

COLORADO SCHOOL OF MINES

# RESEARCH

2019-20



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WHAT'S IN YOUR  
**WATER?**

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## Water | 22

What happens when our water supply is contaminated with substances that have an adverse effect on the human body and environment, and what steps can we take to treat that water?

Persistent chemical compounds are lurking in our water supply, but Mines researchers are working on new treatment methods to remove and destroy these chemicals from our water. The meter shown here is part of a larger treatment system currently being put to the test on the Mines campus.



FROM THE RESEARCH TEAM ▼

## A preferred partner for solving complex problems

Mines has long been a university with cutting-edge, use-inspired research at the forefront of change. And in the 2018-19 academic year, when faced with quickly evolving and often complex societal needs, we significantly expanded our research portfolio, while remaining true to our commitment to tackling some of the most difficult challenges in earth, energy and environment. We increased our external funding this year by 25 percent—evidence that we are a preferred partner for industry and government agencies—and provided new perspectives on important challenges that affect people around the world, including:

- Finding solutions to groundwater contamination, such as treating pollutants created from industrial and military firefighting foams, which Mines recognized as a problem long before it rose to national attention.
- Lending our expertise on the extraction of natural resources, like our work with universities and mining companies in Colombia and Peru, to support sustainable practices for artisanal and small-scale mining, which generates about 25 percent of the world's gold but exposes humans to dangerous levels of mercury.
- Finding new applications for 3D-printed metals, which Mines is moving from "interesting" to indispensable when used as replacement parts for U.S. military vehicles and within nuclear reactors.
- Developing innovative solutions to energy storage, generation and maintenance, such as new approaches to renewables and robotic repair of power plants.
- Exploring new healthcare methods by creating customized medical technologies, like nanoparticles that can break up mucus in lungs.

In many of these examples, Mines has been specifically sought out by our legislature, industry and international partners for our expertise and willingness to take on problems at real-world scales. I hope this issue inspires you to learn more about our work and partner with us in solving problems that matter.

**Stefanie Tompkins**

Vice President for Research  
and Technology Transfer



**Subsurface | 06**

**How can we manage the extraction of natural resources in a manner that is sustainable, supportive of local economies and minimizes environmental impacts?**

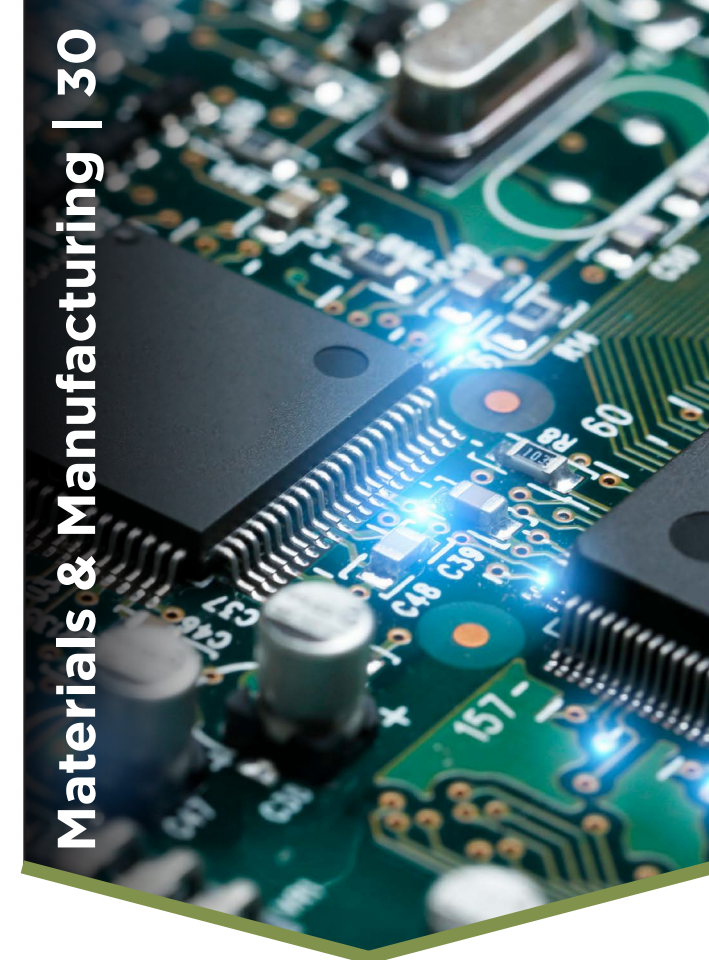
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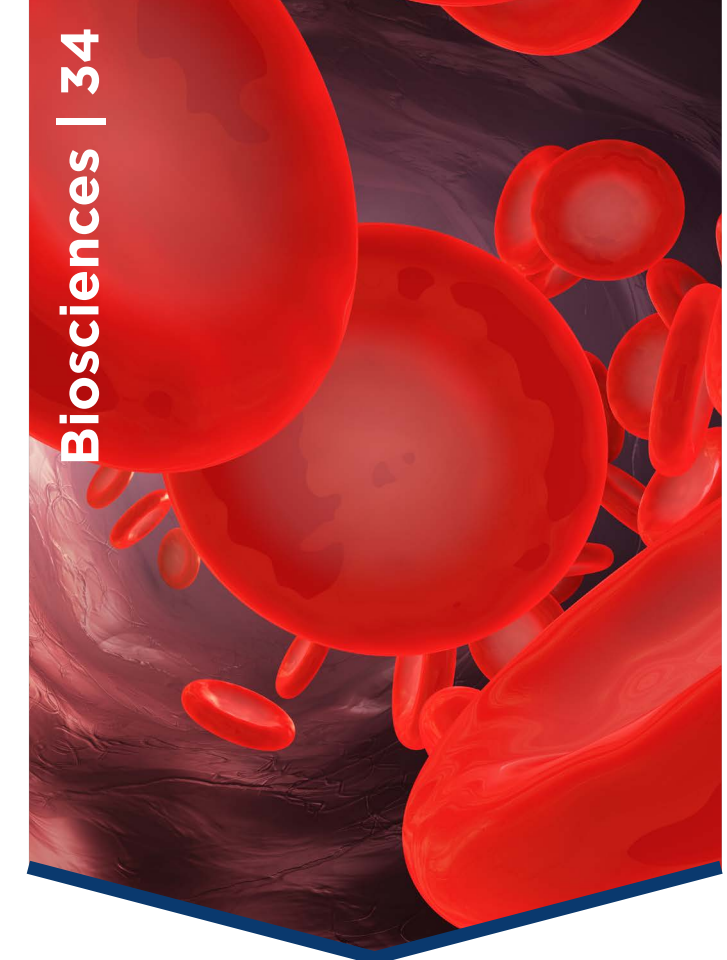
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**Biosciences | 34**

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COLORADO SCHOOL OF MINES

# RESEARCH

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Colorado School of Mines  
President and Professor  
Paul C. Johnson

**Vice President for Research and Technology Transfer**  
Stefanie Tompkins

**Associate Vice President of Research**  
Sridhar Seetharaman

**Chief Marketing Officer**  
Jason Hughes

**Editor**  
Ashley Spurgeon

**Contributing Writers**  
Lori Ferguson, Jenn Fields, Sarah Kuta, Mark Ramirez, Emilie Rusch

**Photography**  
Agata Bogucka, Joe DeInero

**Graphic Design**  
Christina Vessa, Wan Jun Aida Wan Ahmad Johari

**Cover:** Harmful chemicals are lurking in our water supply, but Mines researchers are working on treatment methods to eliminate the threat. (Designed by Wan Jun Aida Wan Ahmad Johari and Aubrey Bradford)

## Picking up speed

### Mines researchers are making tunnel boring machines faster and smarter

Underground tunnels can solve many problems—they can alleviate traffic congestion, enable rapid transit and even improve military supply lines. However, the machines that make tunnels possible are big, heavy and slow, usually boring only a few inches per minute below the surface. But Mines researchers are hoping to change that standard with solutions that will make tunnel boring machines operate faster and smarter.

#### How could “smart” tunneling be possible?

Using artificial intelligence techniques and copious amounts of data, researchers will learn how to operate tunnel boring machines better, with the intention of making the machines move faster, support continuous tunneling and prevent damage to nearby infrastructure. Data from sensors measuring pressure, force, movements and vibrations suggest optimal settings in real time, giving operators the ability to adjust controls without stopping the machine or before running into hazards along the way.

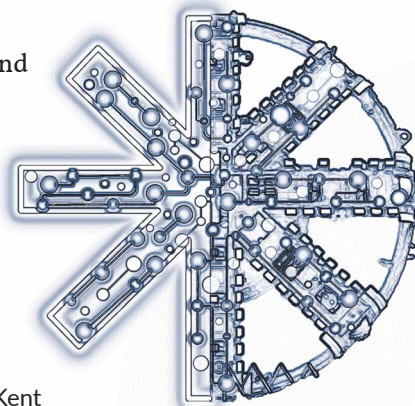
#### What are the possible results of this research?

It typically takes about 24 hours to construct a 500-meter small-diameter tunnel, but in working with key industry collaborators, Mines researchers think they can get it down to 83 minutes or less. According to Mike Mooney, Grewcock University Endowed Chair and director of Mines' Center for Underground Construction and Tunneling, Mines research has also shown that tunneling speed can be improved by 30 percent to 100 percent using AI.

#### Who can benefit from this technology?

While a city's infrastructure could rapidly expand with faster moving tunneling technology, researchers are also collaborating with the U.S. Department of Defense to drastically speed up the construction of small-diameter supply tunnels.

- ▶ To learn more about Mines Underground Construction and Tunneling, visit [underground.mines.edu](https://underground.mines.edu).



Tunnel boring machine illustration by Wendy Kent

## An underground lab

### What:

Edgar Experimental Mine. The mine was a working operation in its early days, producing high-grade silver, gold, lead and copper in the 1870s. Mines acquired the property in 1921. Today, it operates as both a classroom and research facility.

### Where:

Approximately 40 miles west of Denver in the foothills of Idaho Springs.

### Why:

Mining—it's in our name. It seemed natural to provide a university-owned facility where researchers could test out ideas for new mining techniques and systems. Edgar Mine also offers a unique environment for Mines students of all disciplines to gain hands-on experience in underground mine surveying, geological mapping, rock fragmentation and blasting practice, mine ventilation field studies, rock mechanics instrumentation practice, underground mine unit operations, mine safety and more.

# Sustainability and mining can (must) go together

Mines and Peru's Universidad Nacional de San Agustín put best practices front and center

By Lori Ferguson

**In Peru, artisanal and small-scale mining is a way of life.**

Miners extract valuable ore, such as gold, copper and zinc, from marginal deposits not deemed profitable to mine on a large scale, often using simple tools and rudimentary practices.

The work is difficult and dangerous. Miners frequently labor under conditions devoid of the most basic safety, health and environmental standards, and residents of surrounding communities experience a host of problems, from air and water pollution to geologic hazards, such as landslides.

In 2002, the Peruvian government began a concerted push to address these industry issues. And in 2018, researchers from the Universidad Nacional de San Agustín (UNSA) in Arequipa—the country's second most industrialized city—decided to partner with another university to find viable solutions to the safety and environmental concerns that plague the industry. They turned to Mines, an institution recognized worldwide as a leader in mining and sustainability research.

Mines faculty recognized the natural fit for the interdisciplinary research approach they favor and appreciated the

challenges that Peru faces—some of Colorado's abandoned mines present engineers with legacy and reclamation challenges that bear a striking resemblance to many of Peru's small-scale mining concerns.

The collaboration was finalized in July 2019 with the formal creation of the Center for Mining Sustainability. The center will address the environmental and societal concerns surrounding small-scale mining and promote the practice in a way that sustains the industry, supports local economies and minimizes environmental impacts.

Paul Santi, Mines professor of geology and geological engineering and the center's director, is excited by the opportunities inherent to the new joint venture. "Mines' technological focus

**Arequipa, Peru**

<b>ALTITUDE:</b>	6,305m (highest elevation)
<b>POPULATION:</b>	1,382,730 people
<b>DISTANCE:</b>	1,022 km from Lima
<b>AREA:</b>	63,345.39 km <sup>2</sup>



Small-scale mining is crucial to Peru's economy, but the work is often difficult and dangerous. In collaboration with Universidad Nacional de San Agustín, Mines is helping address these industry issues and create new best practices in the region.

on engineering and science and our great strengths in geology, water, mining and materials make us an obvious choice to undertake this initiative with UNSA," he said.

Small-scale mining is a reality for many and a practice that's not likely to disappear anytime soon, Santi said. "This is how people in many parts of the world make a living, so our job is to find ways to increase their safety and minimize the environmental and health impacts that mining creates."

Formally speaking, said Santi, the center's vision is to provide research-driven solutions for mining issues by building research capacity, training scientists and

solving key mining, environmental and societal problems. But in his eyes, the partnership boils down to three main goals. The first is the chance to make a meaningful, humanitarian contribution. "Our aim is to improve what's going on in small-scale mining in terms of safety and efficiency, not only to make it a more viable lifestyle but also to improve the safety of the communities around mines by reducing contaminants in the air and water," Santi said.

The second is to assist UNSA in developing a deeper research culture across the institution. "The university's culture is historically that of a teaching institution, but they would like to increase their

focus on research," Santi explained. "This is much like the situation Mines found itself in 30 or 40 years ago—a teaching institution that was leaning more toward research—so I think we're ideally suited to help UNSA achieve its goals."

The third is to do good—and interesting—science. "This is an opportunity to do some cool things in a unique setting," Santi said. The partnership has launched with intensity—nine projects running simultaneously—and is set to complete its current phase in November 2020. "We're operating on a rather short fuse," Santi conceded. "But the collaboration's off to a great start and is running smoothly. We learned a lot from Purdue University's



Illegal gold mining along the Madre de Dios River is often a dangerous practice that can have significant environmental and health risks.  
Photo by Ryan M. Bolton/Shutterstock.com

existing agricultural partnership with UNSA, so we were able to hit the ground running.”

### Actionable ideas, broad impact

Among the projects currently underway is an investigation into a series of large landslides in the Arequipa region. “These landslides have the potential to do great damage—to the Pan-American Highway, to a milk plant and to communities in the area,” said Santi. “We’re running geophysical studies and doing groundwater modeling to figure out how water usage and irrigation practices are contributing to these events and formulate ways to prevent them in the future.”

Another project in the works involves the transformation of mining liabilities such as tailings—the dusty, mud-like waste that is left behind after the valuable portion of the ore is separated from the unusable portion—into benefits. Tailings are often

toxic, and their storage and handling pose a huge problem for mining operations worldwide, said Reza Hedayat, a civil and environmental engineering assistant professor who is among the faculty addressing the issue. “We’re currently evaluating the properties of the tailings to see how they can be recycled and reused, perhaps as bricks or construction and road-based materials,” he said.

Tailings present a large potential detriment to the environment as they can contribute to air and groundwater pollution, Hedayat continued. “If we can engineer processes that will allow us to turn waste materials into materials of need, it would be incredibly valuable.”

It’s this kind of sustainability—another Mines strength—that plays a key role in every mining endeavor. “If we can become more adept at extracting valuable materials

from the ore, as well as at reusing whatever byproducts are produced, we can reduce the overall environmental impact of artisanal mining, which is so important,” Hedayat said.

For Priscilla Nelson, developing knowledge that leads to something approximating zero waste is a laudable goal. And the only way to truly achieve sustainability, says the professor and former department head of mining engineering, is to be good stewards of Earth’s resources. “Materials are not being produced by geological processes at the rate we’re using them,” she pointed out, “so we have to be more thoughtful.”

Nelson is particularly excited about the tailings project. “Right now, tailings are being stockpiled in tailing dams, leaving us with a lot of materials for which we have no use,” she said. “Recycling these



Workers at a small mine in Secocha, Peru pick through waste rock as they look for ore-rich pieces.  
Photo by Paul Santi

materials not only reduces the impact on the environment but also provides much-needed materials for other purposes.”

### Looking to the future

The importance of mining to Peru’s economy—the industry comprises nearly 14 percent of the country’s GDP and approximately 60 percent of its exports—coupled with Mines’ expertise in mining engineering makes the partnership a natural one, Nelson said. And the benefits of the collaboration aren’t confined to UNSA and the Arequipa region. “We’re not just solving problems—we’re building a long-term relationship,” she observed. “And as we work toward a point where our two faculties know and trust each other, the center will become a resource for the world.”

Santi concurs. While the nine current projects have a regional focus that’s

specific to Peru and fall within UNSA’s mission, he points out that the aim of the partnership is to generate solutions that can be applied to small-scale mining anywhere in the world.

“Ultimately, we want faculty from Mines and UNSA to be viewed as worldwide leaders in artisanal and small-scale mining research. We want people in Africa, Asia and developing countries to look to us for answers regarding the best sustainable small-scale mining practices,” he said.

Santi and his colleagues embrace the challenge. “The work we’re doing with UNSA is different from other initiatives in that it’s easy to see the importance and context of our research,” he said. “We’re working with communities to improve safety and quality of life. Through the center, we have the potential to have a much bigger impact on the world.”



AWARDS & RECOGNITIONS ▼

Alexander Gysi

Assistant Professor of Lithogeochemistry  
2019 NSF CAREER Award

Rare earth elements are essential components of many high-tech devices—permanent magnets in wind turbines, computers, cell phones and more. While we have a good understanding of how these elements can be utilized, how REE deposits form in geologic systems is a different story. Gysi is investigating the REE signatures recorded in minerals formed from hydrothermal fluids to build a framework to better understand where REE deposits form and how to explore and characterize them.

“Fluids actually play a crucial role in the formation of these deposits,” Gysi said. “Hydrothermal veins give us a snapshot of these crustal fluids, and their minerals can be used to read what has been going on in the geologic past deeper in the crust at elevated temperature and pressure.”

Gysi provided an analogy to explain the importance of this work:

“The exploration and mining industry for metals like copper, lead, zinc, silver and gold are currently in a Formula 1 car, relying on years of research in this area by many groups worldwide. In contrast, the rare earth element industry is in a tricycle, trying to catch up when there is a market wave. This is mainly due to the diversity of REE deposit types and their complex mineralogy, as well as difficulties in the separation of the REE. We don’t know how the market is going to evolve in the next few decades as technologies and environmental awareness may change, but as scientists, it’s essential to be forward thinking and work with the industry.”

## An expanding partnership

Mines' relationship with the U.S. Geological Survey started the way most partnerships do—with a shared goal. In this case, the USGS and the university share the common purpose of finding creative solutions to the nation's natural resource security and environmental challenges.

With a relationship going back more than 40 years, Mines and the USGS have explored where the next innovations in earth and space resources, technology and engineering will occur. The Mines campus has been home to the USGS' Geological Hazards Science Center and National Earthquake Information Center since 1977, and USGS scientists have since worked side by side with Mines faculty and students, analyzing data and furthering our understanding of the Earth and the natural phenomena that threaten lives and livelihoods.

Now, that relationship is expanding, with a state-of-the-art facility that will provide a new shared workspace and bring more than 150 USGS scientists and their minerals research labs to campus.

"The expanded USGS presence at Mines will capitalize on our collective expertise to address the availability of mineral and energy resources, environmental challenges and geo-environmental hazards, all of which are of critical importance to national security and the economies of Colorado and the nation," said Mines President Paul C. Johnson. "It will also create an incredibly unique educational environment that will produce the leaders we need to tackle future challenges related to exploration and development of resources here on Earth and in space, subsurface infrastructure and sustainable stewardship of the Earth."

A USGS geologist takes measurements of a fault rupture resulting from the magnitude 7.1 Searles Valley earthquake in July 2019.

Photo by Ben Brooks, USGS



## Mining's human elements

### Anthropologist seeks to bridge divide between industry and small-scale operations

By Mark Ramirez

Assistant Professor Nicole Smith is the only social scientist in Mines' Mining Engineering Department, but that's par for the course for any anthropologist worth his or her salt.

"I've always been interested in why people do what they do and how it differs across the world," said Smith, who earned a bachelor's degree in anthropology from the University of Minnesota.

While pursuing a master's degree from Colorado State University, Smith examined community-based conservation in northern Tanzania. That's where she first encountered the Maasai, an ethnic group known for its distinctive dress and traditionally cattle-centric economy.

For her PhD at CU Boulder, Smith wanted to focus on the Maasai, who in recent years had filled a niche as gemstone traders in the tanzanite mining area of Mererani, Tanzania.

"Livelihoods are more than just bringing in money—it's also a source of identity," Smith said. "Often, livelihoods represent peoples' passions, and there are critical intersections between livelihoods and social and political forms of organization. By focusing on livelihoods, we can gain a better understanding of the impacts of mineral development on people's way of making a living, as well as on their governance systems and culture. This is a fascinating area of study and relevant

to industry professionals and governments who are promoting sustainable economic growth through mineral resource development."

That was Smith's entry into mining. "After working with gemstone traders, I decided I wanted to work closer to the source," she said.

At the University of Queensland, she worked to build the Centre for Social Responsibility in Mining's research on artisanal and small-scale mining. After a postdoc in the humanitarian engineering program at Mines, Smith joined the Mining Engineering Department and is now conducting research for several projects on the opportunities and challenges of small-scale gold mining in Colombia and Peru.

One challenge is formalizing the sector. "Small-scale mining generally occurs in the informal economic sector, but if it's banned, thousands would be out of work," Smith said. "We're looking at the history and impacts of formalization to inform policies that better reflect the reality on the ground."

Another challenge is reducing the use of

**"One of the fundamental tenets of engineering is to serve the public and do good for society, but sometimes that human element can get dropped. It's necessary to bring that back into the conversation." -Nicole Smith**



mercury to refine gold, which poses health and environmental risks. "It means so much more than just giving engineered technologies to people," Smith said.

Smith's research into small-scale mining, also directly affects large operations. "One of the biggest challenges for mining companies is gaining and maintaining the social license to operate," she said. "Industry can benefit from a deeper understanding of people and culture."

Another of her research projects looks at how industry can better assess and standardize their contributions to sustainable development. "How does it compare across companies, how do companies report their contributions to sustainable development and how can they do better?" Smith said. "One of the fundamental tenets of engineering is to serve the public and do good for society, but sometimes that human element can get dropped. It's necessary to bring that back into the conversation."

# A new space race

## Expanding humanity's reach and knowledge beyond Earth

By Emilie Rusch

Space, as the classic line goes, is the final frontier. George Sowers, professor of space resources, calls it the next economic revolution. Most see it as the future. If you're curious what that future could look like, all you need to do is walk through the Center for Space Resources' research facilities at Mines.

Solar power-harnessing asteroid mining experiments share a lab with test equipment that could lead to future lunar settlers 3D-printing their building materials out of Moon dust. Next door, work is underway on a "smart" drill capable of characterizing materials as it drills into the lunar or Martian surface. A tiny lunar rover equipped with an equally tiny mass spectrometer, drill and camera roams around a test bed designed to simulate the Moon's dusty surface.

Meanwhile, on computer monitors across the world, professors in Mines' first-of-its-kind space resources graduate program are training the next generation of scientists, engineers, entrepreneurs, economists and legal minds to responsibly explore, extract and use these resources in space, both to fuel further space exploration and address needs back on Earth.

Mines is on the cutting edge of research to tackle the biggest challenges we face in expanding our reach and our knowledge about the resources beyond Earth. Here are a few of the space-related topics that Mines researchers are working on today:

### A high-res peek inside Mars' ice caps

Access to water as a natural resource will be crucially important for exploring and colonizing Mars. For many reasons, we're just not going to be able to bring enough of the wet stuff the 140 million miles from Earth.

A Mines-led effort to develop the highest-resolution 3D images ever of what lies in the interior of Mars' polar ice caps, however, could provide valuable information to those thirsty first explorers of the Red Planet.

"We know that the ice is there—we don't need to explore its interior for that—but the more we understand its interior structure, the better we can characterize the Mars water cycle and its distribution on the planet," said Paul Sava, professor and Green Chair of Exploration Geophysics, the principal investigator on the three-year NASA project.

To generate the high-resolution images, Sava and his team will use data from the Mars Reconnaissance Orbiter Shallow Radar (SHARAD) instrument, which has been orbiting the planet since 2006.

"We will take 3D processing of SHARAD data to the next technological level by employing new resources and state-of-the-art technology developed in the context of terrestrial seismic imaging that is capable of significantly improving the resolution and clarity of the 3D interior image volumes," Sava said.

### A tunnel on the Moon?

The lunar environment isn't a particularly welcoming one for human settlers. There's harmful radiation, dust and ultracold temperatures—not to mention the near-constant threat of mini-meteorite strikes.

"During the Apollo era, astronauts were on the surface for a maximum of two weeks. Thinking ahead, we want locations where astronauts and maybe even tourists could stay for a much longer time," said Christopher Dreyer, research assistant professor of space resources. "That changes what you do with a habitat. You need to think about the radiation and impact environment. The Moon is getting hit all the time by high velocity impactors as small as a millimeter that will sand-blast your habitat. Getting mass between your occupants and space is necessary to stay for a long time so that radiation exposure and the meteorite impact hazards are reduced. This means thick walls, and that's a challenge."

But what if those more permanent settlements could be located inside tunnels several meters below the lunar surface? That's the idea that Dreyer and Jamal Rostami, Haddon/Alacer Gold Endowed Chair in Mining Engineering and director of the Earth Mechanics Institute, proposed in a paper for the 16th Biennial International Conference on Engineering, Science, Construction, and Operations in Challenging Environments.

Getting a tunnel boring machine to the Moon, however, is no easy prospect. Some estimates put the cost of transporting a single kilogram of material to the Moon at \$50,000. Today's 2- to 3-meter boring machines can weigh more than 100 tons.

Lunar tunnel boring machines will need to be lighter and more streamlined, of course, but also automated and requiring few repairs, Rostami said.

"Every plan for having a habitat on the Moon involves making a trench, creating a structure and covering it with some sort of regolith," Rostami told Agence France-Presse at the 2019 World Tunnel Congress. "Our idea is to actually start underground, using a mechanism we already use on the Earth—a tunnel boring machine—to make a continuous opening to create habitats or connect the colonies together."

### A geophysical mission to Mars

Ever wonder what the weather's like on Mars? Thanks to the NASA Mars InSight mission, the daily temperature, wind and pressure for Elysium Planitia, a flat, smooth plain near Mars' equator, is now available online.

But the InSight mission is about much more than meteorological curiosity—it's the first space mission ever dedicated to seeking geophysical information about another planet.

"There have been many rovers and missions to Mars, but they've concentrated on understanding the surface geology," said Paul Morgan, senior geothermal geologist emeritus at the Colorado Geological Survey and one of two Mines researchers on the international mission's science team. "We can learn a lot from that, but the InSight mission is focusing entirely on the interior of the planet."

To do that, the InSight lander is equipped with three pieces of scientific equipment: a seismometer, the Heat Flow and Physical Properties Probe and the Rotation and Interior Structure Experiment. Morgan worked on the heat probe, which is designed to hammer 16 feet into the Martian soil to measure the heat coming from the planet's interior.

The seismometer is recording "marsquakes" and other seismic disturbances in hopes of answering questions about the crustal dichotomy between the southern and northern hemispheres, the size of Mars' core and the relationship between that core and the planet's lack of magnetic field, said Ebru Bozdog, assistant professor of geophysics and seismologist on the InSight science team.

"We now have the first quakes recorded by the InSight seismometer which have so far been more similar to moonquakes than earthquakes with lots of scattered waves. If this pattern continues, one potential explanation might be that, unlike the Earth, Mars' interior does not have much water to attenuate seismic waves," Bozdog said. "We are looking forward to recording big marsquakes that would also allow us to see the deep interior of the planet."

# The next generation of energy

## Revolutionizing what's possible with renewables

By Emilie Rusch

You don't have to read monthly U.S. Energy Information Administration reports to know that renewable energy production is on the rise across the nation. The giant wind turbine blades strapped down to semi beds barreling down the interstates and the rooftop solar panels installed on your neighborhood big-box stores are a pretty solid clue.

But if you did read them, you would know that renewables accounted for 17 percent of all electricity generated at utility

### Palm tree + wind turbine = SUMR

The Segmented Ultralight Morphing Rotor prototype doesn't look like your typical wind turbine.

For one, it only has two blades. For another, those blades—ultralight and ultralong—are affixed in a downwind position, instead of the traditional upwind configuration.

Inspired by a palm tree's ability to withstand hurricane-force winds, SUMR could one day scale up into the largest wind turbine ever built. With blades able to bend out of strong winds, therefore putting less stress on the other turbine components, SUMR would be capable of producing 50 megawatts of power from an offshore wind farm. Today, the largest turbines in production are rated for just 5-10 megawatts.

"Part of the goal for every new wind turbine design is to reduce what's called the levelized cost of energy," said Kathryn Johnson, associate professor of electrical engineering. "Super flexibility means you don't need as much material or as expensive a material. You could always make something super stiff by adding a ton of carbon, but that's so expensive."

Johnson is part of the team working on the turbine's control systems. Also contributing to the University of Virginia-led project are the University of Illinois, University of Colorado, National Renewable Energy Laboratory and the University of Texas-Dallas. Funding comes from the U.S. Department of Energy's Advanced Research Projects Agency-Energy.

"When things get more flexible, they get harder to control," Johnson said. "The big thing because of the flexibility is the deflection of the blade tips—how much it's moving out of the normal position, upwind and downwind. We're making sure it doesn't come too far upwind and hit the tower—because that would destroy everything."

scale in the U.S. in 2018—a total of 713 billion kilowatt hours from hydropower, wind, biomass, solar and geothermal sources. That doesn't even factor in the estimated 30 billion kWh that came from small-scale photovoltaic systems.

And renewables are only set to grow—in production, options, efficiency, economic viability and more—with Mines researchers at the forefront of determining what's possible.



Photo courtesy of UVA Communications



### Improving solar power

to energy storage provides lower-cost storage than batteries. Furthermore, with our advances in energy capture, the CSP plant with storage can outperform state-of-the-art photovoltaics in terms of solar efficiency."

With funding from the U.S. Department of Energy, Jackson and his team are developing a new method for capturing and storing thermal energy from CSP into engineered ceramic particles. Also contributing to the project are Ivar Reimanis, Herman F. Coors Distinguished Professor of Ceramic Engineering; Sandia National Laboratories; and Carbo Ceramics Inc.

CSP works by concentrating the sun's rays 1,000 times or more using a field of mirrors that focus on a central tower receiver. Jackson's team plans to capture the concentrated solar energy in narrow-channel, counterflow fluidized beds full of oxide particles that will then store the energy without corrosion and less expensively than currently used molten salts.

Such storage on a very large scale should overcome the performance, durability and cost barriers to current energy storage systems based on molten salts.

Today, in places like California, there are so many solar photovoltaic systems that come off the grid at night that fossil-fueled power plants must pick up the slack.

More efficient concentrating solar power, though, could help bridge that gap, allowing renewable energy to cover those high evening power demands, said Mechanical Engineering Professor Greg Jackson.

"Concentrating solar power with thermal energy storage can time-shift solar-driven electricity to times when the sun is not shining," Jackson said. "At the utility scale, our approach

### Fuel cells two ways

Protonic ceramic fuel cells could one day be used to power off-the-grid cabins in remote locations, serve as backup generators during natural disasters and more.

And as Ryan O'Hayre, professor of metallurgical and materials engineering, and postdoctoral researcher Chuancheng Duan have discovered, they can reliably be used in reverse as well, to both efficiently generate electricity and to store that power in the form of chemical fuel at times of lower demand.

"In this way, our reversible fuel cell device can act like a battery," O'Hayre said. "We can use our device to make hydrogen from water when there is excess renewable electricity on the grid that might otherwise go to waste. The hydrogen can be stored for later use or used in the chemical industry for various purposes. If we store some or all of the hydrogen, we can then also run our device in fuel cell mode using this stored hydrogen to produce electricity at times when there is not enough electricity available on the grid."

Protonic ceramic fuel cells are a relatively new class of fuel cell technology, and O'Hayre and Duan have already shown that they have the long-term durability and fuel flexibility needed to become a viable commercial alternative to other technologies.

The new cells would also work in reverse as electrolyzers, efficiently breaking down water into hydrogen and oxygen. The



device could be used to make methane, too, if supplied with a combination of carbon dioxide and water.

"This technology offers opportunities for utilizing and storing carbon dioxide and thereby reduce carbon dioxide emissions," said O'Hayre, whose fuel cell work is funded by sponsored by ARPA-E. "Methane has the added benefit of being easier to store and higher energy density than hydrogen."

# Harnessing heat

## Applying machine learning to geothermal exploration

By Ashley Spurgeon

As radioactive particles in the Earth's core decay, temperatures rise, heating nearby rocks and reservoirs of water.

The water surfaces as steam or hot water, which can be used to power turbines and produce electricity.

However, finding and developing new geothermal resources can be a challenge.

But Sebnem Duzgun, professor and Fred Banfield Distinguished Endowed Chair of Mining Engineering, and her research team have a potential solution—using machine learning techniques to analyze hyperspectral images and geophysical data to develop a way to identify the presence of geothermal resources based on surface and subsurface characteristics.

We talked to Duzgun about this Department of Energy-funded project and what an expansion of geothermal resources could bring to the table.

**Q: What are the benefits of using machine learning to analyze remote-sensing hyperspectral images?**

**Sebnem Duzgun:** Hyperspectral images contain fine details of information about the materials. However, identifying a specific material—like geothermal indicator minerals—from a hyperspectral image cube is a complex process. Machine learning algorithms will allow us to map the abundance of the specific indicator minerals for geothermal sites with high accuracy. Later, these maps will allow us to correlate surface and subsurface characteristics of geothermal sites.

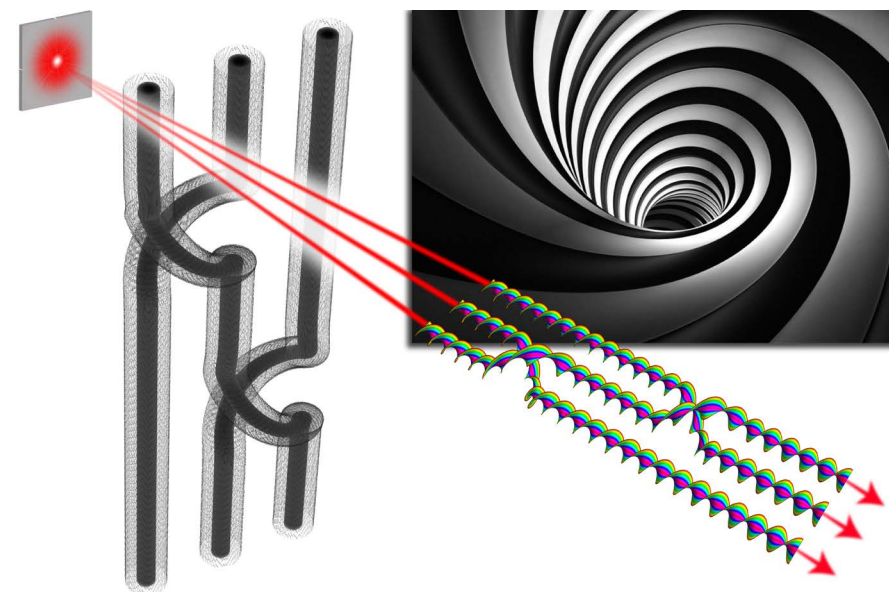
**Q: What are the challenges of this project?**

**Duzgun:** Artificial intelligence algorithms require a large number of labeled data about the existence and nonexistence of geothermal sites, and

obtaining this data is challenging. However, we plan to overcome this challenge using the results of machine learning algorithms for labeling purposes. Although such model-based labeling will contain errors, we believe that understanding the correlation between surface and subsurface data will help us to reduce those errors.

**Q: How might an increase in geothermal resources affect the United States' energy profile?**

**Duzgun:** We aim to enhance the geothermal exploration process, which will ultimately reduce its costs. When the exploration process improves, the investments are also expected to improve. Developing geothermal resources will leverage the energy transition process.



Right: Whirlpools have an empty tube center, so vortices in light are dark curves about which the light swirls. Left: The vertical pipes represent three "braided" vortices, and information can be stored and processed by braiding them in different ways. Center: When viewed within a laser beam, "whirlpools of light" look like barber's poles. (Illustration courtesy of Mark Lusk)

## Trick of the light

### A new step in quantum computing

Quantum computing promises to provide huge leaps in processing power that will significantly outperform even the best conventional computers of today—and tomorrow. But much of what we know about this mysterious field is still being worked out.

Budding quantum technologies rely on an ability to trap extremely delicate states of quantum matter, and this has motivated an alternative approach in which quantum computation is instead carried out by interlacing exotic particles called anyons. The resulting braids are more stable than the trapped states, and the approach is called topological quantum computing because information is stored in the structure of the braiding pattern. Both approaches, though, are only stable at ultracold temperatures, a serious obstacle to widespread technological application.

But as part of a W.M. Keck Foundation grant, Physics Professor Mark Lusk—in collaboration with Associate Professor Mark Siemens at the University of

Denver—is working on a solution to this problem by exploring the possibility of using a laser beam as the medium for topological quantum science.

By leveraging the advanced state of laser technology, the researchers may be able to make robust analogous optical architectures, even at room temperature, and engineer very small structures right into the laser beam that behave like the exotic particles currently being considered for topological quantum computing.

"Light engineered with a microscopic architecture has a complicated fluid-like behavior, almost like many small whirlpools interacting on the surface of a pond," Lusk said. "We're calling this 'topological fluids of light,' because the laser whirlpools can be interlaced, a key property for the storage and manipulation of information."

By determining and controlling the fundamental working properties of topological fluids of light, we can begin to explore room-temperature quantum sciences using laser light.



AWARDS & RECOGNITIONS ▼

**Diego  
Gómez-Gualdrón**

Assistant Professor of  
Chemical and Biological Engineering  
2019 NSF CAREER Award

Metal-organic frameworks (MOFs) are porous crystal materials that scientists believe could revolutionize energy storage, chemical separations and more. But very few MOFs have made the jump from computer-based prototype to synthesized reality. Gómez-Gualdrón hopes to close this disconnect using the power of molecular simulation and machine learning and accelerate the synthesis of new materials.

"We want to change the way experimentalists interact with computational MOF databases. We want them to not only see the expected performance of a MOF prototype but also how likely synthesis attempts will result in the desired material," Gómez-Gualdrón said. "This could impact the pace at which MOFs are discovered for different technologies, as labs will feel more confident in investing time and money in pursuing the synthesis of a particularly promising prototype, if there is some reassurance that a material can be made."

Gómez-Gualdrón shared five potential applications of metal-organic frameworks:

1. Onboard storage of gaseous fuels, such as methane and hydrogen in vehicular applications
2. Nonthermal, energy-efficient separations of chemical mixtures that currently require cryogenic distillation, for instance, separating olefins from paraffins
3. CO<sub>2</sub> capture from flue gases emanating from power plants
4. Conversion of chemicals by artificially mimicking the catalytic properties of enzymes
5. Chemical sensors with exceptional sensitivity and specificity



Inspecting and making repairs to a thermal power plant boiler is often costly and dangerous. But an autonomous robot, like the one shown here that can travel up the walls of a boiler, could prove to be revolutionary.

## Putting ‘Pepto’ into the belly of a boiler

### Building a smart robot to inspect, repair power plant boilers

By Emilie Rusch

Boilers are one of the most critical components in a thermal power plant, but inspecting and repairing them is no easy task.

Today, the only method involves costly scaffolding and human inspectors, all crammed inside the hazardous, confined environment of the boiler itself. If left unchecked, damage to the boiler furnace chamber can cause catastrophic failures.

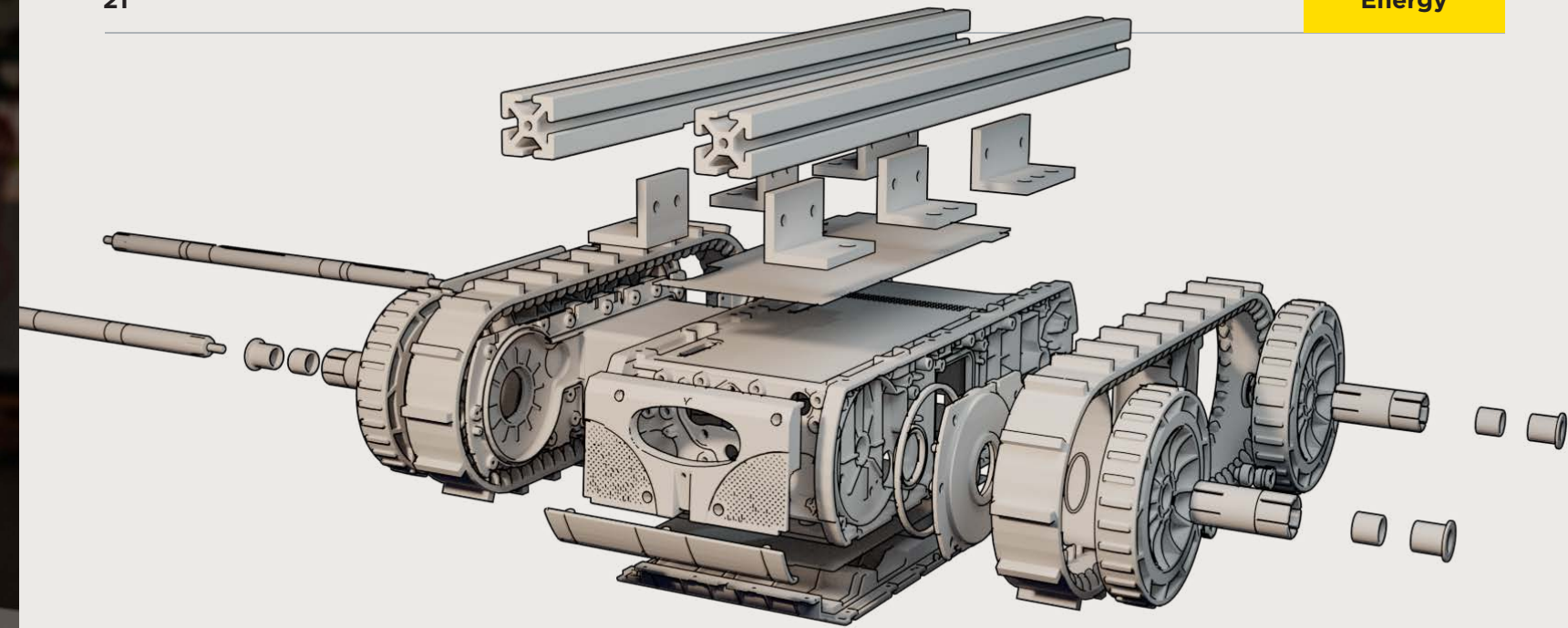
But what if an autonomous robot could scoot up the boiler walls, inspecting the surface and making live repairs as it goes?

That’s exactly what Hao Zhang, assistant professor of computer science, and an interdisciplinary team of researchers are developing, with funding from the U.S. Department of Energy’s Office of Fuel Energy. Also contributing to the project are Andrew Petruska, assistant professor of mechanical engineering; Zhenzhen Yu, assistant professor of metallurgical and materials engineering; and Yiming Deng of Michigan State University.

We sat down with Zhang to talk about how smart robots can revolutionize energy site maintenance methods.

**“It’s critical for the next generation of roboticists and scientists to appreciate the real-world challenges and beauty of robot intelligence to solve these big social and economic problems.”**

**-Hao Zhang**



**Q: How did the DOE funding come about, and what do they want from the project?**

**Hao Zhang:** DOE puts out funding opportunities to address the most critical challenges in industry, and it turns out, one of the key problems they are trying to solve is how to inspect these tall coal-fired power plant boilers. Their goal is to find autonomous robotic solutions that are capable of doing the inspections and/or doing the repairs. Mines is the only awardee that’s addressing the repair problem.

**Q: What are the benefits of using robots in power plant boilers?**

**Zhang:** The first benefit is safety. One of the biggest issues they have now is fall risk and having humans working in a hazardous environment for a prolonged period of time. It can take several days of work to install the scaffolding, and then the inspection takes another few weeks.

The second benefit is to reduce the cost. Today, we need to shut down the power plant to do the scaffolding and inspections. We won’t need to do scaffolding in the future—the robot can just crawl on the boiler wall—reducing

the cost and increasing the frequency of inspection.

**Q: Why does this type of research interest you?**

**Zhang:** It’s a very interesting problem—there’s a huge market out there, but there’s no solution yet. It’s highly interdisciplinary, too. On the team, we have computer science, mechanical engineering, materials science and electrical engineering, and we have industry collaborators.

A lot of coal-fired boilers have been operating for over 40 years. We will see more failures there. It’s a really good time to have some autonomous robotic solutions that can do the inspections and repairs more frequently.

**Q: What are the challenges you have to confront?**

**Zhang:** On the platform side, the challenge is to make the repair tool small enough to put on a robot. These repair tools are large in size and often pricey. We’re trying to make it less than 1 foot.

The other challenge is the robot design. We need to integrate the repair tools and

nondestructive sensors on a robot that must also have magnetic tracks so it can navigate on the boiler. It’s possible that the magnetics could impact the sensor signals. So, we need to figure out how to put all these components together on one platform.

On the software side, the biggest challenge is implementing the artificial intelligence. We need our AI to be able to integrate all the information, recognize any damage and create a 3D map and localize the damage. At the same time, the AI has to be able to navigate the robot autonomously and control the repair tool.

**Q: Why were you insistent on engaging students on the project?**

**Zhang:** It’s critical for the next generation of roboticists and scientists to appreciate the real-world challenges and beauty of robot intelligence to solve these big social and economic problems. This project is a really good opportunity for students to work in an interdisciplinary research team with four professors from different departments and talk with industry collaborators and get a broader picture and broader vision of what’s going on.

# FIGHTING 'FOREVER' CHEMICALS

Persistent chemical compounds are lurking in our water supply, making their way into drinking water, agriculture and other consumables. How do we begin to treat this problem and make our water safe again?

By Jenn Fields



Summer is a quiet time on college campuses, but in July, Mines PhD candidate Charlie Liu was hard at work prepping a pilot water treatment system for a U.S. Air Force field test.

Liu spent one of the hottest days of the year in the cool of the General Research Lab, weaving in and out of various systems Mines researchers had designed and built to treat water contaminated with a persistent chemical compound that poses a serious threat to human health.

Christopher Higgins, professor of civil and environmental engineering and one of Liu's advisors, began leading the charge on what has become a multidisciplinary

hub of research in this field at Mines years ago. His latest research is unveiling an uncomfortable truth: that this family of chemicals, called PFASs, might be more widespread than anyone knew.

The system Liu was working on with faculty members would test how well a combination of filtration and destructive ultraviolet light would clear perfluoroalkyl substances, or PFASs, from groundwater. As a category of chemicals, PFASs are a growing problem around the globe. They're found in products from firefighting foam to nonstick cookware to pizza boxes and popcorn bags, and they're easily transported in water. The research on their effect on human health is ongoing, but there's evidence PFASs can cause cancer and developmental, endocrine, renal and metabolic problems.

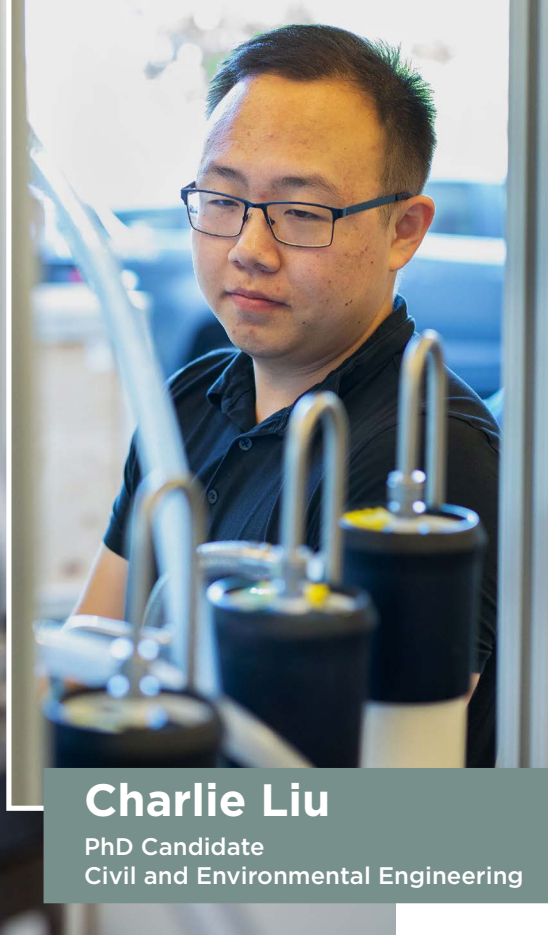
PFASs from firefighting foams have contaminated entire aquifers and watersheds, shutting down municipal water supplies and agricultural operations and exposing thousands of people, pets and even the food supply to these chemicals. More than 400 military sites have PFAS contamination, which in some cases has spread to wells and municipal water supplies in nearby communities, leading U.S. Secretary of Defense Mark Esper to announce immediately after taking office in July 2019 that his first act would be to create a task force to address PFASs.

While Mines researchers have fostered partnerships with epidemiologists and toxicologists for expertise on the biomedical side of the PFAS problem, Higgins has turned his attention more toward fate and transport. "How they



**Chris Bellona**

Assistant Professor  
Civil and Environmental Engineering



**Charlie Liu**

PhD Candidate  
Civil and Environmental Engineering

move from soil to groundwater, how quickly they move in groundwater, those sorts of things,” he said. One of the other challenges for water-treatment specialists is figuring out how to remove and destroy them. PFASs are so persistent that people working on the problem have started calling them “forever chemicals.”

“They do not break down on their own, so we need engineered solutions for these particular contaminants,” said Timothy Strathmann, a professor of civil and environmental engineering who is part of a team at Mines working on PFASs. “There are a lot of contaminants of concern, but many of them will biologically break down over time. What’s exciting for me as a technology developer is we really do need new technologies for these chemicals.”

Mines is a leader in research in PFAS remediation, fate and transport, and exposure. Higgins is the lead researcher on a nearly \$2 million grant from the Environmental Protection Agency that will look at whether it’s enough to remove “forever” chemicals from drinking water now that they’ve also been found in food from farms in areas with contaminated water. The exposure question, he said, is a big one. “How are we being exposed to these chemicals, and what are the most important ways people are being exposed?”

The exposure question is complicated, but it tackles the most basic questions people in communities with contaminated water are asking. “When we go out to these communities, the first thing people do

is they get bottled water, and they’ll even get treated water, but the question is, is it still OK to shower in the water?” Higgins said. “If you irrigate your backyard garden with contaminated water, or if your local community garden has contaminated soil, is it safe to eat that food?”

He was quick to note that the Mines-led team wouldn’t be doing the risk assessment—results from a parallel toxicology study are needed to address that question. Instead, the team would track the important question of just how the chemicals move through the environment and how people are exposed to PFAS contamination in the first place.

Though PFASs have been around for a few decades, recent exposure cases have put the problem on the radar of

government agencies, private companies and the public. Right now, there are federal health advisory levels for just two PFASs—perfluorooctane sulfonate and perfluorooctanoic acid—in drinking water. “It’s all happening at once,” said Chris Bellona, an assistant professor of civil and environmental engineering whose expertise in water treatment and reuse includes PFAS remediation. “The regulatory environment is trying to figure itself out, because there’s not a lot of toxicological data for a lot of the compounds. We didn’t really know the best way to treat these compounds, so we’re trying to figure that out. And the public’s trying to figure it all out—the level of contamination and occurrence nationwide is fairly unknown.”

Higgins said he’s constantly recruiting more experts for PFAS projects, and Mines now has a small army of scientists working on the problem. “It’s dozens of people, if you count the grad students and faculty, not to mention the undergraduates,” Higgins said. At Mines, which has experts in water across disciplines, he’s found a trove of colleagues who can attack the PFAS problem from different angles.

He’s also working with a surprising number of Mines alumni in this field. “When you look out at who is doing this research around the country, it ends up being a lot of Mines graduates,” Higgins said. “We’re recruiting new experts, but it’s also Mines alumni out there who are making a difference, and it’s at the state and federal agencies and also academics.”

Two of those future alumnae are working on fate and transport research with Higgins now. PhD student Anastasia Nickerson is working on a characterization project at three Department of Defense sites that are being sampled at high resolution for both groundwater and soil. “With the instruments in our lab, we have a chance to look for a much broader spectrum of compounds and not even

necessarily know what we’re looking for going in,” she said. “The goal is to get a more comprehensive understanding of what’s happening at these sites, because there can be a transformation of these compounds once they’re on the site. Ultimately what we’re finding is that there’s a lot of variety and high concentrations of compounds that most people aren’t looking for.”

Juliane Brown’s research interest is in the human health risk assessment associated with consuming PFAS-contaminated produce and, specifically, PFAS uptake into the edible parts of plants. “This is a question we’re getting from farmers and backyard gardeners,” said Brown, another PhD candidate. Like Nickerson, she’s looking at a variety of compounds, including precursors that can transform into recalcitrant PFASs. “Most of the people who have done plant-uptake experiments have only looked at a few individual PFASs,” she said. “What we haven’t looked at as much is mixtures, precursors and newly discovered contaminants. We need to start to get a handle on these other compounds that could be in the soil or irrigation water to see if they could potentially get into the edible portion of the plant.”

### Treatments for PFAS-contaminated water

There are two ways to get PFASs out of water: remove them or destroy them. Removal treatment processes use some form of filtration, such as activated carbon absorption to separate PFASs from water, but the PFASs are then trapped in the media that filtered them, and that must be disposed of safely. So Mines researchers are looking at the best ways to separate the chemicals from water, as well as technologies that will destroy them—and the best way to combine separation and destruction.

“You have your separation processes, like a membrane or absorbent materials.

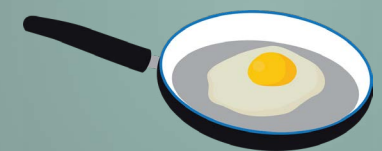
## PFAS in everyday items



Waterproofing on clothes



Microwave popcorn bags

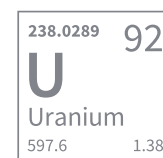
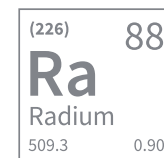
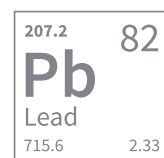
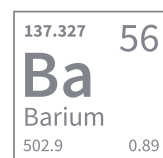
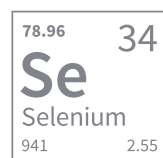
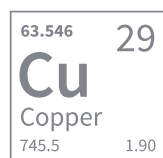
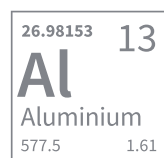


Nonstick cookware



Pizza boxes

## Common chemicals in drinking water



## Christopher Higgins

Professor  
Civil and Environmental Engineering



These are separation processes—they're very efficient for getting the chemicals in the water down below these really low health advisory levels," Strathmann said. "But you create this byproduct stream. So ideally you would then have a second type of technology, a destructive approach."

Strathmann is experimenting with a hydrothermal process to destroy PFASs. "What this uses is elevated temperature and pressures in water," he said. "If you heat water under elevated pressure,

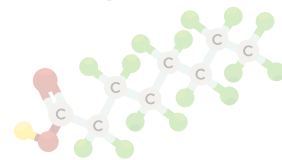
water takes on new properties to make it more reactive. What we've found is this enhanced reactivity of the water is able to destroy these very recalcitrant chemicals, because they can bring about the destruction of these carbon-fluorine bonds that are normally very resistant to breaking because they're among the strongest chemical bonds in nature."

The pilot system for the Air Force that Liu was working on over the summer uses ultraviolet light as the destructive process

on a concentrated waste stream after filtration. "We're evaluating this concept of mixing media," Bellona said, explaining that combining technologies was part of one of his U.S. Department of Defense grants. "Should it have activated carbon prior to ion exchange? Or what if you had mixed media—so, activated carbon and ion exchange in one vessel? What if you had ion exchange before granular activated carbon—is there any benefit there?" Another of Bellona's DOD grants

**"If you heat water under elevated pressure, water takes on new properties to make it more reactive. What we've found is this enhanced reactivity of the water is able to destroy these very recalcitrant chemicals, because they can bring about the destruction of these carbon-fluorine bonds that are normally very resistant to breaking because they're among the strongest chemical bonds in nature."**

**-Timothy Strathmann**



looks at life cycle cost and impact for PFAS treatment technologies.

PFASs made headlines in recent years after high-profile contamination cases came to light, including when the city of Fountain, Colorado, learned their drinking water supply had been contaminated with PFAS from firefighting foam used at a nearby Air Force base. Because Mines has a track record in PFAS contamination research, the city came to them to work with their water utility to clean the town's drinking water supply.

Faculty and students built a pilot system for Fountain that let them test four different media side by side. "It operated for seven months and we never had a single problem with it," Bellona said. "It's completely automated. It's still running right now."

The system Liu was preparing for deployment at an Air Force base was related to the work in Fountain, and working on the project at Mines had many benefits. "We can build everything here, we test on real groundwater and we can analyze everything," Liu said. "I always challenge myself to know everything

in the process, so I built all of these systems, and then I run all the samples and process them all and understand the results, so I understand the whole process. And Mines lets me do that."

Mines doesn't just open doors for building pilot systems. Higgins acquired two high-resolution mass spectrometers for the water lab's work in detecting and quantifying various types of PFASs, as well as searching for unknowns, to create a PFAS library of sorts. The school also has a wastewater treatment plant on campus, which lets researchers work with "real water at real flow rates," Bellona said.

"The work that we're doing, I don't know if it would be possible at any other university," Bellona said. "We have such unique capabilities. All this equipment, it's automated, fully field-deployable, we built it ourselves. We also have all the analytical equipment to test for these compounds, so the thing that really differentiates us from any other research labs is that we do things on scales that allows people to make decisions about full-scale treatment."

## WE<sup>2</sup>ST Water Technology Hub

Tzahi Cath has a knack for coming up with the spaces engineers need for their research. "I've been at Mines 13 years, and throughout these years, I've been fortunate to have the opportunity to, with the help of many others, build a few unique research infrastructures on campus," said the professor of civil and environmental engineering.

Most recently, Cath has helped secure a 10,000-square-foot water research facility in Denver. He'd worked with the company that owned the facility, and in 2017, the company offered to donate the equipment to Mines. "I didn't think twice," Cath said. "I said, we'll take the equipment and the lease on the building and turn it into a wastewater research facility." A donation from the Zoma Foundation helped Mines begin operations.

The WE<sup>2</sup>ST Water Technology Hub celebrated its grand opening in April 2019. "The future that we are trying to build there is really the connection between industry and academia—wherever we can help with science and the engineering we do here to advance technology and advance solutions to the most pressing water problems," said Cath, the facility's director.

Cath and Nils Tilton, assistant professor of mechanical engineering, are already working on a \$2 million desalination project at the WE<sup>2</sup>ST hub funded by the Department of Energy in collaboration with UCLA and the National Renewable Energy Laboratory, as well as a smaller hydrokinetic desalination project with NREL.

The facility is also a boon for Mines students. "It will give students the opportunity to have hands-on experience at the largest scale, and that will make them much better positioned to lead the water industry in the future."

## A new way to water

### Building a smart—and efficient—irrigation system

By Ashley Spurgeon

Have you ever noticed a sprinkler system running during a downpour? It's an inefficiency that's all too common and a waste of valuable water.

According to the EPA, 9 billion gallons of water are used for residential outdoor purposes in the United States each day, mainly for landscape irrigation, and an estimated 50 percent of that water is wasted through evaporation, wind or runoff. But a smart irrigation system used to water parks, golf courses and lawns, like the one being developed by Junko Munakata Marr, professor of civil and environmental engineering, and Qi Han, professor of computer science, could provide an effective solution to this problem.

Here's how the technology would work:

#### The system would use reclaimed water.

The unique system will be built to use treated wastewater instead of typical groundwater. However, this poses a unique challenge due to the fact that reclaimed water is saltier than average tap water, and too much salt can kill plants. With higher salinity levels, more water is needed to flush the salt out of the soil.

#### Sensors would monitor water and soil quality.

To strike the perfect balance between water conservation and appropriate soil salinity, Han is developing a network of

sensors that will report moisture and salinity simultaneously. The sensors will wirelessly transmit data to a central location where a decision is made about when and how much water is applied to the landscape. Ideally, the soil would not be too wet, too dry or too salty, and the system would ensure irrigation only occurs when necessary.

According to Munakata Marr, the system has a lot of moving parts that need to communicate well with each other in order to operate efficiently. It's just a matter of working out the complicated algorithm to solve the optimization problem.

Solar-powered desalination membrane technology could be a cost-effective way to treat brackish groundwater.

Photo courtesy of UCLA Samueli School of Engineering

## Soaking up the sun (and other minerals)

### Distilling groundwater with a solar-powered membrane

**WHAT:** A U.S. Department of Energy project to develop solar-powered desalination membrane technology that could help rural and inland communities treat brackish groundwater at a lower cost.

**WHY:** In the future, there will be less freshwater with more people, contaminated water and droughts. More desalination will require higher amounts of energy to power the process. Places like Texas, Arizona, Florida, Nevada and Southern California that struggle the most with water also have the most sunny days per year, so solar-powered desalination technology is a natural option.

**HOW:** Membrane distillation creates a temperature difference across a membrane, and the technology doesn't allow water to stick to it. Water evaporates from the feed side, diffuses through the submicron membrane pores as a vapor and condenses into highly pure water on the other side of the membrane. Mines researchers are trying to incorporate a solar-powered heat exchanger into the membrane itself, which would heat the membrane at the exact point where evaporation needs to take place.

**IMPACT:** Using solar power to fuel the membrane distillation process could cut the cost of treating high-salinity water by approximately 80 percent, to \$1.50 per cubic meter of water processed on-site, when long-range transportation costs are factored in.

**WHO:** Tzahi Cath, professor of civil and environmental engineering, and Nils Tilton, assistant professor of mechanical engineering, are working with colleagues at the UCLA Samueli School of Engineering and the National Renewable Energy Laboratory.

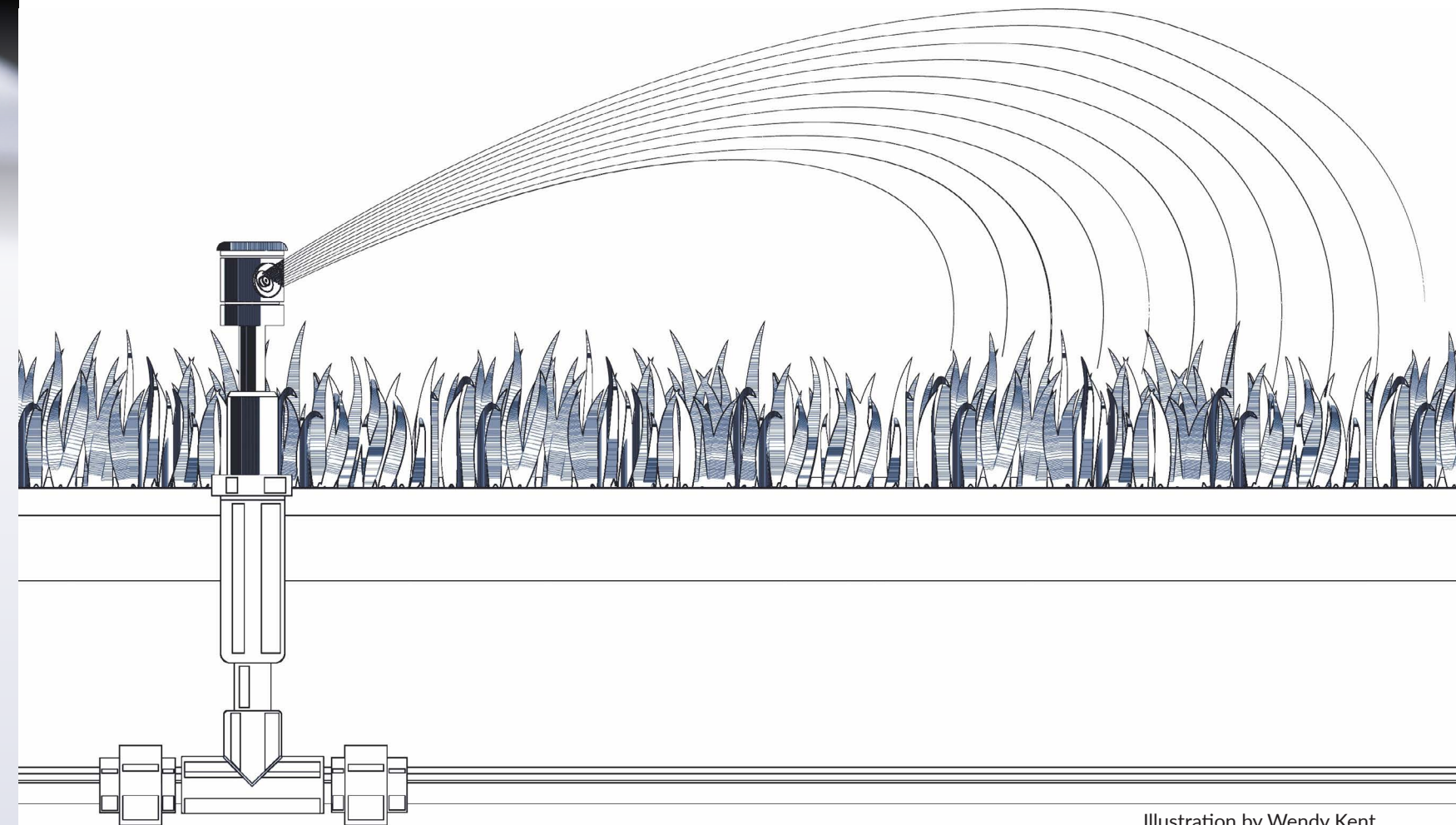


Illustration by Wendy Kent

# Withstanding radioactivity

## Testing how 3D-printed materials perform inside a nuclear reactor

By Sarah Kuta

As our nation's nuclear plants age, it's becoming increasingly difficult to find replacement parts—the shapes and sizes are unique, plus they must be able to withstand a harsh, radioactive environment.

But Mines researchers are studying a novel question: could 3D printing—also known as additive manufacturing—be the solution to this problem?

The researchers, led by Jeff King, associate professor of metallurgical and materials engineering, are testing how 3D-printed materials perform in a nuclear reactor. The results of this four-year, \$2.5 million study, funded by the U.S. Department of Energy, have the potential to revolutionize the nuclear power industry.

“Most of the reactors in the U.S. are more than 40 years old, and many of the companies that made the original parts no longer exist,” said King. “There's a huge problem of trying to find replacement parts and/or certifying replacement parts. One theory is if you could make on-demand parts of specific geometries through additive manufacturing, this could be very helpful in keeping our aging nuclear fleet performing.”

In supply chain logistics more broadly, additive manufacturing is an exciting and potentially transformational technology.

The process makes it easy to quickly and efficiently produce parts on demand, rather than waiting for them to be manufactured and shipped. It can also make it cheaper and easier to produce irregularly shaped components.

For the nuclear industry, the big question revolves around safety and how 3D-printed materials behave inside a nuclear reactor. The researchers want to understand whether 3D-printed materials are uniquely vulnerable to radiation damage or are, in fact, stronger and more durable than conventionally manufactured materials.

“If that's true, then that enables things like longer lifetimes for reactors, greater efficiencies and reduced costs,” King said. “These are the sorts of things that are necessary for rolling out the next generation of nuclear reactors.”

To study this question, Mines researchers used five 3D-printing methods to create 288 samples of stainless steel and Inconel alloys. They sent the samples to the Advanced Test Reactor at the Idaho National Laboratory, where they were exposed to neutron radiation for 80 or 160 days.

With irradiation now complete and a cool-down phase underway, researchers will soon begin testing the strength

and thermal properties of the samples and looking at them under an electron microscope to see what changes occurred at the microstructure level. They'll then compare this information to data collected at Mines from irradiated samples of the same materials.

Mines is a pioneer in this complex, multifaceted line of research—in fact, it's the first university to irradiate additively manufactured specimens in a nuclear reactor. The study wouldn't be possible without collaboration among many departments, including metallurgy, materials science, mechanical engineering and nuclear engineering, as well as the Alliance for the Development of Additive Processing Technologies and the Nuclear Science and Engineering Center.

Though it's still early, the researchers are hopeful about the study's potential to advance nuclear power, one of the most sustainable and environmentally friendly energy sources available today.

Mark Graham, a graduate student working on the project, said, “If we can aid in the advancement and efficiency of this technology, we can hope to provide clean energy to everyone and reduce our predicted impact on the environment before it's too late.”

and thermal properties of the samples and looking at them under an electron microscope to see what changes occurred at the microstructure level. They'll then compare this information to data collected at Mines from irradiated samples of the same materials.

Mines is a pioneer in this complex, multifaceted line of research—in fact, it's the first university to irradiate additively manufactured specimens in a nuclear reactor. The study wouldn't be possible without collaboration among many departments, including metallurgy, materials science, mechanical engineering and nuclear engineering, as well as the Alliance for the Development of Additive Processing Technologies and the Nuclear Science and Engineering Center.

Though it's still early, the researchers are hopeful about the study's potential to advance nuclear power, one of the most sustainable and environmentally friendly energy sources available today.

Mark Graham, a graduate student working on the project, said, “If we can aid in the advancement and efficiency of this technology, we can hope to provide clean energy to everyone and reduce our predicted impact on the environment before it's too late.”



Photo by Navy Petty Officer 1st Class John Phillip Wagner Jr./U.S. Department of Defense

## Security in 3D

### Engineering solutions to the U.S. military's parts problems



By Ashley Spurgeon

When soldiers are out in the field—literally in life-or-death situations—the last thing they need to worry about is a door falling off their tactical vehicle if they're hit by a roadside bomb.

Unfortunately, this situation is all-too-common for the mine-resistant ambush-protected vehicles the U.S. Army uses in the field. Due to the prevalence of improvised explosive devices, the vehicles were modified in 2007 with cab doors that added a 400-pound armor plate to the existing 800-pound design. But this extra weight exceeded what the door hinges could handle, and soldiers were suddenly forced to figure out how to reattach a 1,200-pound door to their vehicle, often in dangerous situations and risking further harm.

To further complicate matters, a failed hinge could cause a vehicle to be out of commission for a significant amount of time—possibly even years—before a replacement part can be procured, delivered and installed. But Mines' Alliance for the Development of Additive Processing Technologies stepped in with a solution to the problem when the U.S. Army CCDC Ground Vehicle Systems Center requested help creating an

effective replacement that would hold up in the field.

“We used preexisting data from some DOE projects we had worked on to decide how to additively manufacture a direct replacement for the hinge that was breaking,” said Aaron Stebner, Rowlinson Associate Professor of Mechanical Engineering and executive director of ADAPT. “Then we did destructive testing to prove that the additively manufactured hinge performed better than the part it was replacing.”

ADAPT developed a second iteration of the hinge that took the seven separate pieces of the original and additively manufactured the part as one piece that was less likely to break.

“The end result were these hinges that had about half the stress of the original part, they were printed as one piece instead of seven different pieces and could be printed in a few hours, as opposed to the months it would take the Army to procure a replacement part,” Stebner said.

Increased confidence in 3D-printed parts is clearly the way forward for the U.S. military, providing safer, more reliable equipment for soldiers at home and overseas.



John Speer

John Henry Moore Distinguished Professor of Metallurgical and Materials Engineering  
Elected to the National Academy of Engineering

Steel is the world's most used construction material, due to its low cost and high durability. But when it comes to the automobile industry, where fuel efficiency is a concern, the material's weight becomes a problem. Speer has spent his career investigating this problem, focusing on the conception, invention and reduction to practice of quenching and partitioning steel.

“The latest generation of steel microstructures could prove useful in numerous applications and markets because of their great drive to increase fuel economy,” Speer explained when discussing a new generation of advanced high-strength steel in the automobile industry with *Physics Today*.

Speer shared four ways next-gen steel is changing the manufacturing industry:

1. It enables the production of lighter vehicles (primarily automobiles) with increased fuel economy and reduced carbon emissions.
2. Higher-strength steels with high ductility (the ability to undergo deformation without fracture) allows for designs that improve passenger safety.
3. The whole supply chain must work to solve new problems that arise when working with higher-strength materials or using new steel alloys that may not behave in the same ways as earlier steels.
4. Translational R&D is needed to tune new concepts to individual company strategies and work through various manufacturing challenges.

## Eric Toberer



Associate Professor of Physics  
2019 U.S. Presidential Early Career Award  
for Scientists and Engineers

Thermoelectric materials could significantly enhance the United States' energy portfolio, via technologies such as solar thermoelectric generators, cogeneration and waste heat recovery. They could even lead to a deeper understanding of charge transport in complex semiconductors and advance applications such as transparent conductors, photovoltaic materials and power electronics.

Toberer's research revolves around designing new crystalline materials with certain functional properties, such as the thermoelectric effect, in which changes in temperature are converted into electricity and vice versa.

"Everything has this effect, but most of the time, it has a tiny effect that you would never notice," Toberer explained. "You would never build an engine out of this, but there are certain materials where the electrical power that a temperature gradient produces is enormous. That's really exciting, because it's essentially a solid-state version of a heat engine."

Thermoelectric materials are already in use today, just in reverse to the process Toberer is investigating. Instead of thermoelectric generators creating electricity from heat, electricity is applied to materials to produce direct cooling.

Toberer named three areas where thermoelectric technologies are used:

1. Compression for refrigeration
2. Optical electronics
3. Precise temperature control for accurate clinical testing

Photo courtesy of the Discovery Channel



# ENGINEERING A SUPERHERO

## Project:

Create a real-life Iron Man suit out of 3D-printed titanium for the new show, *Savage Builds*.

## People involved:

Adam Savage, host of *Savage Builds*

Craig Brice, director of the advanced manufacturing program at Mines

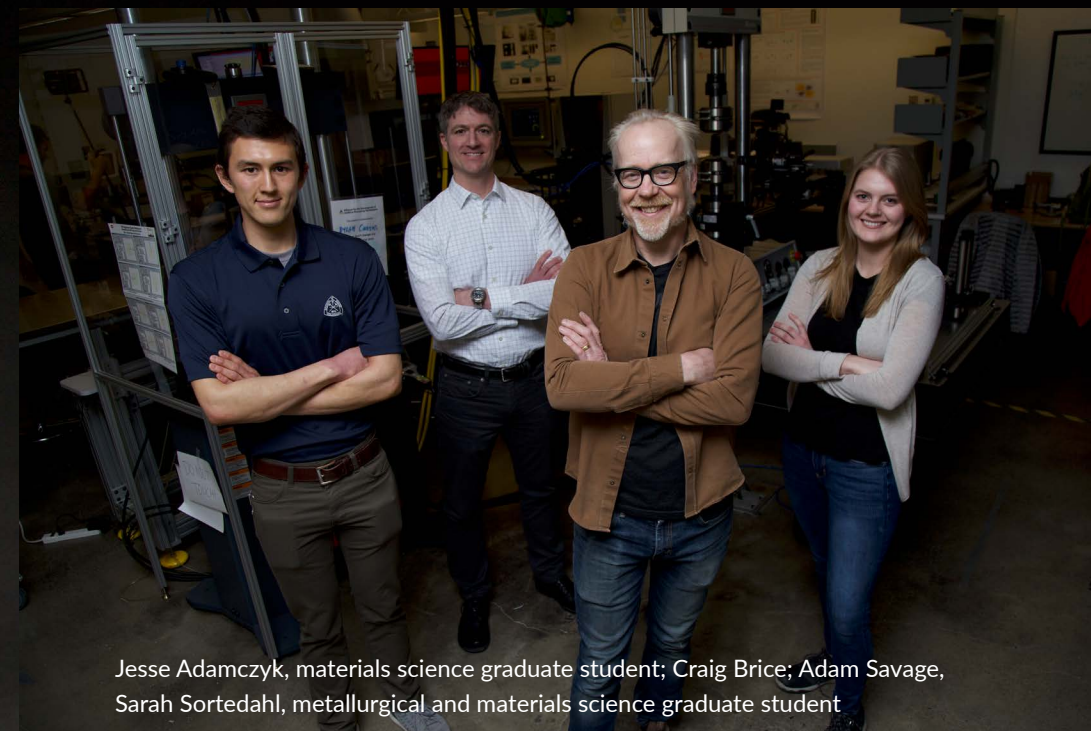
A team of Mines student volunteers

EOS, a 3D-printing company

## Process:

With 3D computer-model representations from Marvel Entertainment, Craig Brice turned the digital designs into real-world functional parts that could withstand immense force (like the impact of a bullet), yet still be light enough to fly. The CAD models were sent to Electrical Optical Systems, where 250 individual pieces were 3D-printed. The finished parts were sent back to Mines, and students helped post-process and piece together the parts. The chest plate was backed with carbon fiber for impact resistance.

► For more about this project, watch the video at [minesnewsroom.com](https://minesnewsroom.com).



Jesse Adamczyk, materials science graduate student; Craig Brice; Adam Savage, Sarah Sortedahl, metallurgical and materials science graduate student



## Zhenzhen Yu

Assistant Professor of  
Metallurgical and Materials Engineering  
2019 NSF CAREER Award

In almost every manufacturing sector, joining dissimilar materials poses significant challenges due to mismatches in their thermal, physical and chemical properties. However, a layer between metals could serve as a buffer that is compatible with both sides. Yu and her research team plans to use five or six different elements to create a high-entropy alloy for the interlayer, with the help of computational design methodology.

"Conventionally, the material design process is trial and error. But think about the periodic table and how many elements you have in there—if you want to choose five or six metallic elements and combine them together, you could have more than 7,000 different choices," Yu said. "We're going to do a computer design process, using advanced software to filter out the options and quickly narrow down the ranges we should look into."

Multiprincipal element alloy interlayers could have a wide range of applications, particularly in the automotive, aerospace, additive manufacturing and power generation industries.

Yu shared five things to consider when looking to accelerate interlayer alloy design:

1. Chemical compatibility with the dissimilar base materials
2. An effective diffusion barrier
3. A combination of good strength and ductility to accommodate the thermally induced stress
4. Feasibility for massive production
5. Cost

# Medicine gets personal

## Advancements in bio technology provide a more customized approach to medical care

By Jenn Fields

As medical care becomes more personalized, Mines researchers are forging ahead in the field by developing nano-sized biotechnology that was once the stuff of science fiction—which prompted one professor to bring up the 1966 movie *Fantastic Voyage*.

“It showed the actors being shrunk down to the size of a microbe and being injected into the body—fantastic plot, right?—and they’re going to break down this clot with a laser,” said David Marr, a professor of chemical and biological engineering whose research explores how nanoparticles can deliver targeted drug treatments in stroke and cystic fibrosis patients.

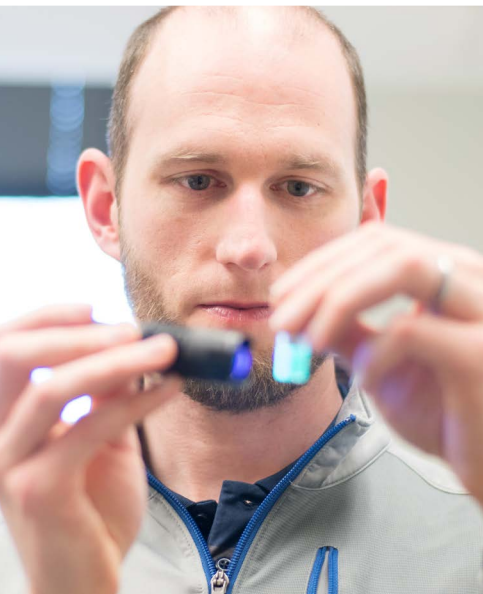
“I think a lot of the ideas I’ve had have been like, well, why can’t we do that?” he said.

Though “personalized” or “precision” medicine usually refers to the recent rise in genetics-based cancer treatment, the overall trend toward more individualized medical treatments has expanded into tiny biosensors and nanobots that can travel to parts of the body that were previously inaccessible.

“A lot of the population-level solutions are already known,” said Kevin Cash, an assistant professor of chemical and biological engineering whose research in biosensors includes intradermal optical “nanoparticle tattoos” that can read

important biological markers in patients. “So now we’re getting into, OK, for this patient, how can we make it better?”

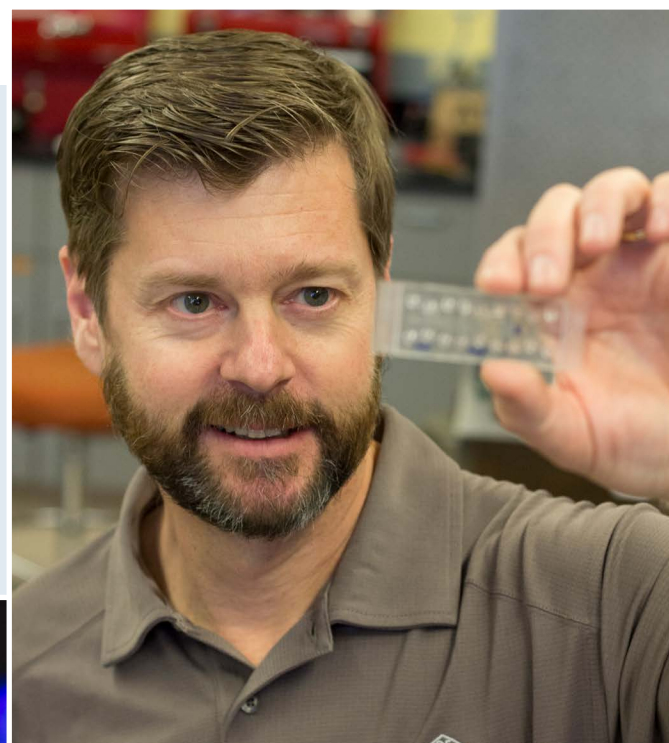
Cash and Marr are both working with Children’s Hospital Colorado’s nationally renowned Mike McMorris Cystic Fibrosis Research and Care Center. Their projects are exploring whether it’s possible to use nanoparticles to break through the difficult-to-penetrate biofilm in the lungs of cystic fibrosis patients—Marr’s research is exploring drug delivery via inhalable bot-like nanoparticles, while Cash’s is focused on analysis for individualized drug treatment.



OUR RESEARCHERS TAKE A CLOSER LOOK ▼

Left: Assistant Professor Kevin Cash is working on intradermal optical “nanoparticle tattoos” that can read important biological markers in patients.

Right: Professor Dave Marr is developing nanoparticles that can be injected, magnetically formed into microwheels within a patient’s body and directed to a specific site for targeted drug delivery.



Marr’s idea for applying nanotechnology to cystic fibrosis treatment grew from his work on strokes. He’s the lead researcher on a \$2.6 million National Institutes of Health grant to explore using nanoparticles that can be injected, magnetically formed into microwheels within a patient’s bloodstream, then rolled to a blockage for drug delivery. Keith Neeves, a former Mines researcher who is now a bioengineering professor at University of Colorado’s Anschutz Medical Campus, is his research partner on the grant. The pair won a second NIH grant to extend the same nanoparticle research into cystic fibrosis treatments.

“For strokes, it’s an occlusion in the brain,” Marr said. “The problem is, how do you get drugs to the site of this blockage and bust it up? It dawned on us that the size of these particles was ideal for inhalable therapy,” he said. “If the particles were too big, they would stay in your mouth. If they were too small, you could inhale them, but when you exhale, they would go right back out. So there’s a Goldilocks size. It turns out our particles are the right size.”

In addition to a dangerous buildup of mucus in the lungs, one of the challenges cystic fibrosis patients face is chronic drug-resistant respiratory infections. Of the inhaled nanoparticles, Marr said, “Imagine them acting as little wheels that will work their way through the mucus. For a lot of these biofilm diseases, the antibiotic just sits on the surface and can’t get

through the biofilm. The idea is that these wheels will be able to dig through the mucus and deliver the antibiotic directly.”

Cash’s biosensor work, on the other hand, is designed to stay in one place—near the skin’s surface, where a patient or doctor can easily scan it, but just deep enough to give the sensors access to blood. It’s also meant to be unobtrusive and discreet.

“Our goal is to make it something you don’t really see and is just in the background constantly monitoring what’s going on,” Cash said. “We want it to look boring, because boring is good.”

The intradermal sensors are made of soft polymer beads that are about 100 nanometers in diameter. “We can put components inside the nanoparticles that can detect oxygen, glucose, sodium, potassium—all things that are important biologically,” he said. The optical or fluorescent sensors give a reading by emitting varying degrees of light.

Because the biosensors give real-time results, they’d be useful in a hospital, where clinicians can get readings quickly, but they’d also save a patient the time and expense of driving somewhere for a blood test. “The applications are pretty wide-reaching,” Cash said. “Almost any disease that you need to know what’s going on over time, this is a useful tool to have in your arsenal.”

However, for his cystic fibrosis research, Cash can use the nanosensors outside of

**“We need smart engineers to go out, try solving these problems, fail, try again, fail, learn from these failures and build better systems. That’s what Mines students are amazing at: ‘This is a big problem that no one knows how to address, and that’s what I want to do.’”**

**-Kevin Cash**

the body, on biofilm samples from cystic fibrosis patients, to learn more about the biofilms themselves and whether the drug-resistant infection on the other side is treatable with a particular antibiotic.

Cash noted that while challenges like these—real-time, accessible testing—are something medical researchers have been trying to solve for decades, the students on his research team are well suited for the task. “We need smart engineers to go out, try solving these problems, fail, try again, fail, learn from these failures and build better systems,” he said. “That’s what Mines students are amazing at: ‘This is a big problem that no one knows how to address, and that’s what I want to do.’”

### A few significant breakthroughs in medical technology in the past 100 years



**1936**  
The heart pacemaker was first demonstrated. Pacemakers didn’t become widely successful until 1958.

The first intraocular lens was implanted to correct a cataract.

**1950**



**1973**  
The first insulin pump was patented.

An adaptive artificial knee was produced.

**2004**



## Designing possibilities

### Addressing the adaptive equipment needs of people with disabilities

By Mark Ramirez

#### 1. Climbing wall holds for the visually impaired

Indoor climbing walls can be a challenge for the visually impaired. Holds are usually in different colors or marked with tape to indicate the difficulty of a particular climbing path.

“Feeling around until they can find the next hold or while someone is barking commands at them isn’t really a great experience for climbers,” Bach said.

In this case, the idea was relatively simple: holds with built-in speakers, set up so only four holds emit sound at any one time—one for each hand and foot. However, at a projected cost of \$50 to \$60

When thinking of a typical senior design project for a Mines student, chances are, a neoprene bootie for a geriatric hawk is not the first thing that comes to mind. Or next-generation rock climbing wall holds, with sounds for the vision-impaired and programmable LED patterns.

But breaking the mold is the bread and butter of Human Centered Design

each, “there’s no way a gym will invest in that,” Bach said.

The solution, a bit counterintuitively, was to pack even more features into the holds. “We put an LED in each hold that can display different colors—you can even start creating different apps and games for it,” Bach said.

“Say you want to climb a 5.11-difficulty route—the wall can remember the holds used and see who did it faster,” Bach explained. “Suddenly, we’ve got something that can appeal to everybody. Not only does it make climbing

Studio, a two-semester capstone course at Mines focused on developing adaptive equipment for people (and sometimes animals) with disabilities.

Launched in 2015 by Mechanical Engineering Associate Professor Joel Bach, HCDS operates much like a design firm, with Mines students expected to work on at least three projects over two

accessible, it’s hitting the economics of what gyms need.”

Smaller challenges included the presence of chalk dust—anathema to electronic devices—and the noise levels in climbing gyms. These were solved with tighter seals and by allowing the holds’ speakers to be adjusted based on hearing ability.

The last hurdle is powering the holds—having to remove and recharge batteries constantly would be impractical. “We’re looking at wireless charging technology, and if we can do that, we’ll be ready to go commercial,” Bach said.

#### 2. Improved binding for sit ski

Traditional ski bindings, which hold an athlete’s boots to their skis, are designed to release for safety—otherwise, a ski catching on something could easily result in a broken leg.

However, that’s not the case for those who use sit skis, such as Chris Devlin-Young, a Paralympic alpine ski racer who has won scores of medals. “He never wanted his bindings to release,” Bach said, since that

would mean a loss of control—equivalent to a car suddenly losing its wheels. And yet sit ski racers have been stuck using the same bindings under their frames, with essentially the entire seat clipped into two potential points of failure.

“In February 2016, Chris crashed at the X Games and broke his collarbone because his bindings failed,” Bach said. “That was a Thursday. The next Tuesday, a team

started working on a new binding design, and by May they had a prototype.”

The new design is drastically simplified. Instead of toe and heel plates, a block of aluminum is bolted to the ski. The plate at the bottom of the sit ski then seamlessly slides into the plate and is further secured with a couple of pins.

#### 3. Socks for hawks

Anne Price, chief lecturer with the Raptor Education Foundation, reached out to Bach and his team for help with a geriatric ferruginous hawk in August 2018.

The bird of prey, which came to the foundation in 1996 after her owner could no longer care for her, suffers from a condition that causes ulcers on her talons. This required bandages, but the hawk kept

stepping in her water bowls, leading to infections and the bandages coming loose. The hawk also had a habit of removing her bandages, so they needed something secure.

The team started work on the project in mid-October 2018, then tested prototypes the following March. The final product was ready later that month.

“The biggest challenge was having an uncooperative client,” Bach said (referring to the hawk, not her handler). The team worked around this by 3D-printing a model of a hawk’s talon and using that to design a washable, reusable, quick-drying neoprene bootie that her handler could easily take on and off and secure using just one clip.

semesters. The program welcomes new students every semester, which means project knowledge doesn’t disappear when a cohort graduates.

The model works well with the types of projects HCDS takes on. Each requires a different set of skills, and start and end dates often don’t conform to the academic calendar.

“We have projects that take a couple of months. One has been going for three years now,” Bach said. “We can start a project at any time—if it’s an immediate need, we can introduce it to students right away.”

The Human Centered Design Studio worked on 15 projects last year. The following are just a few that were recently completed.



**Karin Leiderman**

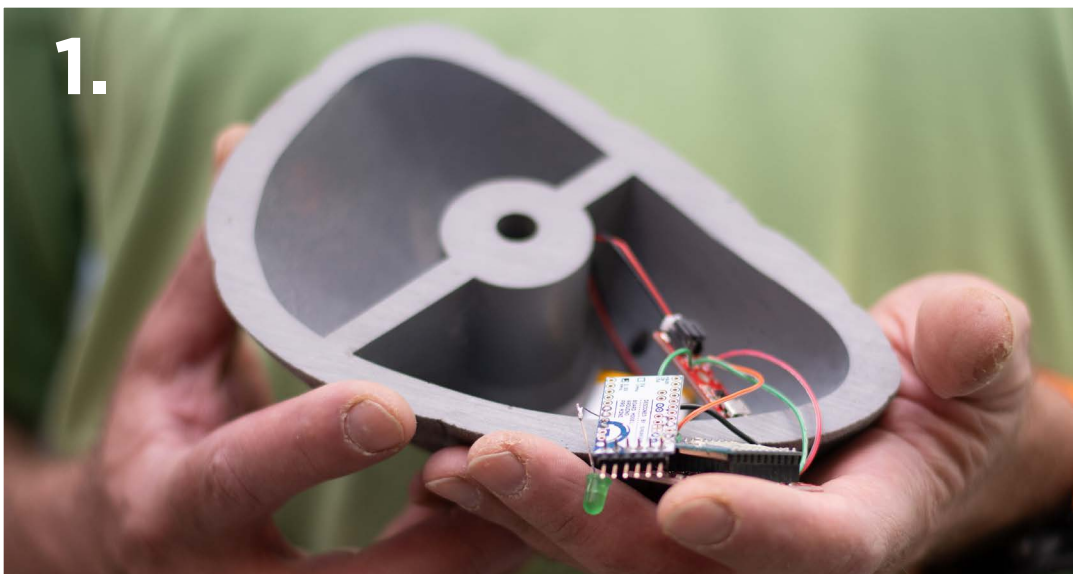
Associate Professor of Applied Mathematics and Statistics  
2019 NSF CAREER Award

There are numerous components that work together within the blood clotting system, all under the influence of blood flow. However, the complexity of this system makes it difficult to predict clotting responses to perturbations, such as drugs or diseases, and to identify the mechanisms underlying these responses.

“This is where math comes in handy,” Leiderman said. “This research involves the formulation of mathematical equations that describe how components of the clotting system interact in space and time—for example, we write down equations that describe how clotting proteins move around in fluid, interact with other proteins in the fluid, on cell surfaces and everywhere in between. Once the equations are formulated, we then have to figure out how to solve them numerically—many of them are nonstandard and require development of new numerical techniques to be solved. We aim to develop a comprehensive mathematical and computational framework that couples the biochemistry, biophysics and biomechanics of blood clotting and simulates with computational efficiency.”

Leiderman shared four ways predictive mathematical models could serve as powerful tools:

1. Models could elucidate previously unknown biochemical mechanisms.
2. They could formulate testable hypotheses.
3. The success of this research could help design new experiments.
4. The models could lead to patient-specific pharmaceutical therapies.





## Under a watchful eye

### Using nocturnal radiant emissions to inform science and public policy

By Ashley Spurgeon

Some of the most iconic images of humanity's presence on Earth come from above the clouds—high-resolution images of nighttime lights taken by the satellites in orbit just beyond our atmosphere. But these images aren't just for show. Rather they—and other nocturnal radiant emissions—are being used for scientific and public policy applications by the Earth Observation Group that recently joined Mines' Payne Institute for Public Policy.

The EOG is dedicated to the development of data products that use satellite imaging to provide valuable insights on gas flaring and volcanic activity, poaching, power

outages and electrification, geomagnetism and more.

We asked Christopher Elvidge, director of the EOG, about the applications of this research and how this data can help us better understand the scope of humanity's effect on the Earth.

**Q: What can nighttime observations tell us?**

**Elvidge:** Daytime satellite data are great for monitoring crops, vegetation, ocean color, snow and ice. At night, it's possible to detect human activities, such as power consumption, the outlines of human development, vessels carrying lights and gas flaring.

**Q: How are nocturnal radiant emissions being used for public policy applications?**

**Elvidge:** The data from the Defense Meteorological Satellite Program and Visible Infrared Imaging Radiometer Suite are available on an open access basis and span 1992-2019 and form one of the longest continuous series of global satellite data products. The data are used to map urban and peri-urban boundaries, population, economic activity, spatial distribution of fossil fuel greenhouse gas emission, density of constructed surfaces, astronomical light pollution, power outages, rural electrification and

nocturnal lighting impacts on organisms, such as sea turtles.

Each year, there are more than 10,000 natural gas flares identified with VIIRS data, which are individually cataloged with locations and estimates of flared gas volumes, and the data are used by the World Bank and many university researchers.

In 2015, EOG began work on an algorithm to detect boats with their lights on. This led to a new nightly global product, called VIIRS boat detections, used by navies, coast guards, fishery agencies, researchers and environmental organizations. EOG

sends email and text alerts for detections for more than 1,000 protected waters and fishery closures in the Philippines, Thailand and Indonesia. In the Philippines, the alerts are used to plan and conduct enforcement actions for illegal commercial fishing operations in restricted coastal waters.

**Q: What are the challenges of this research?**

**Elvidge:** We are always limited by the capabilities of the sensors we have access to. The VIIRS collects data only once or twice per night, and these are after midnight. Perhaps in the future, we will have low-light imaging data collected

at multiple time during the night, with higher spatial resolution and more spectral bands.

► For more information about the Earth Observation Group and Mines' Payne Institute for Public Policy, visit [payneinstitute.mines.edu](http://payneinstitute.mines.edu).

# TAKING US INTO 2020

## AND BEYOND

New additions to the Mines faculty are working to solve some of the most crucial engineering grand challenges—and inspiring the next generation of students to do the same.



**Peter H. Aaen**  
Professor and Department Head  
Electrical Engineering

Multi-physics-based modeling and measurement methodologies for high-power and high-frequency electronic devices



**Daniel Adams**  
Assistant Professor  
Physics

Perturbative nonlinear optics and high harmonic generation; phase retrieval with applications in coherent diffraction imaging



**Mehmet Belviranlı**  
Assistant Professor  
Computer Science

Increasing resource utilization in heterogenous architectures



**Wendy A. Bohrson**  
Professor and Department Head  
Geology and Geological Engineering

How magma changes chemically and physically as it ascends through and is stored in the Earth's crust



**David (Cully) Culbreth**  
Professor of Practice  
Economics and Business

Driving growth in technology and consulting service businesses



**Nikki Farnsworth**  
Assistant Professor  
Chemical and Biological Engineering

Development of novel biomaterials to investigate cellular interactions with their environment and develop therapies for life-threatening diseases



**Patrick Farrell**  
Assistant Librarian, Systems Architecture  
and Web Services  
Arthur Lakes Library

Web and digital services with emphasis on applying human-centered design principles to the development of services and the implementation of systems



**Dorit Hammerling**  
Associate Professor  
Applied Mathematics and Statistics

Spatio-temporal statistical methods applied to the geosciences



**Amy Hitchner**  
Assistant Librarian, Metadata Initiatives  
Arthur Lakes Library

Enable resource discovery and access for researchers and position the library to take advantage of new possibilities in library metadata



**Richard C. Holz**  
Provost and Professor  
Chemistry

Structure and function studies of metalloenzymes, including the design, synthesis and characterization of small molecules that function as inhibitors



**Ge Jin**  
Assistant Professor  
Geophysics

Hydraulic fracturing monitoring and fiber optic-based production logging



**Joseph Kraus**  
Associate Librarian, Reference  
Arthur Lakes Library

Science journal usage; scholarly communication; library unconferences; alternative metrics



**Leslie Lamberson**  
Associate Professor  
Mechanical Engineering

Applied extreme mechanics of materials, with particular emphasis on fracture and damage of materials under high rate loading



**Shannon Davies Mancus**  
Teaching Associate Professor  
Humanities, Arts and Social Sciences

The ways in which genre functions as a performative framework for environmentalist narratives



**Jedidiah McClurg**  
Assistant Professor  
Computer Science

Synthesis and verification of software-defined network programs; programming languages, formal methods and networking



**C. Michael McGuirk**  
Assistant Professor  
Chemistry

Design, discovery and characterization of non-classic gas adsorption in metal-organic frameworks



**Jonathan Miorelli**  
Visiting Teaching Assistant Professor  
Chemistry

How the structure and evolution of a molecule's or material's electron density gives rise to its observed reactivity; ways to implement and assess the use of computational chemistry in the classroom



**Christine Morrison**  
Assistant Professor  
Chemistry

Structural and functional versatility of iron-sulfur clusters



**Kelly Rickey**  
Teaching Assistant Professor  
Mechanical Engineering

Heat transfer at the nanoscale level with a focus on photovoltaics and thermoelectric materials



**Danica Roth**  
Assistant Professor  
Geology and Geological Engineering

Coupling of Earth surface processes with climate, biology and anthropogenic influences



**Jennifer K. Ryan**  
Associate Professor  
Applied Mathematics and Statistics

Designing and developing better techniques for simulating real-world phenomena



**Chelsea Salinas**  
Teaching Associate Professor  
Engineering, Design and Society

Design thinking strategies; developing devices for individuals with physical and mental disabilities



**Lauren Shumaker**  
Teaching Associate Professor  
Engineering, Design and Society

Analysis of experimental pedagogies in diverse classroom environments; assistant director of the Thorson First-Year Honors Program



**Matthew Siegfried**  
Assistant Professor  
Geophysics

Using satellite remote sensing techniques and field-based and airborne geophysical methods to understand the physical properties of Earth's glaciers and ice sheets



**Emily Smith**  
Teaching Assistant Professor  
Physics

Develop and implement lab instruction to address departmental learning objectives for laboratory experiences



**Lori Tunstall**  
Assistant Professor  
Civil and Environmental Engineering

Development of processes and materials for novel applications of additive manufacturing



**James Wong**  
Teaching Assistant Professor  
Mechanical Engineering

Fracture mechanics and fatigue life modeling



**Qin Zhu**  
Assistant Professor  
Humanities, Arts and Social Sciences

Cultural foundations of engineering ethics, global and comparative engineering education and the ethics and policy of emerging technologies

► Keep up with Mines faculty research advancements and projects by visiting [minesnewsroom.com](https://minesnewsroom.com).

# HOW IT WORKS

A look back at one of the first rotary drill bits that revolutionized the oil and gas industry and provided the basis for today's technology

One of the most significant inventions that revolutionized the oil and gas industry was invented by Howard Hughes, Sr. and Walter Sharp in the early 20th century—a two-cone rotary rock drill bit that could withstand drilling thousands of feet into hard bedrock to reach vast reservoirs of oil.

The drill bit pictured here is a model from 1919 with a 5 7/8-inch gauge and was one of the first two-cone rotary drilling systems. With two detachable, cone-shaped cutters

of hardened steel, the drill chipped, crushed and powdered hard-rock formations, speeding up the drilling process and saving oil companies valuable time and money.

This design paved the way for more advanced drill bits, like the tri-cone model that is still the industry standard today. Now, many drill bits use synthetic diamonds attached to cylindrical carbide compacts that are 40 to 50 times stronger than traditional steel bits and have increased longevity.

## REPLACEABLE WASH PIPE

Abrasive muds rapidly cut away the cast-in watercourses of older reaming cone bits, eventually requiring the purchase of new bit bodies. But a replaceable wash pipe improved performance and increased the bit body life.

## DIAMETER GAUGE

To maintain a specified diameter while drilling through rock, this bit has an adjustable gauge, set at 5 7/8-inches.



## DUAL CONE BIT

Two cone drill bits became a crucial tool for tapping vast, deep oil fields. Roller cone drills bits in use worldwide today still rely on design principles introduced by the Hughes two-cone drill bit.

## MODERN MODELS

Today's rotary drill bits utilize the same concepts introduced by the dual cone bit, though now a tri-cone model is preferred. Performance may have improved over the years, but the invention of the rotary drill bit remains one of the oil and gas industry's most significant technologies.





1500 ILLINOIS ST.  
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[research.mines.edu](http://research.mines.edu)

**Mines Research**

# \$84 Million

## in total research funding for FY19

**25** percent growth in research funding

**51** new invention disclosures

**7** new licenses for Mines inventions

**4** NSF CAREER Awards

**1** U.S. Presidential Early Career Award for Scientists and Engineers

**1** faculty member elected to the National Academy of Engineering