bringing entrepreneurs, executives and Colorado's great educational institutions together under one roof to work collaboratively to ensure college graduates are ready to hit the ground running in the industry today and in the future."

Hybrid power system to combine fuel cell, combustion technology

Robert Braun

Mines has been awarded $3 million in funding from the U.S. Department of Energy's Advanced Research Projects Agency-Energy to develop a first-of-its-kind hybrid power generation system that could provide electricity to supermarkets, big-box retailers and other commercial buildings at high efficiency and low cost.

Rob Braun, associate professor of mechanical engineering, is the lead investigator on the project, which is a collaboration with researchers at Colorado State University and industry partners Kohler Power Systems and Air-Squared Inc.

"We feel this project could introduce a paradigm shift in the fuel cell field by demonstrating that a hybrid fuel cell system can drive both radically lower costs and increase electric efficiency beyond 70 percent for small-scale, distributed power applications," Braun said.

Mines received the competitive award from ARPA-E's Innovative Natural-gas Technologies for Efficiency Gain in Reliable and Affordable Thermochemical Electricity-generation program, which supports hybrid system designs that integrate fuel cells with a gas turbine or reciprocating internal combustion engine.

The system being developed at Mines will combine a lower-temperature, pressurized solid oxide fuel cell stack with a custom-designed natural gas-powered internal combustion engine, leveraging both cost and thermodynamic synergies to deliver high-efficiency power production. Exhaust gas from the fuel cell will be coupled with the engine, and a compressor will supply pressurized air.

"At 100 kilowatts, this system would be almost double the efficiency of any other generators—large combined-cycle power plants at 500-megawatt scale are the only things that come close, and yet are still some 10 percentage points lower in efficiency," Braun said.

The Mines team, which will focus on the design modeling, control and fuel cell testing, includes Neal Sullivan, associate professor of mechanical engineering and director of the Colorado Fuel Cell Center, and Tyrone Vincent, professor of electrical engineering. CSU will work on the custom engine in conjunction with Kohler Power Systems.

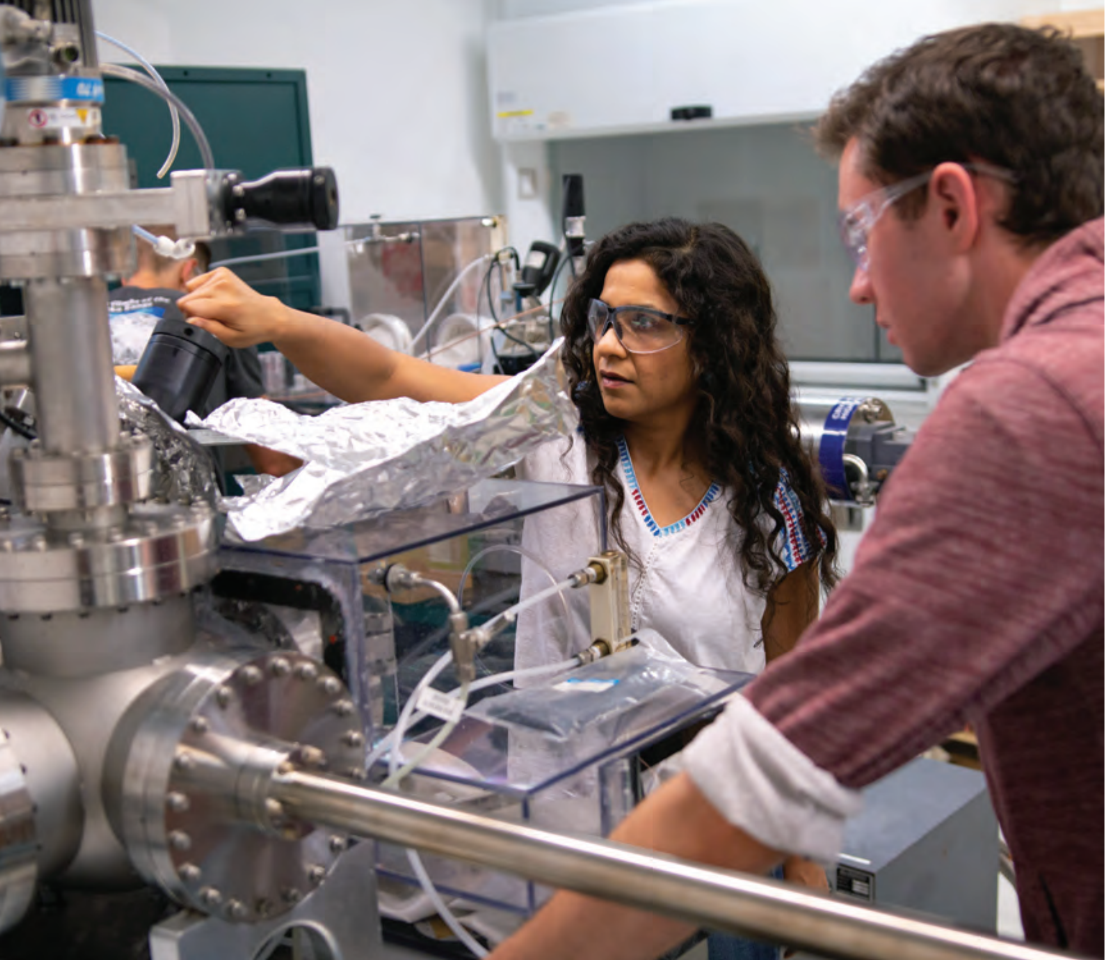
The CoorsTek Center for Applied Science and Engineering, which opened to students in the spring, is designed to encourage interdisciplinary collaboration at Mines.

CUSTOM-BUILT FOR **COLLABORATION**

By Jenn Fields

New CoorsTek Center for Applied Science and Engineering encourages cross-disciplinary research

Though it was Dead Day, and no classes were in session in the CoorsTek Center for Applied Science and Engineering, students were clustered at tables in the bright natural light of the building's atrium. In nearby study nooks, one student scribbled directly onto the table between her books and laptops. She noted with a grin that in this building, you can write just about anywhere. Baskets of markers sit near easy-erase walls, encouraging Mines students and faculty to do just that when an idea sparks.



Meenakshi Singh, assistant professor of physics, and Bradley Lloyd install new equipment in the shared laboratories of CoorsTek Center.

> “They’re all unique systems that will make Mines research in the characterization of materials world-class.”
> –Ryan Richards

“To see so many folks here, on Dead Day, is just awesome,” said Jeff Squier, a physics professor who was one of the many people involved with the building’s creation.

That energetic vibe is one he’s grown used to since the CoorsTek Center opened, and it’s not just found among the students: Faculty members are also finding that the new space and its cutting-edge research facilities are creating new opportunities for collaboration, both through partnerships with other institutions and with fellow Mines professors in different departments.

The new CoorsTek Center is the crown jewel of the $27 million commitment the Coors family and CoorsTek made to Mines in 2014; the construction of the building was also enabled by $14.6 million from the state of Colorado. It’s the new home of the Physics Department, whose faculty moved into their offices in December 2017, and students attended the first classes in the building in January. The building replaced Meyer Hall, built in the 1960s.

The 95,000-square-foot center is home to interdisciplinary laboratory hubs, including the Quantum Theory Lab, the Multiscale Materials Characterization Facility, the Alliance for the Development of Additive Processing Technologies, or ADAPT, and others. Designers built the laboratories to spec for an array of specialized equipment, including the electron microscope that was part of the donation from CoorsTek, and created forward-thinking classrooms, breakout rooms for small groups and other educational spaces for students.

Despite the large windows that filter in light throughout the building, there are places where light isn’t welcome, such as Squier’s planned laser lab. But Squier noted how the broad views northwest, across Kafadar Commons and to the foothills beyond, had made faculty offices on the upper floors more inviting. On the main floor, the same northwest-facing windows open to create a larger space for events that can spill out onto the commons: Physics majors presented their senior thesis work here in the spring, and an undergraduate research symposium brought students from a range of disciplines here to discuss their findings.

It’s a place where ideas can grow and scientists can thrive, said Physics Professor Lincoln Carr, whose work in quantum computing and other areas of quantum theory are based in the CoorsTek Center. “If you’re sitting in a small space, you don’t have the expansive imagination to solve these problems,” Carr said.

Advancing characterization research

The interdisciplinary labs in the CoorsTek Center, such as the Multiscale Materials Characterization Facility (MMCL), are an exciting environment for research collaboration, said Ryan Richards, associate vice president of research and chemistry professor. The lab's instrumentation is helping bring Mines researchers and their collaborators to the forefront of science in fuel-cell technology, photovoltaics and other fields.

"We've been very fortunate over the last few years to win some major research ~~initiative~~ instruments from the National Science Foundation," Richards said. "They all complement each other, and they're all unique systems that will make Mines research in the characterization of materials world-class."

Access to the suite of instruments in the MMCL—such as the transmission electron microscope, or TEM, which was part of the CoorsTek and Coors family donation, and environmental X-ray photoelectron spectroscopy, or XPS—can help researchers solve problems from multiple angles, Richards said. "In the TEM, morphologically, you can see what's happening in terms of its shape, and in the XPS you can see what's happening to the electrons, which gives us a complete picture of what's going on."

The combination could help researchers who are trying to develop new materials, such as more-sustainable electrocatalysts to replace platinum in fuel cells, he said.

All of the lab's instrumentation hasn't arrived yet. Corinne Packard, associate professor of metallurgical and materials engineering, won an NSF grant for a time-of-flight secondary ion mass spectrometer, or TOF-SIMS. The instrument, which measures the chemical composition of materials at small scales and concentrations, arrived on campus in July.

The XPS and the TOF-SIMS are new to Mines, and both are "amazingly unique," she said.

"The fact that they're going to be in a suite with other instruments for characterization means we can perform analysis on the same piece of material, sometimes in the exact same location, to learn different things," she said. "If I see an interesting microstructure—if we see grains and grain boundaries and second phases of material, but they're too small for one technique—then we can take that material and rapidly go into a new technique or a new instrument or new area."

She noted that the space is built for the equipment. "It's a highly engineered space to make sure we get the best performance out of these instruments. The electrical requirements, the isolation requirements—this building was built to suit the instruments."

Collaborators are already using the MMCL. Mines partners with the National Renewable Energy Laboratory to bring researchers with expertise in multiscale characterization together through the International Center for Multiscale Characterization. The group's areas of interest are diverse, said Packard, who is the ICMC's co-director. "We're interested in all kinds of applications, from structural ceramics for harsh environments to microelectronics used in satellites." Their cooperative research and development agreement is making it easier for NREL partners to access the lab.

"The instrumentation that's going into that facility, some of those are capabilities that NREL doesn't have, or we have more advanced or different versions. The XPS, the TEM and the TOF-SIMS—they offered advanced capabilities," Packard said. "It's not that NREL doesn't have those things. It's that ours have some unique capabilities that theirs don't, and theirs have some unique capabilities that ours don't. That's what makes the center's collaboration so great. By having complementary capabilities instead of redundant capabilities, we can access information about chemical, electrical and structural properties across all length scales in any material."

Packard also noted the opportunities the lab creates for students. "Graduate students will be the ones who are in this lab, using it all the time," she said. "The people who are doing real research and are on the cutting edge of it are the graduate students who are getting their education here."

Fresh ideas in additive manufacturing

In one of the teaching lab spaces on the first floor, Squier turned a corner into a closed area that will serve as an advanced laser lab. Like other projects in the new building, the space itself is still a work in progress. It was full of cardboard boxes of equipment in May, but ~~he expects it to be~~ up and running for students this fall.

Corinne Packard, associate professor of metallurgical and materials engineering, assembles a time-of-flight secondary ion mass spectrometer, part of a suite of state-of-the-art characterization tools in the CoorsTek Center.

The advanced laser lab is something “we were never able to do before,” he said. “About three years ago, when this project started, an alum called us, and their company offered us brand-new optics for 10 cents on the dollar. So we got something like a quarter of a million dollars of optics for a fraction of the cost, and that will help equip this new student lab. It was serendipitous—wow, we’ve got this new building coming up.”

Thanks to the new space in CoorsTek, Squier said, “We can really put much higher-power laser systems in here—real-world laser systems that are of interest for pushing the science and engineering applications for different companies, and teaching the students all about that.”

Squier builds ultrafast optical laser systems, which produce short pulse durations. “They’re hazardous—you have to do it in an enclosed area,” he said. “So we’d like to show (students) how to build those and do different experiments involving ultrafast optical instrumentation. That’s really pushing the state of the art, so it’s neat to be able to have space for that.”

Squier will also be working in another new lab space in CoorsTek Center—the lab that will serve the Alliance for the Development of Additive Processing Technologies, or ADAPT consortium.

Squier is collaborating with Aaron Stebner, an associate professor in mechanical engineering and technical director of ADAPT, to combine their areas of expertise in a real-world application.

Moog Inc., a designer and manufacturer of components used in aerospace and defense, has donated a laser additive manufacturing (AM) machine to ADAPT; the new machine is still boxed up, waiting to go into the lab. “Aaron’s teaching me about the real engineering aspects of laser additive manufacturing,” Squier said. “These are machines that are printing metal parts, with a laser, in three dimensions [...] I’ve developed tools for imaging inside the brain, working with biologists. Over coffee, we discovered we can adapt those tools for imaging inside the laser AM process.”

Stebner and Squier are now developing tools—initially intended for imaging inside of the brain—to help provide a control loop, improving the quality of parts that can be manufactured using 3D metal printers.

“This is the kind of collaboration that just didn’t happen before,” Squier said. “But now he’s one floor below me. I think it’s kind of a neat aspect of how the building has provided the seed for new collaborations across disciplines.”

Joel Howard, left, and Bradley Lloyd calibrate newly installed equipment in CoorsTek Center.

University Professor Emeritus Thomas Furtak, former head of the Physics Department, tests new equipment installed in shared laboratory space in the CoorsTek Center.

Building for collaboration

In the center's Quantum Theory Lab, faculty and students have access to a lower-tech but nonetheless essential instrument for their work—a glass erasable wall that runs the length of the room.

"We work out problems in there every day," Carr said. "It sounds like not much, but that makes all the difference. We walk in and brainstorm."

Quantum theory is booming at Mines. Carr recently won a National Science Foundation grant from the Office of Advanced Cyberinfrastructure, boosting the university's commitment to quantum computing, and over the past year, Mines has hired a cluster of four professors who are focused on quantum entanglement and computing. They're working on an array of problems in quantum theory, he said.

For example, one of the four new faculty members, Physics Assistant Professor Meenakshi Singh, is building quantum neuromorphic computing hardware, which could allow the building blocks of computers to learn not just individually but in groups to become more efficient, like the human brain's neurons, only with a quantum advantage. "She's thinking about getting them to talk to each other through quantum entanglement," Carr said.

This sort of work, combined with the expansive new facility, has impressed faculty candidates who come to campus, he said. "It has led to Mines attracting some of the best and brightest across the country that are working on really cutting-edge ideas."

Michael Kaufman, vice provost for strategic initiatives and dean of materials and energy programs, noted that Mines has a tradition of collaboration with private industry—including the technical ceramics innovators and other scientists at CoorsTek. "If you look at Mines historically, we kind of have this reputation of being great at solving problems, so we have a lot of collaborations with companies."

"With CoorsTek specifically, one focus of creating this interdisciplinary center was to enhance our interactions with them. So, besides the brick and mortar of the building, they also created a number of fellowships." The idea, Kaufman said, was for students to be co-advised by faculty from Mines and CoorsTek staff with the projects being co-selected and co-developed by both parties. It's also a great networking opportunity for students thinking about where they might work when they graduate.

"If you can put people with different backgrounds of knowledge together, then they're learning from each other and they can really tackle and understand bigger problems from multiple different angles," Richards said. "Very often there's a big disconnect between the foundational science and the more applied engineering, and even more so these days you factor in computational modeling with both of those things. Those people really do speak different languages." Just having scientists and engineers from different disciplines in the same space, though, bridges any communication gaps.

The collaborative space the CoorsTek Center has become is a natural outgrowth of the relationship between Mines and the Coors family, which boasts 11 Mines graduates, said Faithe Gorman-Smith, director of corporate communications at CoorsTek.

"The Coors family, CoorsTek and Colorado School of Mines have a long-standing history and partnership in Golden, Colorado—all tracing back more than a century," Gorman-Smith said. "Our shared vision is to bridge academia and industry to collaborate and solve complex problems, culminating in bringing young scientists and engineers together, training them in state-of-the-art facilities by expert faculty and providing them with opportunities to collaborate with the brightest researchers in the industry."

CoorsTek Chairman John Coors envisions the effects of the research collaborations reaching far beyond Golden.

"For CoorsTek, our investment in Mines is an investment in the future, where discovery and innovation can occur in unscripted, unpredictable and remarkable ways," Coors said. "I consider this an investment in people we will never meet, who will live better lives through the amazing solutions made possible by advancements in engineered ceramics."

BREAKING NEW GROUND

By Electa Draper

Mines scientists developing underground robotics that could revolutionize mining, exploration, rescue and even law enforcement

Sriram Siva, a graduate student in Assistant Professor Hao Zhang's research group, pilots a robot through the Edgar Experimental Mine.

It's hard enough to work in an airless black void. Take away visibility, communications capability and open access and you have some of the reasons why a subterranean environment is even more difficult to navigate than outer space.

Below the surface, humans ~~often have to~~ contend with uneven terrain, confined and irregular spaces that all look alike, falling rocks, massive cave-ins, flooding, deadly gases, suffocating heat and a maze of unmapped passages that go in all directions.

"The subterranean environment is a more challenging environment than space," said Andrew Petruska, Mines assistant professor of mechanical engineering. "There is a whole added level of problems underground."

This is where robots come in.

Combining brains and brawn

But while robots don't necessarily care about risks or oxygen, they must become more intelligent to help humans master the underworld—to explore, map and mine the entirety of this hazardous realm. Mines researchers across various disciplines are working on robotic technology that will integrate the strengths of humans and machines, expand applications, increase productivity and reduce risks and costs.

As someone who recently visited a natural cave, which he entered by dropping 40 feet into total darkness, crawling on his belly and at times scooting sideways on rough surfaces, Petruska can appreciate the ruggedness and mobility of unmanned ground vehicles and the untethered flight of unmanned aerial vehicles.

But their limitations underground are significant. A driving platform that can carry a heavy payload of sensors, navigation tools, data storage and battery power is not going to get through smaller underground passages.

A subterranean-exploring robot isn't going to know where it is, because there is no GPS at work down there. It can't communicate with operators because radio signals and Wi-Fi only go so far before being blocked by rock. Ultra-low-frequency radios or earth-mode communications require big antennas and guzzle power.

A ground-based robot isn't going up a vertical passage. And any big pile of rubble or steep-walled, water-filled pit is a game-ender.

"A small drone can fly up vertical bores, but can't carry much equipment or go very far for very long—typically about 30 minutes," Petruska said. "It also will lose its way without GPS. If the drone does make it back, it won't be able to tell you much."

The demand now is for innovative systems that enable networked robots to rapidly and extensively navigate, map and monitor complex subterranean environments where humans can't set foot and that have no communications systems or power sources. The payoff would be enormous for engineers, scientists, industry, environmental agencies, emergency responders and the military.

Computer science graduate student Brian Reily pairs air and ground robots in the Edgar Experimental Mine.

Robots for rescue and law enforcement

The Defense Advanced Research Projects Agency (DARPA) anticipates more military combatants and drug cartels moving underground to escape detection and recognizes the continuing need for civilian rescue operations in the wake of mine collapses, natural disasters and terrorist acts. Last fall, DARPA issued a Request for Information on "unique and revolutionary capabilities as they pertain to subterranean environments." Petruska and a team of Mines researchers have undertaken this challenge to create and enhance technologies in the requested areas of autonomy, perception, networking and mobility.

"When we're looking at underground operations, the holy grail here is in the world of search and rescue," Petruska said. "We really want a system to find somebody and bring them back alive […] without endangering more lives."

Mining engineers have designed ventilation systems, ground supports and many safety features to make active mines more hospitable workplaces. Still, in routine hard-rock mining operations, the foreman and crew have to wait for the dust from drilling and blasting to settle and then check to see if all the explosives went off and what rocks moved where, Petruska said. Rocks, walls and ceilings can keep moving. It's hazardous recon. In this scenario and others, miners need a robot to go in and record all that information, then return and relay that data.

Robotics itself is not new to mining. For several decades, miners have remotely operated excavators, drills and bulldozers. Fleets of ore-hauling trucks now operate completely autonomously—sometimes controlled from hundreds of miles away using cameras, sensors and more sophisticated software.

The next wave of mining technology will include fully automated excavators with robotic components that can handle all functions—self-driving with its own blade, bucket or boom controls—without any human intervention. The benefits will include increased productivity, lower overhead and health costs, avoidance of the labor shortages prevalent in some regions and improved human safety, as mining jobs evolve and take humans away from hazards.

"Robotics is always this balance between not wanting people to lose their jobs but not wanting to expose them to harm," Petruska said. "We're always conscious of that."

John Steele, emeritus associate professor of mechanical engineering at Mines, said it's been his experience that the introduction of robotics doesn't change the number of human jobs, but rather the type of work they do.

With more autonomous vehicles, sensors and data analytics, mining giant Rio Tinto is extracting copper almost 7,000 feet below the surface near Superior, Ariz., where "temperatures routinely hit 175 degrees Fahrenheit" and "warm water falls from overhead rocks like rain," according to ~~Forbes~~ magazine and the ~~Wall Street Journal~~. This mine, the Resolution Copper Mine, won't be seen as exceptional for long.

"The mines of the future will be deeper in the ground—hotter, with more groundwater, lower ore grades and all sorts of environmental and safety concerns," said Professor Priscilla Nelson, head of Mines' Department of Mining Engineering. "We have to rethink the mines of the future. Robotics and big data will be incredibly important. Successful mining companies will have to continually upgrade in these areas."

Charting new territory in artificial intelligence

To move beyond the level of automation now in play, the Mines team and others are pushing the boundaries of artificial intelligence. The goal is to develop robots that can reconnoiter, scan, monitor, map and communicate in real time with other robots in their network, whether they are in an unstable mined area, hazard-filled abandoned mine, criminal-carved tunnel system or previously unexplored cavern. And humans want to receive this information without significant delay.

"Future mining could prove to be much more efficient if, for example, we can develop robots that extract only ore body and leave all the waste in place," Steele said. "Mines has done preliminary work in this area, but it is a very challenging problem—one for the next generation of mining roboticists."

All these tasks demand multidisciplinary knowledge and skills, including computer science, geophysics and mechanical, mining and electrical engineering, Petruska said. It helps that Mines owns an underground laboratory—the Edgar Experimental Mine near Idaho Springs, a silver and gold mine operated since the 1870s.

Petruska is a hardware and controls expert. Hao Zhang, assistant professor of computer science, brings the software.

Zhang founded the Human-Centered Robotics Lab at Mines in 2014. He studies collaborative autonomy, multisensory perception and robot adaptation for effective applications involving robot-robot, human-robot and ~~human-robot swarm~~ teams.

His work is computational, developing new algorithms, pathways and software that can enable long-term collaborative autonomy.

Zhang has been working with the Environmental Protection Agency as it considers the use of robots to find out what's going on inside the thousands of old mines deep inside mountain ranges. These spent and mostly unmapped mines hold water laced with sulfuric acid, toxic heavy metals and other pollutants. These subterranean flows sometime escape to surface waterways with disastrous effect, such as in 2015, when the Gold King Mine near Silverton, Colo., spilled 3 million gallons of mineral-laden water into rivers in three states.

In Colorado alone, an estimated 230,000 abandoned mines crisscross underground. About 230 mines are known to be leaking heavy metals.

Underground robots of the future ideally will network—airborne and amphibious ground robots communicating together—to maximize mobility, range, data collection and the manipulation of objects, Zhang said. These robots must be able to autonomously navigate in unknown spaces—a much-studied problem in AI and robotics—usually referred to as SLAM, simultaneous localization and mapping.

The list of desired capabilities is daunting. The sensory capabilities of a network or swarm must include some combination of vision, sonar, radar, 3D surveying with pulsed laser light (LIDAR), object recognition, dating, chemical analysis and radio frequency identification (RFID) to recognize or track anything else mobile in a mine, human or machine. And the list goes on.

Software and hardware developers also must rely on Mines' domain experts such as Jürgen Brune, mining engineering professor of practice and director of the Edgar Experimental Mine, and Sebnem Düzgün, professor of mining engineering, whose research areas include big-data analytics, AI (in earth resources) and risk assessment in earth sciences.

Robots in mines must have the equivalent of "all the human senses and cognition," plus extras such as infrared or thermal vision, Düzgün said. For example, "an autonomous vehicle must have vision and touch recognition—if the road is rougher it has to slow down so it doesn't rattle itself to death."

Continued investment in this technology is inevitable. "We will be mining forever," Nelson said.

For those who think the extractive industries have run their course, Brune said, they should consider that their cellphone contains at least 28 mined elements.

For him, the main purpose of technology is to make mines safer.

"I worked in mines for almost 30 years. Ultimately, I'm a mine safety advocate," Brune said. "We want to separate the miner from the hazard. With robotics, you won't need as many truck drivers; instead, you will need a group of persons highly skilled in electronics and control technologies."

"Robotics won't solve all the problems," Brune said. "How the human in the loop will interact with the system is a bit of a challenge."

New safety protocols and regulations will be needed in adopting autonomous mining systems, Düzgün said. Just as with the introduction of driverless cars on the highways, Steele said, the mixed environment of autonomous and human operators is challenging.

With advances in AI, robots will come to resemble humans in ways that will fascinate and disturb.

"Humans can form an emotional attachment to robots," Zhang said. "It's an open problem. This is a big research field. We don't know if it's good or bad. Robots are still objects. But they're special objects."

Mechanical engineering graduate student Clair Strebinger works with a large-scale reactor, which simulates methane gas explosions in longwall coal mines to better predict and mitigate such hazards.

SEARCHING FOR MINERALS BY THE NUMBERS

By Jenn Fields

Mathematicians and geologists collaborate to model the subsurface and increase the chances of successful exploration and extraction

While most people don't look forward to aging, it's not such a bad thing for geologists. The theory goes that the older you get, the more rocks you've seen—and the more likely you are to identify a good place to search for ore, said Thomas Monecke, an associate professor of geology and geological engineering at Mines.

"That's one of the cool things," Monecke said with a laugh. "Geologists become more valuable with age."

There's an element of truth to the jokes that underscores a major issue in the mining industry. As the demand grows for everything from the rare metals in our smartphones to the aluminum used in the blades of wind turbines, the mining industry is searching farther afield for new mineral deposits. And while 3D subsurface modeling is possible, it's not as reliable as it could be, which is why companies are still quick to rely on the instincts of experienced economic geologists, Monecke said.

Mines mathematicians and statisticians believe they can provide better, more scientifically rigorous tools for analyzing the subsurface, and thus reduce the financial and environmental risk mining companies assume when they dig. It's why Mines geologists and mathematicians are collaborating in a new research initiative that could give geologists and mining companies greater certainty that they're on the right track before the first shovel even hits the ground.

The Center for Advanced Subsurface Earth Resource Models, which brings together over 30 researchers from Mines and Virginia Tech as well as several industry partners, recently won funding from the National Science Foundation's Industry-University Cooperative Research Program.

The interdisciplinary push would bring advanced mathematics and statistics to every step of mineral extraction, from exploration to drilling to environmental remediation. Through the collaborative effort, Mines faculty hope to develop machine-learning techniques that would allow geologists to better predict subsurface features and quantify uncertainty, taking some of the risk out of decision-making processes for the mining industry.

They also plan to improve subsurface visualization tools and develop advanced analysis and interpretation methods for enhanced characterization of rock.

Mines already has many of the resources a collaboration of this nature requires: specialists in economic geology, mining engineering, geostatistics and characterization, as well as faculty focused on quantification of uncertainty, inversion modeling and data mining. And it has the infrastructure to develop and implement high-performance computing 3D subsurface models.

"The geosciences of the future are going to rely more and more heavily on these creative mathematical techniques," said Stefanie Tompkins, vice president of research and technology transfer at Mines and a geologist by training. "It gives us a great edge and changes how we explore and characterize the underground. The stakes are high, and you need sophisticated mathematical tools," she said.

Mineral extraction is risky business, but the payouts can make it worth taking a chance. Luis Tenorio, associate professor of applied mathematics and statistics at Mines, said he's noticed that geologists have traditionally been ready to take big risks for big rewards. He recalled a conversation with a geophysicist who said his company would spend millions to find ore even though their success rates were low because the payout, if they find it, could be in the billions.

Just how low those success rates are might surprise people who aren't in the industry, Monecke said. "The rate of discovery for metal deposits in remote places—what we call 'greenfields' exploration—is just under 1 percent over the past decade or so."

Mines geologists and mathematicians are working together to create tools that reduce the financial and environmental risk mining companies assume when they dig for materials.

But deeper analysis of the data could increase success rates and have another benefit. "At the same time, we might want to reduce the environmental risk," said Soutir Bandyopadhyay, associate professor of applied mathematics and statistics at Mines.

Ultimately, the mathematicians hope to help geologists to have better information to work with, whether that's through machine learning, high-performance computing or uncertainty quantification. "What mathematicians and statisticians do is try to provide ways to give informed decisions in ways [miners and geologists] can understand," Tenorio said. "So statisticians come up with neat ways to visualize the data—in 3D, for example. So then people can make a decision."

"The basic idea is where to drill to get any mineral," Bandyopadhyay said. "For example, if you want to look for copper, you know that copper is in these areas and now you want to drill at a new location, and you want to predict what would the copper level be at that location. And you want to quantify the risk associated with that.

"Based on our algorithm, I can say, OK, the probability is that there will be this amount of copper."

Roots in geostatistics

Statistics has long been used in mineral exploration and extraction. "Most of the spatial techniques we use were developed by geologists a long time back," Bandyopadhyay said. "They proved the basic theory behind it. Later, we mathematicians made everything more formal and proved different statistical properties."

In fact, the roots of the techniques Mines mathematicians will ultimately use for this research initiative were first developed by geologists, such as Danie Krige.

Krige was a South African geologist whose work in gold fields in the 1940s led him to develop a statistical method of evaluating underground resources. Much like modern geologists, he was concerned about mining companies making good decisions based on limited data.

"Krige needed a tool to make these predictions, so he came up with a mathematical method, which is very simple but effective," Tenorio said. "And then mathematicians generalized it to applications in many other fields."

Even now, success in mineral exploration is limited by information. Monecke gave an example of the sort of challenge explorers and miners face. Imagine a future gold mining operation, he said, and keep in mind that drilling costs anywhere from $30 to $70 a foot. "You could have an open pit that's one mile by half a mile in size, and one corner is 0.3 grams (of gold per ton of rock), another is 0.5 grams and the next is 10 grams," he said. "So it's very heterogeneous, and it's complex in shape. So imagine you would drill a hole here and it's not very high, so you are kind of discouraged. Then you drill another hole here, and it's very high, but they're far apart. So what do you do now? Do you drill halfway? Do you go over there? That's all very expensive."

"But you do have to drill eventually, because that's the proof that there is the metal," Monecke said. "So what we're trying to do today is combine different fields of sciences, mostly geosciences, but computational sciences and mathematics, to optimize that process."

Sometimes geologists are working with a paucity of information, but other times, mining generates so much information that it's unusable. "They have so much data sometimes, but they cannot fuse it all together to extract even more data," Tenorio said. This is where the mathematicians come in—a huge data set will provide them with a way to build subsurface visualization tools. They even hope to create visualizations similar to Google Earth, but for the Earth's subsurface.

For risk assessment, making good, solid predictions, even based on a large data set, isn't easy. "Accounting for every point in a 3D section makes a huge data set," Tenorio said. "If you want to analyze it, it becomes unwieldy; you cannot do it. You have to make approximations, and that's where computational math comes into play."

Tackling interdisciplinary communication

Interdisciplinary work is often complicated. It can take a long time to get everyone on the same page. "The math people don't even know what you're talking about, because they obviously don't have a geology degree," Monecke said. "So to find the right language to communicate is an issue. You have to learn to communicate with each other."

What can happen in these situations is that everyone ends up working on the wrong thing, Tenorio said. Geologists might be using the wrong tool because they don't know the math as well, "and

Soutir Bandyopadhyay

> "Most of the spatial techniques we use were developed by geologists a long time back. They proved the basic theory behind it. Later, we mathematicians made everything more formal and proved different statistical properties."

Luis Tenorio

“In the interaction between mathematics and statistics and an applied field like geology, there’s going to be a back-and-forth. Geologists are going to learn math, but then mathematicians are going to learn that there are some questions in geology that are so complex to answer—because in real life, physics is very complex. We’re going to need new mathematical methods to attack some difficult problems.”

then the mathematicians, because they don’t know anything about geology, they’re developing tools that are useless to the people in applications,” he said with a laugh.

“So that’s what we’ve been doing for the last three years—working on the language.”

Through the initiative, Mines researchers will become accustomed to working across these lines—both across departments at the university and with industry and government agency partners. And Mines students working with professors on the initiative will graduate with a depth of understanding of how math and applied geology can interact—and, most likely, an appreciation for cross-disciplinary cooperation.

“You truly have to bring people to the table who are experts in their field,” Monecke said. “But do you have the ability or the willingness to learn what is way, way outside of what you do?”

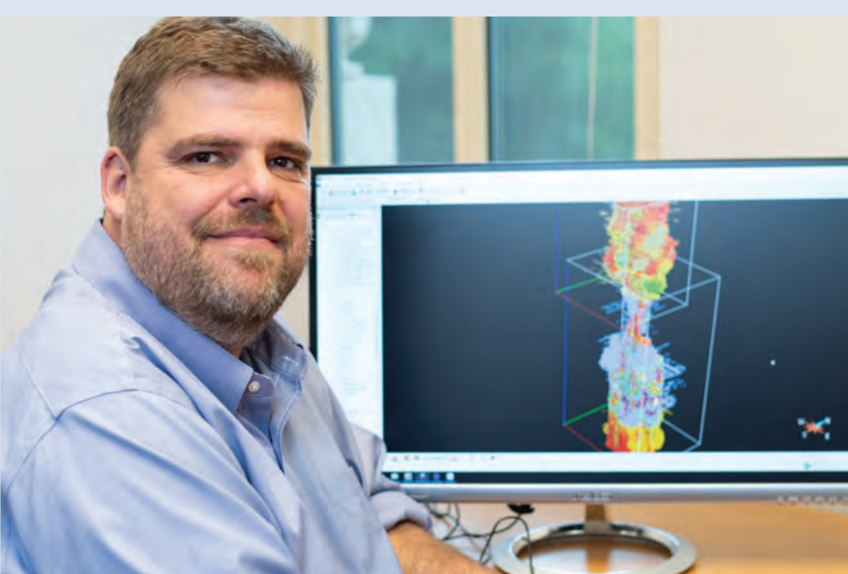
It’s an exciting prospect for Mines researchers that will push them intellectually and push their research forward.

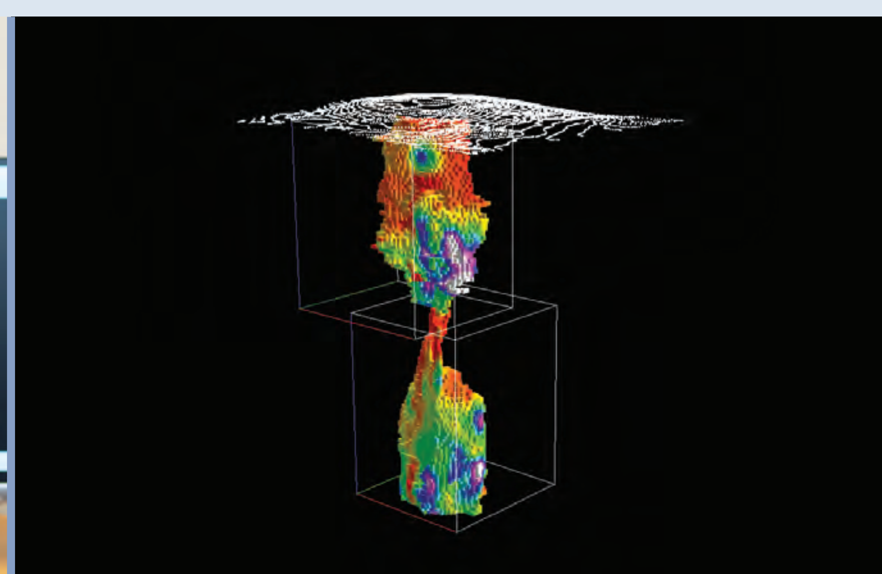
“In the interaction between mathematics and statistics and an applied field like geology, there’s going to be a back-and-forth,” Tenorio said. “Geologists are going to learn math, but then mathematicians are going to learn that there are some questions in geology that are so complex to answer—because in real life, physics is very complex. We’re going to need new mathematical methods to attack some difficult problems.”

For Tompkins, the initiative represents a new way forward in geology—one that Mines students will benefit from in the long term.

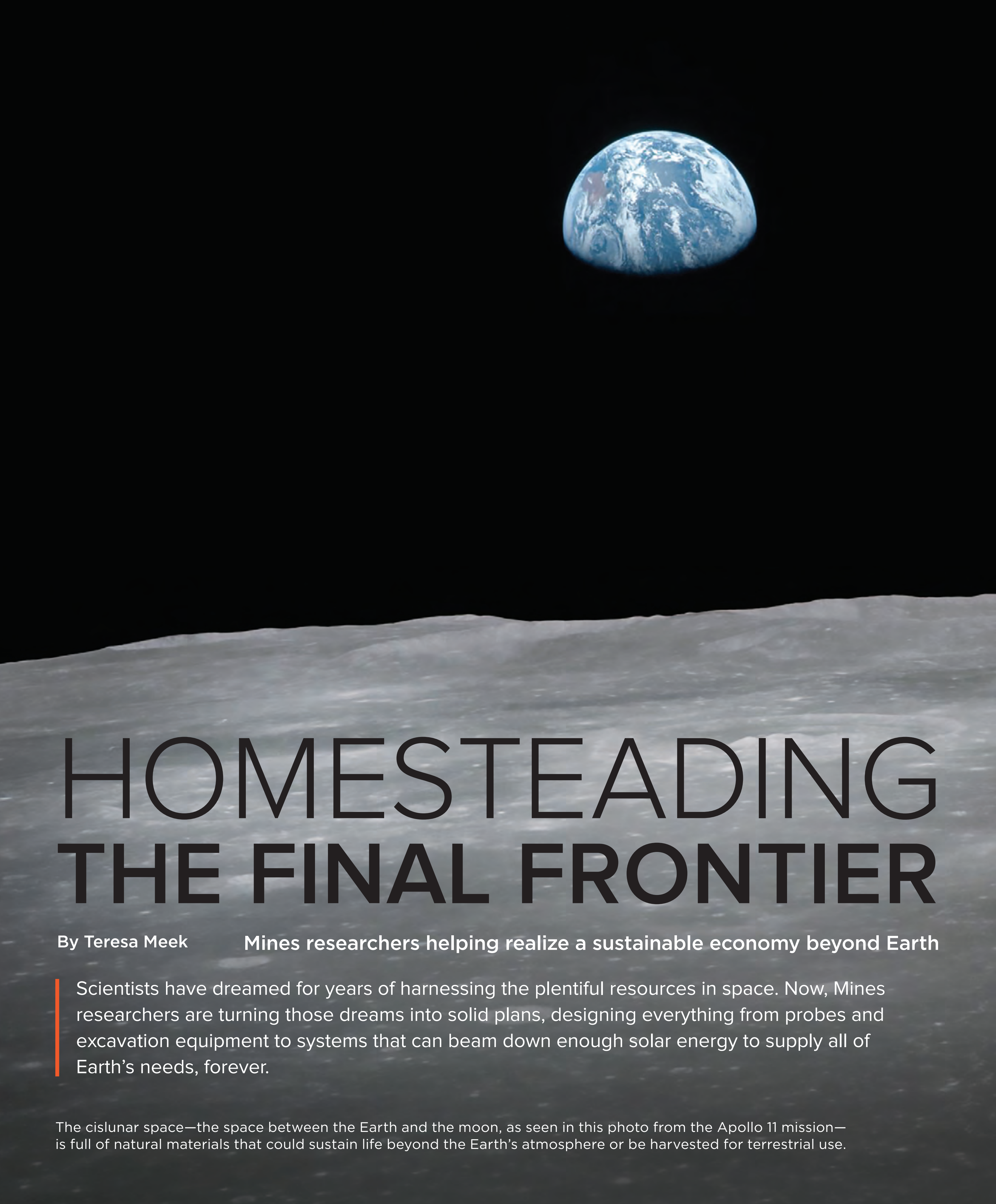
“This world underneath us is invisible to us—it’s the ultimate problem,” Tompkins said. “If you’re a detective, you’re getting tiny, scattered clues from many decades of gathered information, and then you’re supposed to put together this picture of everything, and you can’t see any of it. That’s what geologists do.”

“The fact that we are at a point where we can bring the math and the geology together to the next generation is something that excites me.”





Thomas Monecke, associate professor of geology and geological engineering, is part of a Mines effort that brings together geologists and mathematicians to better model what’s underground. The computer model above shows the distribution of copper grade in the giant Horne volcanogenic massive sulfide deposit in Rouyn-Noranda, Quebec.



HOMESTEADING THE FINAL FRONTIER

By Teresa Meek

Mines researchers helping realize a sustainable economy beyond Earth

Scientists have dreamed for years of harnessing the plentiful resources in space. Now, Mines researchers are turning those dreams into solid plans, designing everything from probes and excavation equipment to systems that can beam down enough solar energy to supply all of Earth's needs, forever.

The cislunar space—the space between the Earth and the moon, as seen in this photo from the Apollo 11 mission—is full of natural materials that could sustain life beyond the Earth's atmosphere or be harvested for terrestrial use.

Though these ideas may sound far-fetched, a quick tour of Mines' Space Resources Program reveals an accelerating series of efforts that are creating a blueprint for the next phases of space exploration and development. The Mines program, the first of its kind anywhere, launched last year with pilot courses that attracted scientists and engineers from around the world. This fall, it began offering courses leading to graduate certificates and master's and doctoral degrees.

Though the Space Resources Program is new, Mines researchers have been studying how to extract and use space materials for over 20 years. Much of the work has taken place at the Center for Space Resources, headed by Mechanical Engineering Research Associate Professor Angel Abbud-Madrid, who now leads the program.

Every year, the Center for Space Resources hosts a roundtable attended by engineers from NASA, United Launch Alliance, Honeybee Robotics and other private companies, as well as Mines faculty. It's more than just talk—researchers are getting down to the nitty-gritty of building and testing equipment. At the end of this year's roundtable in June, they formed teams in a workshop to devise techniques for extracting ice from the moon.

At Mines, professors and students are also working with NASA engineers and private companies to develop an entire space economy, replete with the necessities for sustaining human life, as well as build transportation systems, manufacturing facilities and tourism.

Eventually, this space ecosystem is designed to become self-sustaining, in addition to serving as a jumping-off point for further exploration.

Here's a look at how the space economy will unfold, propelled by Mines research.

An abundance of resources

The cislunar space—the space between Earth and the moon—is full of natural materials that could sustain life beyond ~~the~~ Earth's atmosphere or be harvested for terrestrial use. The moon also has an abundance of water in the form of ice, particularly in its polar regions.

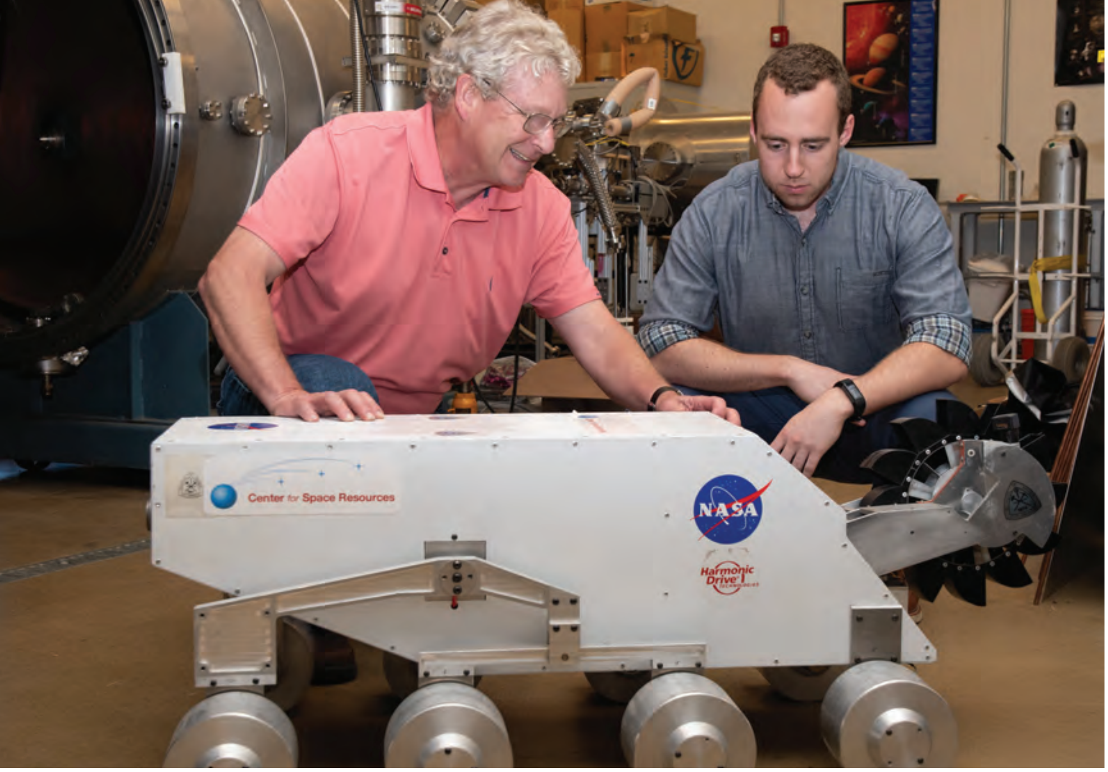
Asteroids also contain large quantities of water, as well as aluminum and silica, which could be used to build solar panels. A single giant asteroid named Psyche 16, which NASA plans to visit in the mid-2020s, contains massive quantities of nickel and iron that could be worth $10,000 quadrillion—way more than the entire $78 trillion global economy—if the materials could somehow be extracted and brought down to Earth.

Farther afield, Mars abounds in water, as well as oxygen, nitrogen, iron, titanium, nickel, aluminum and soil that could be used as a radiation shield.

And the sun? Its power output is 10 trillion times the consumption of the entire human race.

The decision to tap into these resources, however, must be based on economic reality and sustainability, just as it is on Earth.

Right now, getting to space is expensive. It costs $10,000 to launch a single pound of equipment or material into space, Abbud-Madrid said. The economic burden of getting there has precluded private companies from taking a serious interest in space's resources until recently. But the picture has started to change.



Sowers and undergraduate student Colby Moxham review the operation of a bucket-wheel excavator designed to operate on the lunar surface.

Making transportation economically feasible

The main reason space travel is exorbitantly expensive is the launch, said George Sowers, a Mines mechanical engineering professor of practice who is part of the core faculty of the Space Resources Program. Climbing out of Earth's gravitational field is difficult, and the more weight that is added to a space vehicle, the harder it becomes. Because spacecraft must carry enough fuel not only to take off but to fulfil their missions and return to Earth, their payloads are massive. Ninety percent of a rocket's weight consists of the fuel needed to launch a small capsule containing astronauts and supplies.

"Imagine if you drove from Los Angeles to New York and you had to take all your gas with you," Sowers said. "Then you'd need a bigger car, which uses even more fuel. The process spins out of control, and pretty soon you're driving a giant tanker truck."

That's the vicious circle space entrepreneurs are caught in today. But if astronauts could lighten their load by refueling in space, the scenario would change dramatically. The cost of landing a kilogram of mass on the surface of the moon could be reduced from $35,000 to $11,000, Sowers said.

Affordable transportation is the key that unlocks the economic potential to make space exploration and development a reality for private companies, including United Launch Alliance, where Sowers was president before joining Mines last year.

Using space resources would make it possible. All that water on the moon and in asteroids could be broken down into hydrogen and oxygen, the most efficient chemicals that currently exist for propelling rockets. Spacecraft could fill up at cislunar gas stations instead of transporting all their fuel from Earth.

Refueling in space would also make rockets less expensive to build. "You wouldn't have to design spacecraft to withstand the violent force, fire and smoke of a rocket launch," Sowers said. Lighter, thinner spacecraft are appropriate for space, where there is no resisting gravity. When infrastructure is in place, they could be built in situ with local materials and replicated through 3D printing.

Mining in space

Once in space, astronauts will need the right tools to extract the water they need for personal consumption and fuel. To create these tools, Sowers, Abbud-Madrid and Mechanical Engineering Research Assistant Professor Christopher Dreyer, another member of the Space Resources core faculty, are studying the properties of the moon's surface, known as regoliths, and the ice that surrounds them. They have developed an experimental probe to measure the depth, temperature and compaction of the regolith-and-ice mixture to determine what kinds of instruments are needed to penetrate it.

"It could be as hard as concrete, or even harder. Or it could be like dirty snow," Dreyer said. In addition to adjusting for a variety of conditions, drill bits need to be made of special materials to withstand temperatures of 40 degrees Kelvin (negative 387 degrees Fahrenheit).

Another possibility is extracting water from asteroids. Dreyer and a co-investigator are working under a NASA grant—Mines received $140,000—to do just that. In a large vacuum chamber at Mines, they blast the surface of asteroid simulants (terrestrial materials developed by minerology experts that are mixed with water to form a paste) with concentrated beams of light. As the mock asteroids heat up, they fracture, releasing water vapor, which collects on a plate of stainless steel chilled with liquid nitrogen. There, it freezes, adhering to the plate. "We call it a cold trap," Dreyer said.

In space, an asteroid would be contained in a giant bag maneuvered into place by spacecraft and sealed. Solar energy would be directed at it, and ice that forms on the cold trap would be melted into water or separated into hydrogen and oxygen to use as fuel.

Harnessing solar energy

As transportation becomes cheaper and more space resources are collected, studied and used, the space economy will expand. "An infrastructure will slowly develop, always with a trade-off in mind of how much it costs to ship something to space versus making it in space," Sowers said.

With an infrastructure in place, one of the most exciting developments could be providing solar energy to Earth, a project that will likely grow in importance as Earth's own resources are depleted. Space materials could be used to build an enormous solar power system that would beam enough of the sun's energy to supply the needs of the entire planet.

On Earth, rectennas—large, rectangular grids of wires spaced several feet apart and mounted 20 feet above the ground—would act as receivers, Sowers said. Farmers could grow crops and plow the land beneath them with no ill effects from the sun's microwaves.

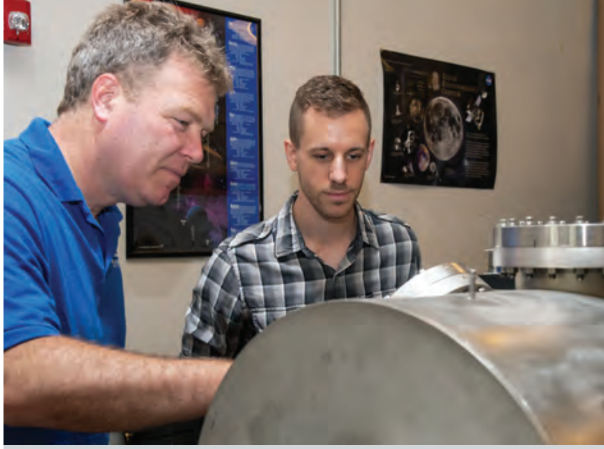
Because so much strife results from disputes over resources, having an unlimited energy source could usher in more peaceful times. "In a post-scarcity world, there is no more reason to have conflict," Sowers said. Instead, people might spend their money on pursuits such as space tourism, something billionaires are already investing in. Settlements on the moon or in cislunar space could develop, with space stations that serve as launching points for journeys to Mars and beyond.

Though these later-stage developments are still a ways off, the process for using resources in space is well underway and could happen sooner than many people think. A NASA mission is currently cruising to the asteroid Bennu, where it is expected to land in December 2018 to collect materials and probe for water. If private companies maintain their interest, extracting resources from asteroids could start within a decade, researchers say. NASA has said it wants to send humans to Mars in the 2030s.

But the journey into cislunar space and beyond is not likely to be a smooth one. It will proceed in fits and starts as scientists adjust their theories to yet-unknown conditions. In addition to the physical hurdles, a space economy will raise tough new questions about international rights and ownership. Despite these challenges, progress is bound to continue—as long as scientists and engineers can make good use of the materials at hand.

"If we learn how to live off the land in space, it will allow us to keep going further and further," Abbud-Madrid said.

Abbud-Madrid and mechanical engineering master's student Hunter Williams examine the center's large vacuum chamber, which simulates lunar, Martian and asteroid environments for resource-extraction experiments.



Dreyer and geophysics PhD student Jared Atkinson work on an experiment to determine the geophysical properties of lunar regolith.

A multidisciplinary pursuit

The expertise needed for using space resources spans almost every discipline at Mines.

Developing drills and excavators is a traditional part of mining engineering. Both faculty and students, some of whom have won prizes in NASA competitions, are involved in re-engineering traditional mining equipment to work on the moon and planetary surfaces.

Once resources are extracted, skills in chemical engineering and metallurgy come into play to process metals and turn water into fuel.

Computer engineering is needed to develop the 3D printing that will enable astronauts to make spare screwdrivers and wrenches and, eventually, to develop full-scale manufacturing.

Communications will also be vital. Computer Science Associate Professor Qi Han is developing a network to coordinate multiple space vehicles as they take measurements of space bodies and send their information to a command-and-control spaceship that will transmit the data to Earth.

"We utilize every single department of the school" Abbud-Madrid said. "That's why Mines is so well-suited to having a Space Resources Program."

Analyzing algae to speed up biodiesel development

Nanette Boyle, assistant professor of chemical and biological engineering, has been awarded $750,000 over five years through the ~~U.S. Department of Energy's Early Career Research Program~~ to develop predictive metabolic models for algae—work that could help speed up the commercialization of strains that produce renewable biodiesel.

"Algae have been touted as the next big thing in biofuels research but they haven't really reached their potential yet," Boyle said. "They have a lot of advantages over crop plants in that they grow faster, they can be grown in brackish or wastewater and they have higher yields of the precursors for biodiesel. But part of the reason they haven't reached that potential is we don't have as advanced engineering tools as we do for the traditional model organisms like *E. coli* and yeast."

Boyle's research will focus on *Chromochloris zofingiensis*, which is valued for both its ability to accumulate a large amount of lipids, the precursor of biodiesel, as well as astaxanthin, a high-value antioxidant that is used as a nutraceutical. The metabolic model will be developed using a systems biology approach, in hopes of predicting ways to engineer around one of the biggest challenges in growing algae compared to other organisms: changes in light when grown outside.

"The most economical way to grow algae is outdoors, where they're getting free CO2 and light, but this comes at a cost—the metabolism of the cells is constantly changing because of the day/night cycles," Boyle said. "Typically, these cells store some kind of carbon—in this case, starch—during the day so they can use it at night. If we're trying to engineer them to make biofuels, we want them to put as much as carbon as possible toward the biofuel and not starch."

As part of the research, Boyle will conduct large-scale outdoor tests at the DOE-funded algae test bed, the Arizona Center for Algae Technology and Innovation, at Arizona State University, where Boyle completed her undergraduate studies.

"Along the way, we're also going to be learning a lot more about cellular physiology," Boyle said. "These day/night cycles are important for algae but also plants, humans and animals as well. Circadian rhythms play a large role in our lives so it's really important to understand the variations that occur from day to night."

Boyle joined Mines in 2013. She received her PhD in chemical engineering from Purdue University and conducted postdoctoral research at University of Colorado and UCLA.

Understanding alloys that can take a hit

Amy Clarke, associate professor of metallurgical and materials engineering, has received a ~~Young Investigator Award from the Office of Naval Research~~ to study certain alloys for their ability to withstand explosive blasts.

The project, "In-Situ Studies of Strain Rate Effects on Phase Transformations and Microstructural Evolution in β-Titanium and Multi-Principal Element Alloys," will receive $510,000 over three years. Clarke's team will investigate metastable β-titanium and multi-principal element alloys that exhibit transformation-induced plasticity (TRIP) and/or twinning-induced plasticity (TWIP) for blast resistance.

The team will conduct state-of-the-art multiscale characterization of microstructural evolution during and after quasi-static and dynamic loading to fundamentally understand TRIP/TWIP. "This new knowledge will drive the design of lightweight metallic alloys with tailored deformation mechanisms for blast resistance and performance in extreme environments," Clarke said.

At Mines, Clarke is the site director of the Center for Advanced Non-Ferrous Structural Alloys and affiliated with the Advanced Steel Processing and Products Research Center. She holds master's and doctoral degrees in metallurgical and materials engineering from Mines and worked as a scientist at Los Alamos National Laboratory before joining the Mines faculty in 2016.

Improving our understanding of high-strength steels

Kester Clarke, assistant professor of metallurgical and materials engineering, has received a National Science Foundation CAREER Award for work to improve the fundamental understanding of advanced high-strength steel, research that could ultimately help make automobiles safer and more fuel-efficient.

The project, “Controlling Austenite Stability and Response During Deformation of Advanced High Strength Steels,” will receive $500,000 over five years.

Over the last 15-20 years, sheet steels used in automotive bodies have achieved strengths that are five times those of previous alloys, advances driven in large part by increasing fuel economy and safety standards, Clarke said. Typically, increasing strength results in a compromise in ductility—the ability to stretch or bend without fracture—but metallurgists have been able to minimize the severity of the trade-off in these new advanced high-strength steels by designing the steels’ microscopic structure to resist fracture.

“We’ve come a long way already—we’ve been able to make steels at really high strengths—but we’ve done a lot of that pretty blind. If we understand all of this a little more, we’ll be able to further create steel microstructures that have even more exceptional properties,” Clarke said. “The hope would be to then be able to apply that to automotive uses. But once you understand this fundamental stability, it can be applied to industries outside of automotive that use steels and even industries that use other materials.”

Clarke’s team will focus on uncovering the relationships between the processing of these steels, their microscopic structure and their properties and performance. Among the variables they will examine are the way the steel is deformed, how fast that deformation occurs, the pressure under which the steel is deformed and the temperature at which it is manufactured.

A Mines alumnus, Clarke joined the faculty in 2016. He holds master’s and doctoral degrees in metallurgical and materials engineering from Mines, a BS in materials science and engineering from Wayne State University and a BA in psychology from Indiana University.

‘Peeking under the hood’ of polymers in energy devices

Steven DeCaluwe, assistant professor of mechanical engineering, has been selected for the U.S. Department of Energy’s Early Career Research Program and will receive $750,000 over five years to support the development of novel neutron scattering experiments to understand and improve functional polymers used in hydrogen fuel cells and lithium-air batteries, paving the way for more efficient, durable and lightweight energy devices for electric vehicles.

“At this critical moment, it’s about giving people cheaper and cleaner ways to get around,” DeCaluwe said. “What we’re trying to do here is take a peek under the hood. When you modify the design for a device, you can usually see how the performance changes—but to improve it, you want to know why. Neutrons really let you see beneath the surface and understand why you’re getting the performance you get.”

Neutrons are well suited for studying energy devices, DeCaluwe said. They are low-energy and can measure materials without the risk of changing them. They are also more sensitive to the differences between “lighter” elements and those close to each other on the periodic table—with X-rays, nearby elements can often look the same.

Neutron reflectometry is a technique that can analyze “buried” layers and interfaces but is currently restricted to materials in static states. DeCaluwe’s research will enable neutron reflectometry to also look at active materials during device operation.

“With energy technology, we’re trying to make devices cheaper and more durable. Hydrogen fuel cells are starting to get a small foothold as something people can use but they still need to be cheaper, and lithium-air batteries are at this stage just a promising idea,” he said. “These measurements will provide direct insight into material limitations, helping us figure out how to get these devices to live up to their great promise.”

DeCaluwe joined Mines in 2012. He has a bachelor’s degree in elementary education and mathematics from Vanderbilt University and taught first and second grade for three years before earning his PhD in mechanical engineering at the University of Maryland.

Unearthing the origins of Nevada gold

Nearly 80 percent of all gold produced in the U.S. comes from Carlin-type deposits in northern Nevada, which are characterized by extremely fine-grained gold that can only be found through chemical analysis, but scientists still don't agree on how they came to be.

Elizabeth Holley, assistant professor of mining engineering, has received a National Science Foundation CAREER award to tackle that scientific debate. Her project,"Did Carlin-type Gold Come From Magmas?", will receive $534,546 over five years.

"Despite more than 50 years of production, we don't completely understand the geologic processes that formed these deposits. The most contentious debate is whether or not the gold came from magmatic fluids," Holley said. "If we could determine which processes, such as magmatism, were key to gold mineralization, mineral exploration efforts could target sites where these processes have occurred. Currently, it's difficult to say whether Carlin-type deposits formed outside of Nevada, because we don't know which ingredients were necessary."

Holley's innovative approach is to examine the Battle Mountain district in Nevada, a less-studied region with potentially clearer links to magmatism. The Battle Mountain district contains porphyry and skarn-type gold deposits known to have formed in association with magmatic activity, as well as some smaller deposits with Carlin-like characteristics.

Holley and her team will employ geochronology and thermo-chronology to try to tie the deposits to the ages of magmatism. Holley's team will also look at the signature of the mineralizing fluids, using stable isotopes and fluid inclusions to see if they can get a "magmatic fingerprint" on the fluids that caused the gold mineralization.

"The traditional approach has been to examine the Carlin-type deposits themselves, where any link to magmatism would be hard to identify," she said. "We're taking the opposite tactic by starting with deposits that clearly have a magmatic signature and working outward to more distal environments where that signature may be more subtle."

A Mines alumna, Holley joined the Mines faculty after completing her PhD in geology in 2012. She holds a master's degree in geochemistry from the University of Otago, New Zealand, and a bachelor's degree in geology from Pomona College.

Digging into the roots of subsurface rock cracks

Reza Hedayat, assistant professor of civil and environmental engineering, has been selected for the U.S. Department of Energy's Early Career Research Program.

Hedayat will receive $750,000 over five years to support the development of novel multiscale experiments to identify the geophysical signatures accompanying subsurface crack network growth.

"Understanding crack network growth in rocks is important for both the design and optimization of hydraulic fracturing operations, carbon sequestration and geothermal energy," Hedayat said. "Key subsurface processes, such as crack network coalescence, occur quickly and there lies the challenge we face—simulating subsurface conditions in the laboratory and developing tools to predict and monitor cracking."

The behavior of the Earth's subsurface is controlled by discontinuities and cracks, ranging in scale from micro-cracks (micrometers) to fractures (millimeters to meters) to faults (tens of meters to kilometers).

To better understand how those crack networks interact and grow, Hedayat will use a true-triaxial testing system that is capable of simulating subsurface stress conditions. Compression experiments will be conducted on both transparent rock analogues with a random crack network and on natural sandstone and shale rock blocks.

"Monitoring cracking processes in real time with advanced high-resolution imaging techniques and using creative laboratory conditions that simulate the in-situ environments offers unprecedented opportunities for identifying the underlying causes and conditions," Hedayat said. "At Colorado School of Mines, we are uniquely positioned to conduct this research and I am grateful to the Petroleum Engineering Department for providing access to the true-triaxial loading system."

Since joining Mines in 2015, Hedayat's research has focused on developing and using geophysical techniques for characterization of geomaterials and evaluation of underground structures. He holds a PhD in civil engineering from Purdue University.

Leveraging graphics cards for faster computer performance

Bo Wu, assistant professor of computer science, has received a National Science Foundation CAREER Award to develop techniques to support multitasking in graphics processing unit computing.

Wu's project, "Compiler and Runtime Support for Multi-Tasking on Commodity GPUs," will receive $501,546 over five years.

Designed to accelerate parts of a single application and work as coprocessors with general-purpose central processing units, GPU computing has become mainstream in recent years, used in machine learning, graph analytics and scientific simulation, as well as data centers and cloud computing infrastructures where users increasingly demand accelerated applications.

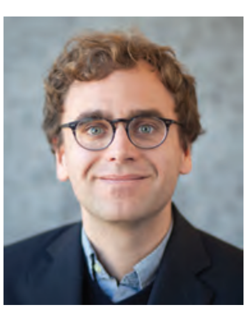
"When users connect to services on the internet like Google's search or Apple's Siri, their request is handled on the same server as many other users' requests. To handle this traffic, many companies are now leveraging the computing power of the graphics cards present in many modern computers. However, GPUs lack necessary hardware support to guarantee quality of service in such scenarios," Wu said. "This CAREER project aims to tackle this problem by developing software which slightly changes existing applications to allow them to coordinate their execution for both performance and fairness."

Wu's team will develop both compiler and runtime techniques to help accomplish transparent, efficient multitasking. Compiler techniques will help circumvent the hardware limitations of GPUs and allow a set of additional features, such as preemption, while runtime systems will permit the scheduling of applications to best utilize the potential of the GPU and guarantee quality of service.

As part of the project, Wu will work to advance GPU education at Mines for both computer science and non-computer science majors.

Wu joined Mines in 2014 after earning a PhD in computer science from The College of William and Mary. He holds a master's degree in computer science and a bachelor's degree in mathematics from Central South University in Hunan, China.

Modeling fluid dynamics for improved wastewater treatment



Nils Tilton, assistant professor of mechanical engineering, has received a National Science Foundation CAREER Award to develop a computational fluid dynamics model to improve efficient, low-energy options for wastewater treatment and desalination.

Tilton's project, "Robust Numerical Modeling for Rational Design of Membrane Filtration Processes," will receive $547,364 over five years.

"Shortages in potable water are creating a large demand for water treatment and desalination. California's recent drought, for example, is motivating municipalities to invest in seawater desalination plants. The problem is that desalination requires a lot of energy, and the generation of that energy by power plants requires a lot of water. In the process, you also make more pollution, which exacerbates climate change and drought," Tilton said. "Finding new, more energy-efficient ways of producing potable water is key to securing long-term water and energy security."

Tilton's work will focus on membrane separation processes, such as reverse osmosis and nanofiltration. Both offer promising low-energy solutions for desalination and wastewater treatment—that is, until the membranes get bogged down.

"You're basically filtering water by forcing it through a membrane that acts like a sieve—water goes through the membrane while salts and other contaminants are blocked," Tilton said. "The problem is, all that stuff builds up on the membrane and increases the pressures needed to force the water through. With time, the salts also form a hard mineral scale, like the calcium deposits you get on shower walls, that impedes filtration, damages the membrane and increases maintenance costs."

That retention of solutes can be tackled by patterning a mesh-like net of physical spaces on the membrane to alter the fluid flow at the surface. The impact of those feed spacers, however, is not well understood.

Tilton and his team will develop a new method for simulating the interactions between polarization, scaling and mixing due to feed spacers, then design better patterns for the meshes to minimize polarization.

Tilton joined Mines in 2014. He holds a PhD, master's degree and bachelor's degree in mechanical engineering from McGill University in Montreal.

Investigating mixed-molecular solids using atom probe tomography

Jeramy Zimmerman, assistant professor of physics, has been selected for the U.S. Department of Energy's Early Career Research Program and will receive $750,000 over five years to support his research on understanding and controlling aggregation processes in mixed-molecular solids—work that has direct applications to something in most everyone's pocket or purse right now: their smartphones.

"In many phones, each pixel in the display is actually an organic light-emitting diode," Zimmerman said. "We currently aren't sure why they don't work as efficiently as they should. The information we are collecting will allow us to unravel this mystery."

"Jeramy's use of 3D atom probe tomography methods to characterize mixed molecular solids on the molecular level and to correlate and control their structure and properties is truly groundbreaking research," said Michael Kaufman, vice provost for strategic initiatives and dean of materials and energy programs. "This prestigious Early Career award from DOE recognizes this early success and will enable him to take his preliminary research to the next level, which could significantly impact several important technologies that utilize these types of materials."

The idea for Zimmerman's research originated during a phone interview with Mines in 2013. A 2002 graduate of Mines, he earned a PhD from the University of California, Santa Barbara, in 2008 and held postdoctoral fellow and assistant research scientist positions at University of Michigan from 2008 to 2013 before returning to Mines in 2014.

Since rejoining Mines, Zimmerman's group has been developing techniques to use atom probe tomography on molecular organic systems, allowing them to get chemical and structural information on a smaller scale than ever achieved before.

"It is very exciting to receive this award as we are the only group currently performing this analysis and it provides previously unavailable information that allows us to understand solids made from mixtures of different molecules," Zimmerman said.

Future Breakthroughs

Materials science graduate student Jesse Adamczyk, second from left, is joined in Physics Associate Professor Eric Toberer's lab by the next generation of pioneering scientists. From left are Tara Braden, Sean Ross and Nichole Schneider, all taking part in the undergraduate research program at Mines.

Morgan Bazilian was named the inaugural executive director of the Payne Institute in February and is research professor of public policy in the Division of Economics and Business at Mines. He is a former lead energy specialist at the World Bank and is a widely recognized expert in energy and natural resources planning, investment, security, governance and international affairs.

Bridging science, engineering and public policy

When Jim Payne '59, with his wife, Arlene, founded the Payne Institute at Mines in 2015, he endowed it with a clear objective: "My vision is to leverage the university's first-rate academic research and have the institute serve as one of the country's premier venues for those engaged in public policy discourse on the challenges shaping our future."

Thus, we are establishing a new cross-campus organization that will act as a bridge between the world-class science and engineering insights and experience found across Mines and the policy sphere. As with many university-affiliated institutes in energy, natural resources and the environment, the work will initially come in the form of partnerships, gatherings, thought leadership and research support.

Through the Payne Summer Internship Program, students from across campus address issues such as the role of major oil and gas companies in the current transition to cleaner energy technologies; possible chemical and material uses for coal outside of power generation; links between mining and energy requirements in developing countries; mapping instances of energy, natural resources and conflict; and how energy, water and food services are delivered in refugee camps.

A key inquiry focused on what role minerals and metals will play in the energy transition. This work involved collaboration with researchers at Mines' Critical Materials Institute, Columbia University and Bruegel, a Brussels-based economic think tank.

This area of study perfectly fits the strengths of Mines faculty and offers a positive and forward-looking agenda for the mining industry. This summer's work provides a basis for the Payne Institute and Mines to be leaders on this critical topic.

The primary mineral and metal technical challenges of the energy transition are slowly emerging, as are geopolitical ramifications. While the direction of travel in the energy transition is beginning to become clear, its pace and contours remain elusive. Still, the tremendous growth in some specific technologies—such as electric vehicles, storage batteries and solar photovoltaics—appears assured based on recent growth and cost trends.

Those technologies, along with possible system-wide changes in continued electrification and digitalization of the energy system have very different profiles in terms of their requirements for minerals and metals than the existing portfolio. These potential impacts on markets and resources have begun to provide fodder for a nascent literature.

Parts of the somewhat heterogeneous mining and extractive industries are adapting by refining their business practices and marketing toward that of an industry crucial to supporting a shift to a low-carbon and environmentally friendly energy system. Markets are responding with upticks and increased volatility in pricing in metals from nickel to zinc to cobalt.

Many, if not most, of the countries with the largest potential and existing markets for these minerals are emerging and developing economies. There are other concerns as well—governance and a changing geopolitical landscape both contribute to uncertainty. We hope the Payne Institute can make a positive contribution to this ongoing discourse.

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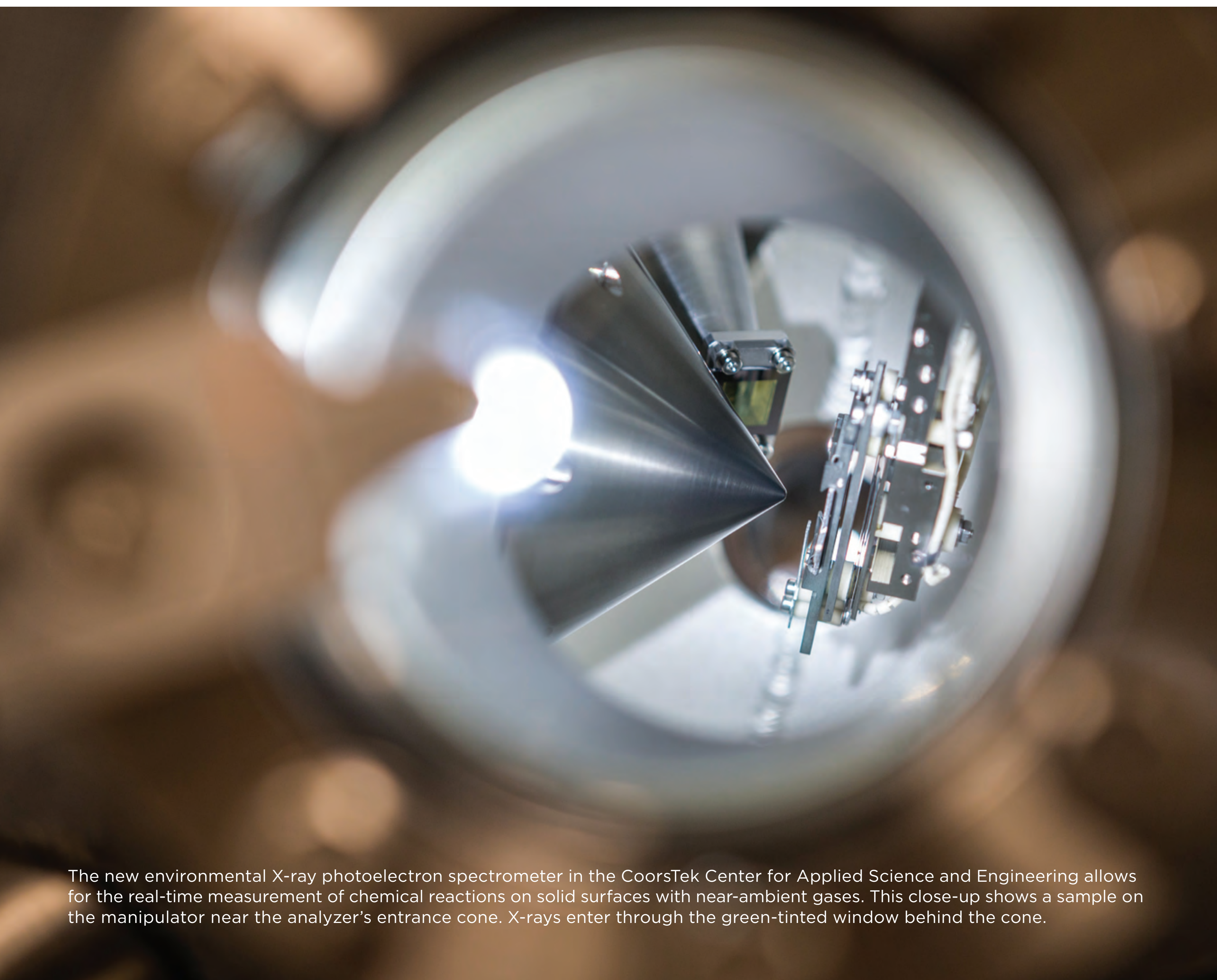

The new environmental X-ray photoelectron spectrometer in the CoorsTek Center for Applied Science and Engineering allows for the real-time measurement of chemical reactions on solid surfaces with near-ambient gases. This close-up shows a sample on the manipulator near the analyzer's entrance cone. X-rays enter through the green-tinted window behind the cone.