Colorado School of Mines

# ENERGY AND THE EARTH

RESEARCH 2008

# **RESEARCH** at Colorado School of Mines

Mines occupies a unique role in the educational fabric of Colorado and the nation. The school, which was founded in 1874 to serve the needs of the local mining industry, was the first public institution of higher learning to open its doors in Colorado. Since then the school has gained an international reputation for excellence in engineering education and the applied sciences with special expertise in the development and stewardship of the Earth's resources. We are a focused institution with an outstanding faculty and student body of some 3,300 undergraduate and 800 graduate students. Our graduates have gained prominence in industry, academia and research institutions throughout the world.

This publication highlights some of the School's research activities, which enhance and invigorate the educational experience of our students, who in turn inspire and motivate our faculty. This magazine focuses on two global issues, energy and the environment, which will drive much research and human activity for the foreseeable future. Global climate change is undoubtedly one of the greatest challenges the world faces. The emission of $CO_2$ and other greenhouse gases has to be reduced. This goal will only be achieved by collective actions on the energy and policy fronts, and Mines is playing a significant role in these actions. The spectrum of our energy-related research, because of the School's history and location, is unparalleled in terms of breadth and richness. Mines has cutting-edge degree and research programs in the following areas, many of which are detailed in this magazine:

- Fossil (petroleum, gas and coal) resource exploration, extraction and processing
- Renewable energy production and distribution (solar, wind, fuel cells and biofuels)
- Power distribution systems
- Environmental impact, mitigation and remediation
- Policy, social license and economic analysis.

An example of our commitment to energy research and education is exemplified by our recently launched nuclear science and engineering graduate program, which capitalizes on our traditional strengths of the stewardship of nuclear materials from uranium mining, reactor material design and the disposal of radioactive waste products.

This focus on energy and the environment is closely coupled to the activities in our core disciplines such as physics, engineering and economics. We fully realize that to succeed in our mission we must collaborate with industry, national labs and other universities. The recently formed Colorado Renewable Energy Collaboratory, an association that includes Mines, the University of Colorado at Boulder, Colorado State University and the National Renewable Energy Laboratory, is a great example of the benefits of effective collaborations. This consortium is already having a real impact on the scientific and economic life of Colorado.

One of our biggest challenges is funding research at the requisite level to achieve criticality. Public universities are the backbone of U.S. science and engineering. But nearly all are faced with funding shortages at the state and federal level. The model for research funding has to change with stronger partnerships between industry and academia. The typical engineering school receives some 10 to 20 percent of its research funding from industry. Mines is well positioned in that the institution receives some 50 percent of its funding from industry and looks forward to growing this partnership.

I trust that you will enjoy the snapshots and vignettes in this publication describing the research life at Mines. Your support is important as Mines continues to make progress on endeavors important to all of us.

John Poate

John M. Poate
Vice President for Research and Technology Transfer

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John Poate is an internationally recognized expert in science and technology with a distinguished career in academia and industry. He obtained his Ph.D. in Nuclear Physics at the Australian National University. Most of his research career was pursued at Bell Labs where he headed the Silicon Processing Research Department. Since then he has served as Dean of the College of Science and Liberal Arts at New Jersey Institute of Technology and Chief Technology Officer of a semiconductor capital equipment company. His awards and distinctions include Fellow of the American Physical Society, President of the Materials Research Society, Chair of the NATO Physical Sciences and Engineering Panel, winner of the John Bardeen Award of the Metallurgical Society, and appointment to the inaugural class of Fellows of the Materials Research Society.

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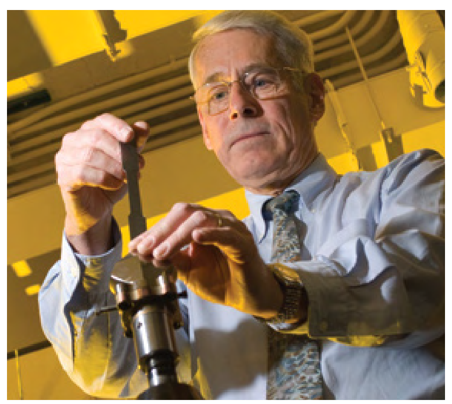
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## Features



## **A MESSAGE** from the Editor

I thought I knew Colorado School of Mines—and then I became lead writer and editor for this publication.

Having spent nearly seven years pursuing degrees at Mines, I figured I had a good handle on what the School has to offer. But as I delved into the cutting-edge work of diverse departments and centers, and discovered the expertise and distinction of faculty members I had not known before, it became apparent that my knowledge of Mines only scratched the surface.

Since I'm involved in solar cell research, I was excited to learn more about energy-related research at Mines. From research on increasing electrical efficiency through fuel cells, to research on increasing production efficiency of traditional resources, Mines is on the forefront of energy and environmental technology and development. The School drives industry forward in these new technologies while emphasizing sustainability and stewardship of the Earth's resources. I am proud to be part of this effort.

Mines has been selected by the Colorado State Legislature as the state's first "exemplary institution" of public higher education due to its "high degree of responsibility and capability with regard to its academic and administrative functions."

As you read about the research projects, educators and centers that are shaping the face of energy research at Mines, I think you will learn—as I have—what makes Mines so special, unique and, yes, exemplary.

Jennifer Nekuda Malik

Jennifer Nekuda Malik

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Jennifer Nekuda Malik is a Ph.D. candidate working on thin film copper indium diselenide solar cell research. Her project is a collaboration between the Metallurgical and Materials Engineering (MME) Department at Mines and the National Renewable Energy Laboratory in Golden. Jennifer earned her B.S. and her M.E. at Mines in MME in 2005 and 2006, and will defend her Ph.D. thesis in 2008.


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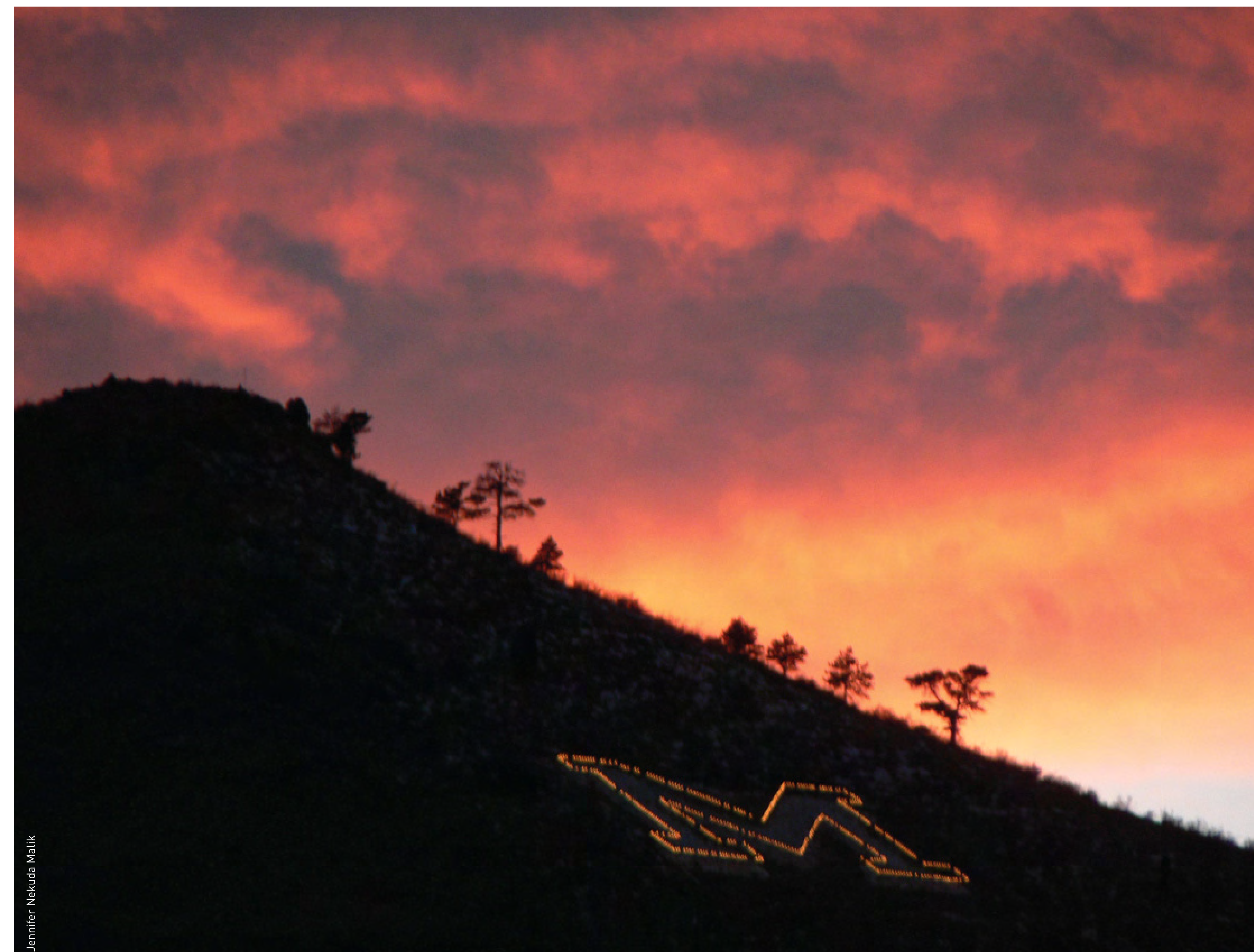

Jennifer Nekuda Malik

# Harnessing Wind Power, Reducing Energy Costs

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Wind can provide up to 20 percent of the necessary energy portfolio for the U.S., according to researchers at the National Renewable Energy Laboratory (NREL). Currently wind energy provides only about one percent of the nation's energy, motivating efforts to further harness and utilize this environmentally friendly, inexhaustible energy source.

To increase the amount of energy harnessed and, in turn, reduce the cost of wind energy, researchers are looking for methods to increase turbine efficiency.

The wind energy research currently conducted by Kathryn Johnson, Clare Boothe Luce Assistant Professor in Engineering and site director for the Center for Research and Education in Wind (CREW), focuses on control systems, including recent projects that model and control both individual turbines and entire wind farms.

Modern utility-scale wind turbines are mounted on towers 50 meters or more above the ground. The significant height positions the turbine blades where the wind is faster. The blades on the turbine act much like the wings on an airplane by providing lift that spins the turbine and generates electricity.

The controllers developed by Johnson aim to increase the aerodynamic efficiency of a wind turbine, or an entire array of turbines, to maximize the energy captured for a given wind speed input.

"Increasing energy capture for a given wind energy system can reduce the cost of wind energy, making it an even more attractive choice," Johnson said. "In a time of increasing concern over global climate change, we must take advantage of many sources of clean energy, and wind is currently the most cost-effective of the clean, renewable sources that still have good potential for significant growth."

The formation of CREW has provided a platform for collaboration and joint funding opportunities. The new center is part of the Colorado Renewable Energy Collaboratory, which includes researchers from Mines, NREL, the University of Colorado, and Colorado State University. Johnson also collaborates with researchers at Boise State University.



## More than Ever, Innovations Lead to Technology Transfer

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To catalyze and stimulate patent applications from Mines' world-class research, the Office of Technology Transfer has implemented new initiatives to help faculty and graduate students. The result? Sixty-four new patent applications in fields ranging from biotechnology to unique advanced materials.

Currently, several energy research projects with important potential for commercialization have patent protection.

Chemical Engineering professors Doug Way, Paul Thoen, and associates have developed palladium alloy membranes that can be used to separate and produce high purity hydrogen from a variety of sources. The membranes can be installed in small, portable devices to make hydrogen and electric power or in large refineries and petrochemical plants.

Another example of energy-related intellectual property comes from Chemical Engineering professor Andrew Herring and associates who have discovered technology that may result in more efficient, cost-effective cathodes and anodes for future hydrogen fuel cells.

In the traditional energy fields, Geophysics professors Roel Snieder and Max Peeters have developed improved technologies and devices to enhance the efficiency of oil exploration.

Prior to 2004, most of the research conducted at Mines was in collaboration with industry partners who owned the resulting intellectual property and proprietary technology. Today, research at Mines is split nearly equally between federally funded and privately funded projects. The spirit of entrepreneurship is steadily growing as evidenced by multiple start-up companies based on the creative inventions and technologies of Mines faculty and graduate students.

## Enhancing Hydrocarbon Production through Reservoir Characterization

Reservoir Characterization Project (RCP) researchers are looking for answers to the question: How can we increase the amount of oil and natural gas available from existing reservoirs through improved reservoir modeling, dynamic characterization and monitoring? RCP research suggests the amount of oil and gas produced from existing reservoirs could be doubled through better characterization.

"We have to use technology to understand and produce our reservoirs effectively – in doing so, we can extend the life of our resources, improve our economic base and manage our resources in an environmentally responsible way," said Tom Davis, RCP co-director.

For more than 20 years, RCP—a research consortium that receives 90 percent of its funding from more than 30 industry partners—has been a leading force in the improvement of hydrocarbon recovery through development and application of new reservoir modeling and simulation techniques that encompass new time-lapse multi-component seismic technology.

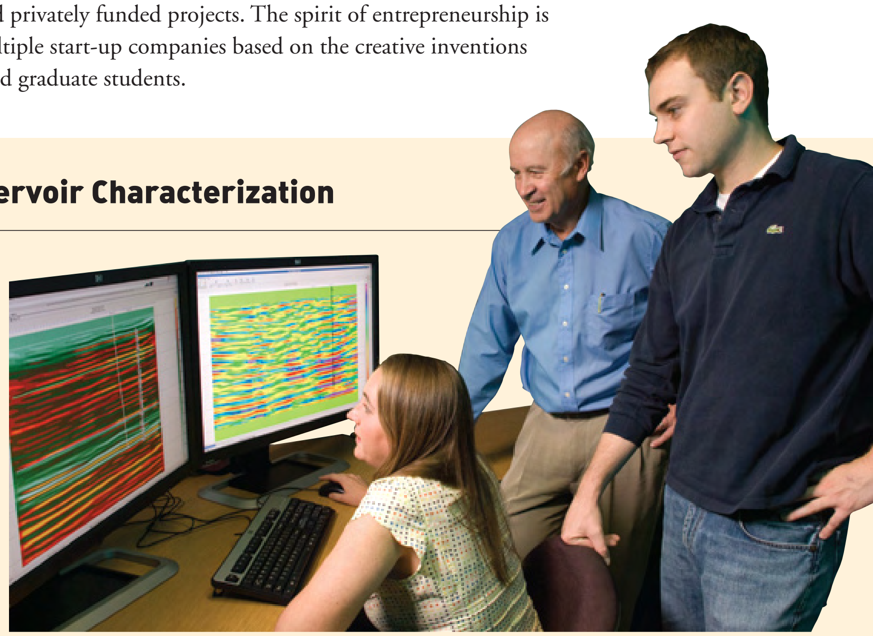
Currently the RCP has two main areas of focus: A tight gas project in Rulison, Colo., and the characterization of the Postle Oilfield near Guymon, Okla.

Tight gas refers to natural gas that is trapped in a very tight formation underground – vast resources occur throughout the Rocky Mountain region. The Rulison project used integrated time-lapse (4-D) data, multi-component (9-C) seismic data with down-hole measurements, geological information and production data, and petrophysical information to characterize the tight gas reservoir. This portion of the project, which began in 2003, is nearly complete and has proven to be extremely successful.

The current phase, the Postle Oilfield, has produced approximately 30 percent of an estimated 300 million barrels of oil. The oilfield poses a unique recovery challenge due to the porosity of its sandstone layer and the trapping of oil within its pores. This critical RCP study will include acquisition and analysis of 9-C and 4-D seismic data to create an effective seismic monitoring system and to optimize carbon dioxide flooding techniques to enhance oil recovery and manage and sequester carbon dioxide.

"RCP is unique among university consortia in that data are collected, processed and interpreted to find solutions to specific oil and gas production problems," said RCP co-director Bob Benson.

RCP currently supports a dozen graduate students in geophysics, geological engineering and petroleum engineering. The students work together to acquire data, generate reservoir models and revise and perfect these models based on continuous feedback.



Geology graduate student Dawn Jobe, Geophysics Professor Tom Davis and geophysics graduate student Mark Wiley examine characterization data.

## Oil Shale Discussion Draws Worldwide Participants

Mines oil shale researchers are working to characterize the properties of the Green River Formation in the Piceance Basin of western Colorado. With a potential yield of more than one trillion barrels of oil, Mines research focuses on gaining a better understanding of the formation, resource properties and heat-related rock changes that can occur during in situ production.

During the Oil Shale Symposium, hosted by Mines and the Colorado Energy Research Institute each October, researchers from around the world present the latest technology developments in a series of technical sessions.

As the leading meeting of its kind, the symposium covers development of oil shale resources including research and development, impact analysis and the regulatory framework that impacts the industry.

The symposium promotes and reviews the development of oil shale resources for members of the energy community including large energy-producing companies (Shell, ExxonMobil, EGL, Chevron, ConocoPhillips and others), government agencies and academic researchers. This year's event, the 27th symposium, saw more than 350 international attendees from industry, academia and government.

R. Glenn Vawter

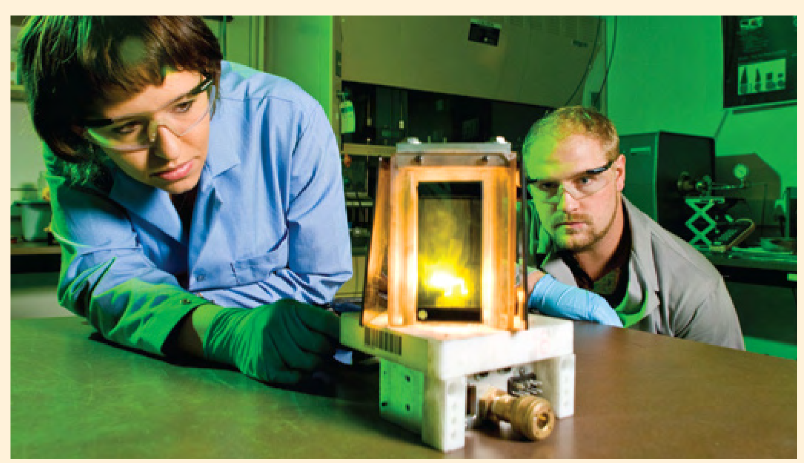
### The Colorado School of Mines Oil Shale Research Center

Mines has received industry support to open a new Oil Shale Research Center, commencing operations in January 2008. The charter members are ExxonMobil, Shell and Total. The research at the Center will address a range of resource characterization technologies, information dissemination and environmental issues, including carbon sequestration to ensure that new hydrocarbon resource developments of this kind will be as close to free of carbon dioxide emissions as technically possible.

## Nuclear Engineering

As concern has grown for the environmental, economic and political impacts of burning fossil fuels, interest has increased in carbon-free sources of generating electricity. Nuclear energy currently provides approximately 20 percent of the nation's electricity, according to the Energy Information Administration. "In the future that fraction is likely to rise and we have to make sure this happens in a clean and safe manner," said Uwe Greife, associate professor of physics and interim academic program director of nuclear engineering.

A Nuclear Science and Engineering Program was established at Mines in 2007 as a graduate level program focusing on the stewardship of nuclear materials throughout their lifespan. This translates to an interdisciplinary degree that spans multiple departments including the Division of Engineering, the Department of Geology and Geophysical Engineering, the Department of Mining Engineering, the Department of Physics, the Department of Metallurgical and Materials Engineering, the Division of Environmental Science and Engineering, and the Division of Liberal Arts and International Studies.



Metallurgical and materials engineering Ph.D. students Marissa Reigel and Collin Donohoue watch a self-propagating high temperature synthesis reaction. This technology is used to create a nitride nuclear fuel pellet using surrogates for the elements with a greater atomic number than uranium.

The program at Mines is unique because it covers every aspect of nuclear energy generation from locating nuclear fuels, to mining those fuels, to processing the fuels for reactors, to characterizing the properties of the fuels, to understanding nuclear reactions, and finally to using proper disposal techniques. The breadth of the Nuclear Science and Engineering Program at Mines gives students a complete picture of the nuclear power generation cycle and also addresses environmental health and safety, associated environmental policies and social license issues.

Mines researchers are teaming up in a Nuclear Science and Engineering Center (NuSEC) and have formed collaborations with other universities, industry partners and national laboratories to increase the overall value of the program. Mines students have the opportunity to work with students from the University of Colorado and Colorado State University as well as with researchers from Los Alamos National Laboratory, Lawrence Livermore National Laboratory and the Idaho National Laboratory, and they have access to the U.S. Geological Survey TRIGA reactor.

## Institute Advances State's Energy Portfolio

The Colorado Energy Research Institute (CERI) was re-established in 2004 by the Colorado legislature to promote collaboration among government, industry, universities and the public on energy-related research, education and development.

Because of Colorado's numerous traditional and renewable energy resources, CERI works to advance the statewide development of clean fossil and renewable energy technologies to establish a sustainable energy portfolio for Colorado.

CERI is located on the Mines campus and has been integrated into many aspects of the curriculum and research at the School. CERI's focus areas include economics, energy research and education, and outreach. Based on these areas, the institute has established many energy-related research initiatives.

CERI scientists are involved in a variety of renewable and traditional energy projects, as well as $CO_2$ emission mitigation and sustainability development. Renewable projects under development include photovoltaics research, hydrogen production by phototropic algae, and renewable energy storage. Oil and gas studies are increasingly focused on natural gas production from the many tight sandstone formations in the Rocky Mountains, oil shale production and related environmental mitigation, and carbon dioxide sequestration research.

With the assistance and support of CERI, the Colorado Renewable Energy Collaboratory was established in 2006 with Mines, Colorado State University, University of Colorado at Boulder, and the National Renewable Energy Laboratory. The collaboratory aims to advance research and engineering developments in all renewable energy technologies.

With financial support from the State of Colorado, CERI also has established a unique energy development outreach program with community colleges and vocational schools across the state. The program advances energy-based knowledge and relevant skills development to help attract, educate and train people for employment, according to CERI Director Dag Nummedal.

Through this outreach program, CERI partners with Delta Montrose Community College, Colorado Northwest Community College, Mesa State College, Morgan Community College, Pueblo Community College, Red Rocks Community College, Trinidad State Junior College and San Juan Basin Technical College.

CERI also provided funding and support for the establishment of the Colorado Fuel Cell Center, highlighted on page 40.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# Plants MATTER

Multinational energy corporations and the academic community are taking biofuels and biorefining seriously

If you heat wood to approximately 500 degrees Celsius in the absence of oxygen you get pyrolysis oil—a flammable liquid that can be used to make liquid fuels or a variety of chemicals. If you heat wood to greater than 700 degrees and include a small amount of oxygen and steam, you get synthesis gas, or syngas, which, among other things, will run a combustion engine, generate electricity, or yield a variety of liquid fuels. All this from wood—or switchgrass, or straw, or just about any dried cellulosic biomass.

While the promise of these and other renewable energy technologies is great, much of the science is poorly understood and technologies for industrial-scale production are immature. To help advance understanding, Colorado School of Mines has entered into a partnership with three Front Range research institutions and several private corporations to form the Colorado Center for Biorefining and Biofuels, known by the acronym C2B2. The collaboration includes the University of Colorado at Boulder (CU); Colorado State University (CSU); the National Renewable Energy Laboratory (NREL); Mines; and more than 10 private corporations including Chevron, ConocoPhillips, Dow Chemical and Shell Global Solutions.

To explore how much energy America could generate from domestically produced biomass, the U.S. Department of Energy and the Department of Agriculture completed a joint research project in 2005 known as the "Billion Ton Study." Their conclusions were that the U.S. could sustainably provide sufficient biomass for one-third of its transportation fuel needs without undermining current food crop production. And these conclusions assumed the use of current conversion technologies and only small changes to agricultural and forestry practices.

While the potential is evident on paper, if the U.S. is going to get anywhere near such a lofty goal, the science must be better understood and complex new systems engineered. Therein lies the mission of C2B2, which is the first major initiative of the recently established Colorado Renewable Energy Collaboratory created in February 2007.

By Nick Sutcliffe and Alan Mencin
*Mines* magazine, Spring/Summer 2007

## Materials from Biomass

While energy from biomass is the main focus of C2B2, materials shouldn't be ignored. John Dorgan, professor of chemical engineering, points out that bioengineering and biorefining can yield many of the materials traditionally produced from petroleum. Illustrating the point, he explains how switchgrass can be genetically modified to synthesize and store polyester. When harvested, cellulose from the plant can be used as feedstock for ethanol production and the polymer extracted to provide a valuable co-product.

Chemical Engineering Professor John Dorgan, who is the C2B2 site director for the Mines campus, points out there are three primary pathways for converting biomass into electrical power or useable fuels: biochemical, chemical and thermochemical.

The biochemical platform, currently the most widespread, involves breaking biomass down into simple sugars that can be fermented into ethanol. An example of chemical conversion is converting plant oils into biodiesel. This process typically involves growing crops rich in triglycerides (such as soybeans), extracting their oils and chemically converting them into liquid fuel. There are also a variety of thermochemical conversion methods, most of which involve heating biomass to produce either syngas or pyrolysis oil.

## Biochemical Conversion

By far the most popular biofuel in the U.S. is ethanol, and production has skyrocketed in recent years. The U.S. produced in excess of 5 billion gallons during 2007, up from 3.7 billion gallons in 2005. And almost all of this was produced using corn as the primary feedstock. The starch in corn is a relatively simple carbohydrate, easily broken down (hydrolyzed) into glucose. Put into solution, it is then biochemically converted to ethanol by microbes commonly referred to as yeast, which ultimately poison themselves when they elevate ethanol concentrations to around 11-14 percent. Industrial ethanol is then derived by simply distilling this "beer."

Although this approach is successfully yielding large quantities of ethanol, it is expensive and the industry is propped up by a 51-cents-per-gallon subsidy. The use of corn grain as the feedstock inflates the price of conversion considerably, and switching to a production process that utilizes cellulosic feedstocks (for example, wood, grasses and corn stover) is viewed as the key to lower costs. In addition, by using non-edible cellulose (for example the corn stalk) industrial ethanol production would put less inflationary pressure on food supplies.

Cellulose, probably the most abundant organic compound on Earth, is a complex polysaccharide composed entirely of glucose. However, unlike starch, it is hard to break down. A triumph of evolutionary design, it is the biological equivalent of armor plate and has become the fundamental building block of the plant kingdom. In their search for a chink in the armor that would allow cellulose to be easily and inexpensively hydrolyzed into simple sugars, researchers have explored the use of heat, sulphuric acid and a family of enzymes called cellulases. The combination of heat and sulphuric acid is effective, but energy intensive. Cellulases—enzymes found in a variety of organisms that break cellulose down into simple sugars—are expensive and industrial scale use is impractical at present. However, they are being intensively studied by C2B2 researchers and may one day offer an efficient pathway for converting cellulose into a sustainable fuel source.

## Chemical Conversion

Ethanol is only one of several biofuels the energy industry is taking seriously—another is biodiesel. Made from vegetable oil, this organic liquid fuel can be manufactured at room temperature using a rather simple chemical conversion process. In the presence of a catalyst and an alcohol, the triglyceride (fat) molecule is converted into fatty acid esters and the byproduct, glycerin.

Once the glycerin has been removed, the resulting fatty acid esters provide an adequate substitute for petroleum-based diesel in almost every application. The drawback is cost: vegetable oil production is expensive and the industry's growth is currently supported with subsidies ranging from 50 cents to one dollar per gallon. A potentially promising alternative is oil from algae, which can be produced much more intensively than traditional crops. While soybeans typically yield about 48 gallons of oil per acre annually, algae grown in carefully monitored shallow, open ponds or clear plastic tubes have the longer term potential of producing yields upwards of 10,000 gallons of oil per acre. The process is capital intensive and requires large quantities of water and nutrients, but its potential has captured the interest of capital investment markets and the energy industry.

A synthetic diesel fuel can also be made by introducing heated animal or vegetable oils into a hydrogen-rich environment in the presence of a catalyst. Called renewable or "green" diesel, it is nearly indistinguishable from the petroleum-based product and is the focus of a recently announced joint venture between ConocoPhillips and Tyson Foods.

## Thermochemical Conversion

Turning biomass into useable fuel via thermochemical conversion processes can involve a variety of different paths, all of which involve heating biomass in either low- or no-oxygen environments.

When cellulosic biomass is heated in the absence of oxygen (a process known as fast pyrolysis), the main product is bio-oil, which can be burned as a substitute for petroleum-based fuel oil in boilers. When cellulosic biomass is heated with a limited amount of oxygen and steam (a process known as gasification), the main product is synthesis gas, or syngas. Among other uses, this flammable combination of carbon monoxide and hydrogen can be burned in a turbine, fed into a solid oxide fuel cell to produce electricity, or converted into a variety of liquid fuels.

Before these processes can be applied on a commercial scale, however, numerous problems must be solved and the chemistry better understood. Syngas made from biomass contains ash and tars, which can damage turbines and degrade catalysts in fuel cells. Understanding how to engineer solid oxide fuel cells that tolerate supply-streams of un-scrubbed syngas is a research focus of William Coors Chaired Professor of Chemical Engineering, Tony Dean. Understanding how to deliver a clean supply-stream of biomass-produced syngas has researchers busy around the world, including Mines Professor of Chemical Engineering, Andy Herring.

## The C2B2 Partnership

C2B2 brings together four diverse research institutions that encompass the full spectrum of biofuel- and biorefining-relevant expertise: CSU has world-class capabilities in the agricultural sciences, as well as the internationally recognized Engines and Energy Conversions Laboratory; CU-Boulder is well known for its expertise in biological and chemical engineering, molecular and cellular biology, and biochemistry; NREL has highly specialized laboratory facilities and decades of experience researching biomass energy conversion technologies; and Mines brings a wealth of knowledge in refining, chemical engineering, materials engineering and fuel cell technologies.

The goal of C2B2 is to develop new technologies and advance them into the private sector as quickly as possible. Companies participate in C2B2 with payment of a membership fee that funds shared research initiatives. In so doing, they gain access to this rich pool of expertise, as well as the research and development resources of sponsoring industrial partners.

The C2B2 partnership has received strong political support at the state level. The formation of the Renewable Energy Collaboratory can be traced back to the 2006 Renewable Energy Summit sponsored by Senator Ken Salazar's office. His staff have remained actively involved by facilitating negotiations and helping to frame the final C2B2 agreement. After campaigning on a strong renewable energy platform, Governor Bill Ritter has embraced C2B2. And on the Mines campus, President Bill Scoggins is enthusiastic, seeing it as "substantive and timely progress toward finding solutions to [our energy] challenges." On the front lines of C2B2 research, Dean is particularly upbeat about the School's role: "We are a key player on a big-league team. We've got a lot to offer and we have a lot to gain in terms of sharing knowledge and sharing facilities. Having NREL so close is a major advantage."

With the partnership just begining, it's impossible to predict where C2B2 will lead, but with four multinational corporations on board, exceptional research capacity at hand and worldwide interest in biofuels at an all-time high, the future looks bright.

## Believing in Bioplastic

Birgit Braun (left), a member of John Dorgan's research group, won the 2007 Arthur B. Sacks Award for Excellence in Sustainability.

"The main inspirations for me during my graduate work were the challenges humanity is facing in the near-to-medium-term future; namely, meeting energy demands for a growing worldwide population in a sustainable fashion while working towards a more environmentally friendly society without sacrificing our living standards," said Braun, who successfully defended her Ph.D. thesis in November 2007.

Plastics play an important role in the energy balance, and the bioplastic research conducted by Braun and other researchers in this field will eventually lead to a decrease in the amount of petroleum-based plastics.

Braun's research is focused on a bioplastic called polylactide (PLA). PLA is a polyester derived from renewable resources that is economically competitive and can be used for packaging and single-use applications. Given that the packaging sector accounts for approximately one-third of the total plastics market, this is an important area of research.

# Power PROCESSOR

GECO brings Supercomputer to Mines

Through the leadership of Physics Professor Mark Lusk (left), Mines has designed and acquired a high performance computing (HPC) cluster that aims to be a national hub for computational inquiries aimed at the discovery of new ways to meet the world's energy demands. Mines researchers have named the supercomputer "Ra," after the ancient Egyptian sun god. "I think the name is appropriate because of the important role the sun plays in nearly every form of energy that we gather," says Lusk.

The cluster is currently being assembled in the Center for Technology and Learning Media building on the Mines campus. Provided by Dell Inc., the cluster of 12 cabinets and 2,144 computer cores is designed to perform calculations at a rate unprecedented in the history of the college. Its estimated peak performance will be approximately 20 teraflops—fast enough to do more than 3,000 calculations every second for each and every one of the 6.6 billion people on the planet. This places the machine well within the top-100 fastest computers in the world.

The new facility, administered by the Golden Energy Computing Organization (GECO), is dedicated to advancing energy-related science. "Our aim is to make a positive, international impact on the discovery and development of new sources of energy," says Lusk.

In order to achieve a balanced energy portfolio, GECO has four priority areas: disruptive scientific discoveries associated with renewable resources; improvements to existing methods of finding, characterizing and tapping existing resources; generation of quantitative assessments of the impact of energy policy on the environment; and the design of new energy-related materials.

Each of the priority areas is itself divided into two challenges. Photo-production of hydrogen and biomass energy conversion fall under the renewable energy priority. Hydrocarbon deposit characterization and hydrate nucleation and growth will be explored to help locate and develop existing resources. Research will be performed on carbon dioxide emissions and carbon sequestration to advance environmental stewardship. And finally, new energy-related materials including polymer batteries and ultracold designer materials for solid state systems will be investigated.

GECO is a collaborative project between researchers at Mines, the National Renewable Energy Laboratory (NREL) and the National Center for Atmospheric Research. "The investigations cross several disciplines and target technological payoffs with time scales from several months to several decades," Lusk notes.

The GECO initiative will have four payoffs for the Mines community: raising the School's international profile as a premier energy-focused research institution; facilitating the acquisition of large-scale funding; making Mines a leader in the effort to develop a Front Range HPC grid for both academic and industrial sectors; and providing the infrastructure and motivation for the creation of a significant HPC educational component.

The educational programs to be established with GECO include a five-year B.S./M.S. degree, wherein students complete an undergraduate degree in either Engineering Physics or Petroleum Engineering and an M.S. degree in Mathematical & Computer Sciences focused on scientific computing. The Engineering Physics program is already in place.

Additionally, Mines will establish a new Ph.D. minor in HPC and will develop a focused HPC certificate program for members of the Front Range industrial community. Hands-on HPC systems administration training will be provided for both students and faculty members.

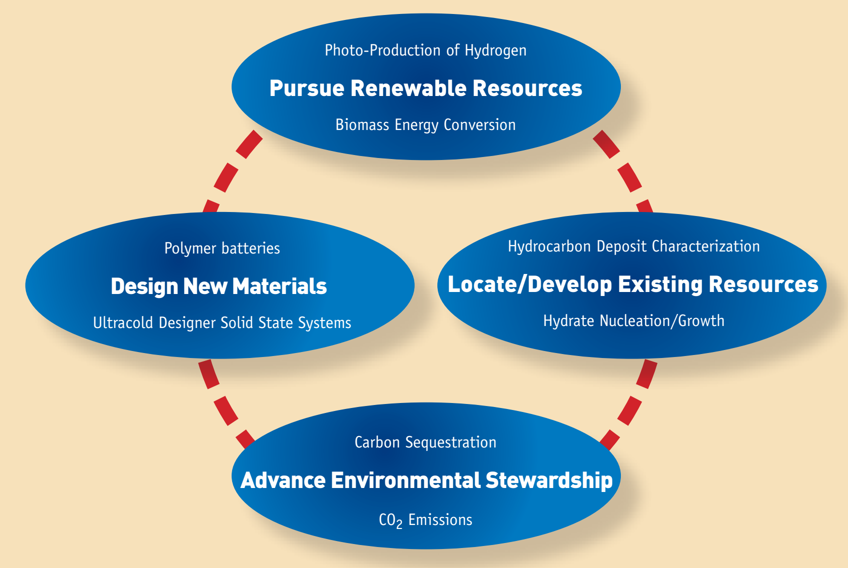
The organization has also established outreach programs for minority colleges and organizations. Salish Kootenai College, a four-year institution on the Flathead Indian Reservation in western Montana that offers a B.S. in information technology and computer engineering, will be the first to collaborate with Mines on educational programs in HPC and will benefit from hands-on learning opportunities.

A second outreach collaboration has been established between GECO and the Mines section of the Society of Women Engineers (SWE). A team of SWE members will be trained on the GECO cluster and will make presentations at local high schools to promote interest in careers in energy-related fields.

Funding to support the supercomputer has been provided by the Colorado School of Mines Foundation, NREL and the National Science Foundation.

Golden Energy Computing Organization GECO

### Four Priority Areas, Eight Challenges



# Fire & ICE

Researchers at Mines have brought to light an alternative energy source that holds significant future promise

Mines chemical engineering student Tim Strobel, left, Delft University of Technology student Gary Andrews and post-doctoral fellow Hiroshi Ohno perform Raman spectroscopy on hydrates.

The Mines Center for Hydrate Research (CHR) is a global leader in hydrate research and recovery, with a program that incorporates a multidisciplinary approach to addressing the challenges associated with hydrate-related energy — an area that has significant importance and impact on both energy and environmental sustainability.

Hydrates are naturally occurring ice-like solids that trap and store natural gas. Gas hydrates form when water and natural gas molecules come into contact under low temperature and high pressure conditions. The water molecules bond together under these conditions to form polyhedral cavities that trap the natural gas molecules. Due to the necessary pressure and temperature conditions for formation, gas hydrates occur naturally in both permafrost regions and deep ocean sediments.

With vast supplies of gas hydrates potentially available around the world, the research conducted at CHR is an important step along the path of advanced technology combined with responsible stewardship. Hydrates are estimated to contain about twice the amount of energy contained within the total fossil fuels available on earth. In the U.S. alone, this translates to an estimated 300 times more natural gas in hydrates than recoverable gas remaining in conventional reserves.

With its incorporation of engineering technology and advancements with fundamental science understanding, CHR research is unique.

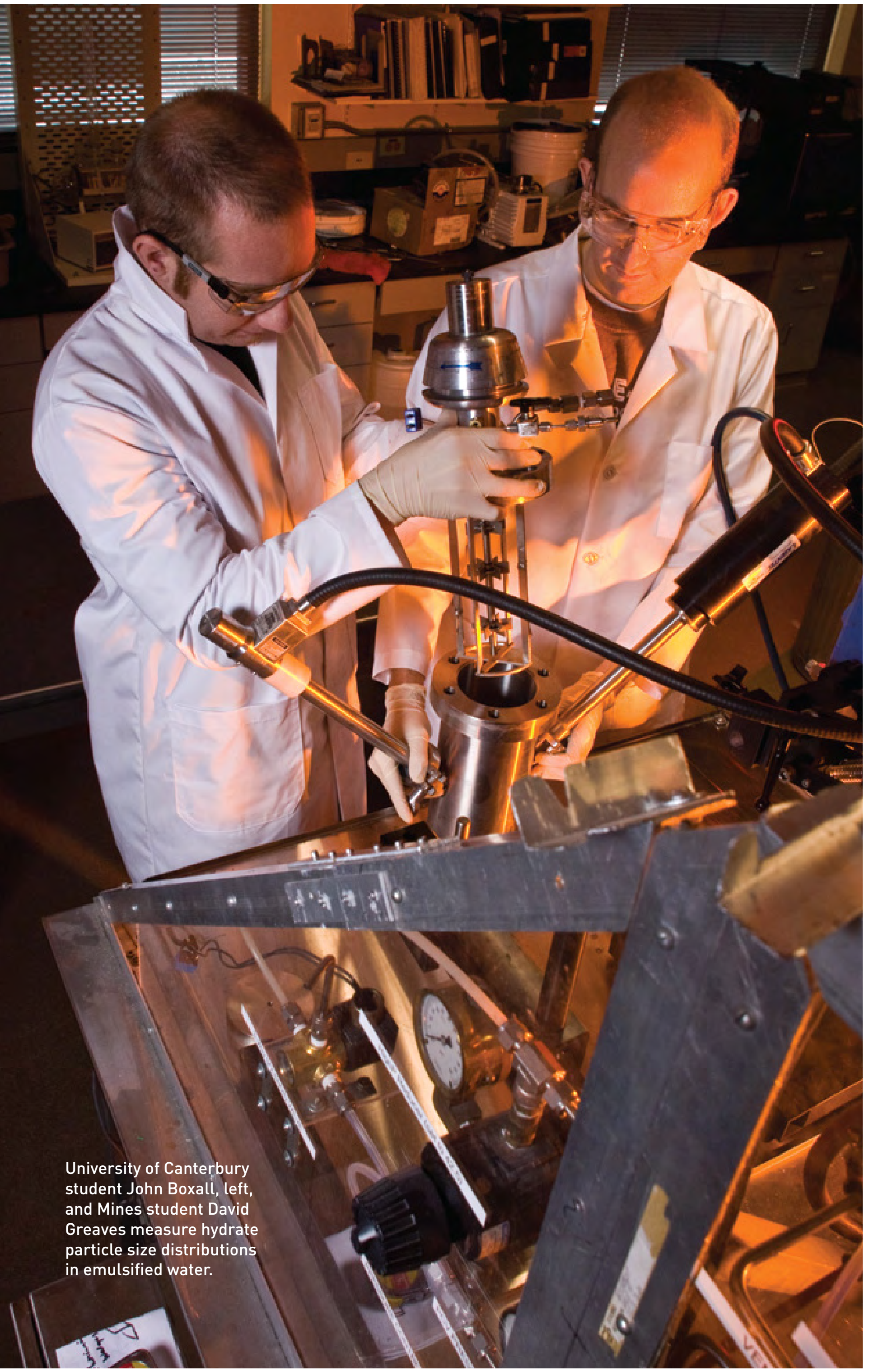
"The Center is focused on discovering and developing technologies with applications that make a significant impact to the energy industry and environment, while applying fundamental science understanding to these applications," said Carolyn Koh, CHR co-director.

Hydrates research at Mines is multifaceted and geared to address several important issues. One of the issues at the forefront of the research is flow assurance. Oil and natural gas flowlines provide the necessary pressure and temperature conditions to form and stabilize hydrates that can cause significant blockages in transmission lines which can lead to severe safety and economic consequences. In order to prevent these blockages, the thermodynamic conditions for hydrate stability and kinetics of plug formation must be understood.

CHR graduate students John Boxall, Simon Davies, Laura Dieker, David Greaves, Jason Lachance, Joseph Nicholas and Patrick Rensing are developing state-of-the art kinetic models that incorporate the key physics determined from sophisticated experiments. These kinetic models are being incorporated into a unique tool, CSMHyK, which allows engineers to simulate hydrate formation and blockages in deepwater oil and gas pipelines.

A second problem associated with flow assurance is hydrate plug dissociation. Once a hydrate plug has formed in a pipeline, blocking the line, it is important to determine how long it will take to break up and allow passage of oil or natural gas through

**Burning hydrate.**
Courtesy of MBARI



University of Canterbury student John Boxall, left, and Mines student David Greaves measure hydrate particle size distributions in emulsified water.

the line as well as assess the safety issues associated with the plug. The CSMPlug program has investigated this issue in oil lines for more than a decade and succeeded in estimating the dissociation time under various flowline conditions.

Other CHR products also are widely used in the oil and gas industry, as well as in academic and national research laboratories. CSMGem is a thermodynamic prediction program for hydrate formation, and even though the kinetic model developments are still in the early stages, some of this technology developed at Mines is already used in the flow assurance industry. The CSMPlug and CSMGem products are provided with the new edition of the bestselling hydrate book, *Clathrate Hydrates of Natural Gases*, co-authored by E. Dendy Sloan and Carolyn A. Koh.

"Industrial interest in hydrates has been motivated by the immediate interest of flow assurance — that is, hydrates blocking the inside of pipelines. The challenge facing the Center for Hydrate Research group is to use the immediate industrial interest vehicle of hydrates inside pipelines, to do the fundamental research which can be applied to long-range research — hydrates outside pipelines," said Sloan, CHR director.

Although there is extraordinary energy potential in hydrates, several factors — including related environmental impacts — play a role in the viability of this energy source. CHR researchers are exploring the challenges in an attempt to engineer solutions for efficient energy recovery and transportation.

According to Sloan, challenges regarding hydrates located outside pipelines include:

- In the permafrost, determining a means of producing hydrates commercially
- In marine settings, determining if hydrates can be commercial
- In the environment, determining the role hydrates play in methane release
- In the international arena, encouraging the concept of "cooperation being a higher value than competition" to bring international resources to bear on the difficult problems.

"There are enormous technological and economic challenges involved in energy recovery from gas hydrates in permafrost and oceanic deposits," said Koh. "The amount of marine hydrates surpasses those in the permafrost by several orders of magnitude. These technological challenges for energy recovery from natural hydrate deposits need to be carefully balanced with the potential environmental and geological impact such recovery procedures can have."

Specifically, gas recovery from hydrates may have significant impact on climate change, seafloor stability, and preservation of the atmosphere. These concerns are manifested in the thesis work of Matt Walsh, a current graduate student, as well as recent Ph.D. graduates of the group, Arvind Gupta and Keith Hester.

Another area of research for CHR is clean energy storage. Due to the significant capacity of hydrates to store gas molecules, they can be manipulated to store both carbon dioxide and hydrogen.

In collaboration with the Monterey Bay Aquarium Research Institute (MBARI), Hester investigated the possible release of the natural gas trapped inside hydrates on the seafloor by replacing it with unwanted carbon dioxide from fossil fuel exhaust. This would sequester the carbon dioxide in hydrates on the ocean floor.

Although this is an enticing solution to reducing carbon dioxide emissions in the atmosphere and retrieving the natural gas stored in the hydrates, several key factors need to be carefully considered including the kinetics of carbon dioxide/methane exchange and the possible environmental impact.

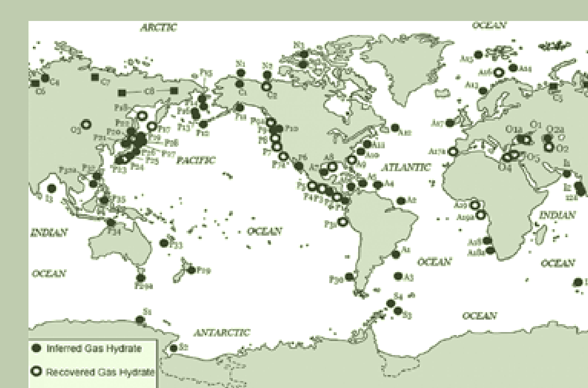
Hydrogen storage in hydrates is also an area of significant interest to researchers at Mines. The structure of the hydrate can be manipulated to store hydrogen, a clean fuel source. The hydrogen hydrate would have to be stored in a refrigerated compression chamber to maintain the necessary temperature and pressure conditions under which hydrates are stable.

This compression chamber could eventually replace the gas tank in cars and the stored hydrogen hydrate could be burned to produce energy to run the vehicle. Instead of emitting carbon dioxide, the only waste product coming out of the tailpipe would be water.

Graduate student Tim Strobel, undergraduate student Yongkwan Kim, and visiting scientist Gary Andrews from the Netherlands are researching the use of environmentally friendly promoter molecules to stabilize the hydrogen hydrate structure at near ambient conditions, while optimizing the storage capacity of the hydrate materials.

Based on the broad and exciting research conducted by CHR, many funding agencies are strong supporters of the program. CHR receives more than $1.3 million annually from industry and national agencies.

An industry consortium including BP, Chevron, ConocoPhillips, ExxonMobil, Halliburton, Petrobras, Schlumberger, Shell and Statoil have provided major support for nearly 20 years. CHR also receives funding from DeepStar, a Houston Energy Consortium, the




Map of natural hydrate deposits.

A hydrate plug.

Courtesy of Petrobras

National Science Foundation, the U.S. Department of Energy, and other energy agencies and companies.

With 30 researchers including faculty, graduate students and undergraduate students, the work of CHR has been featured in more than 200 publications in academic journals and in four books about hydrates and related research.

The Center encourages international collaborations and has hosted visiting scientists from Germany, New Zealand, the United Kingdom, China and the Netherlands for periods of two months to a year. CHR also advises the governments in India, Canada and Japan on the development and recovery of their hydrate energy resources.

Sloan has fostered these relationships and earned international recognition through his work as the chair of the Federal Methane Hydrates Advisory Committee and chair of the Committee on Data for Science and Technology (CODATA) International Database Taskforce.

CHR also collaborates with a number of national and international companies and research institutions. One of the most active research collaborations is with MBARI, researching hydrates on the seafloor in Barkley Canyon off the coast of Vancouver. In a program funded by the DeepStar industrial consortium, experts from France, Norway and the U.S. are collaborating with CHR. The Center also leads the Mines-based industrial consortium with members from Norway, the U.K., Brazil and the U.S.

"These international collaborative programs give excellent opportunities for our research students to travel to the overseas partner laboratories and spend extended periods working on complementary research to that being performed at Mines," said Koh.

Koh and Sloan both said the "exceptionally rewarding aspect of our research is the development and success of our young graduate and undergraduate researchers, and the impact their hard efforts have on the research field."

The strengths and talents embodied in CHR undergraduates and graduates are well known, Koh and Sloan said, making the students highly sought after in academia and industry worldwide.

Solar Energy Research

Due to current high costs, solar energy accounts for less than one percent of the total energy generated in the U.S. Mines researchers are pursuing cost-effective technologies

Physics graduate student David Bobela, left, cools an instrument used to detect infrared light while University of Utah physics graduate student Summer Montgomery and Mines physics graduate student Brian Simonds provide advice on how to proceed with the experiment.

# SUN Sational

Solar energy research at Mines focuses on:

- understanding the science behind solar cells
- applying scientific knowledge to improve photovoltaic development
- decreasing manufacturing costs.

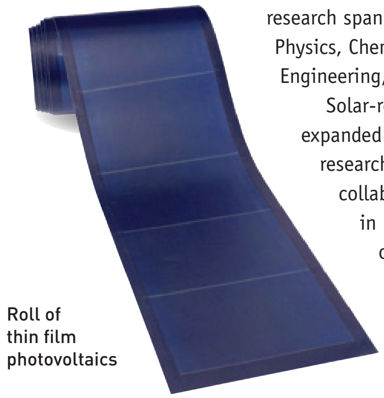
"Energy — the worldwide growth in energy consumption, conserving it, and finding environmentally benign ways of producing it — may arguably be the most significant challenge facing mankind in the 21st century," said Reuben Collins, director of the Center for Solar and Electronic Materials and physics professor at Mines.

Collins noted that the School's historical accomplishments in energy production and related fields, its track record in renewable and alternative energy, and its partnerships with leading energy research organizations and with the energy industry, position Mines to play a leading role in finding solutions to the energy challenge.

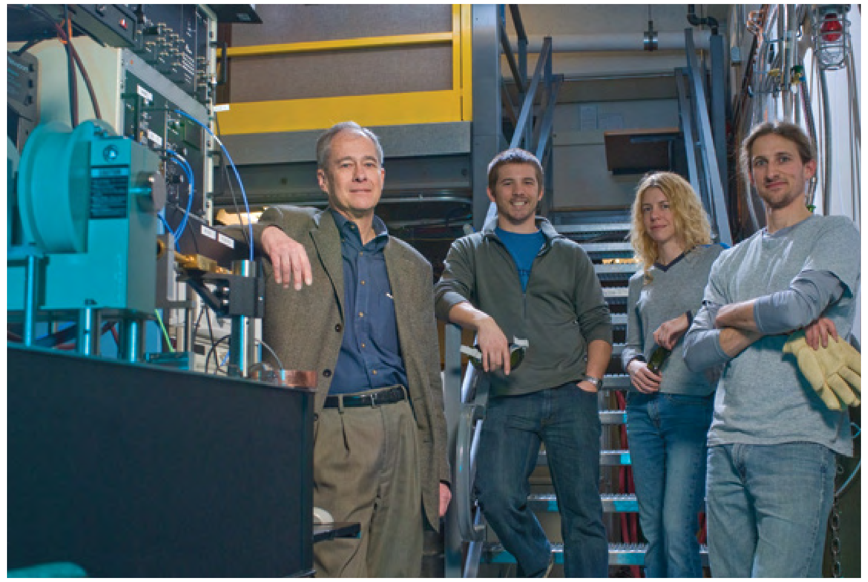
In the late 1970s Craig Taylor, associate director of the Colorado Energy Research Institute and physics professor, received his first subcontract from the newly formed Solar Energy Research Institute (SERI). After its formation in 1977, SERI expanded. In 1991 it was designated as a national laboratory of the U.S. Department of Energy (DOE), becoming the National Renewable Energy Laboratory (NREL).

The solar-based collaboration between Mines and NREL has grown and developed over the last 30 years with research spanning a number of departments including Physics, Chemical Engineering, Chemistry, Division of Engineering, and Metallurgical and Materials Engineering.

Solar-related collaborations at Mines also have expanded to include more than 50 scientists from research groups around the world. Recently collaborations included researchers from Unicamp in Brazil, Ioffe Institute in Russia, University of Erlangen in Germany, University of Toronto in Canada, Ohio University and the United Solar Ovonics Corporation in Michigan.



Roll of thin film photovoltaics



From left: Mines Professor Craig Taylor and students Brian Simonds, Summer Montgomery and David Bobela stand by a microwave apparatus used to measure the response of materials of interest in solar cells to microwaves.

Mines researchers working on solar energy receive funding from several sources including NREL, the Air Force Research Laboratory, University of Utah, DOE, National Science Foundation, United Solar Ovonics Corporation and MVSystems.

"Although we have made progress, much more needs to be done before solar panels can provide an inexpensive alternative to the energy generated from traditional fossil fuels," Taylor noted.

One of the most promising breakthroughs in solar energy is thin film technology — a topic researchers at Mines have been studying for several years. The current solar cell market is dominated by bulk or crystalline silicon with an average efficiency of 14 to 16 percent for commercially available cells. These cells are inherently expensive because of the relatively thick layer of crystalline silicon — about 100 microns (roughly the diameter of a human hair) — needed to convert sunlight to electricity.

By contrast, thin film cells require a layer less than five microns thick — drastically decreasing material cost. The three dominant thin film technologies currently under development are amorphous silicon, cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS). It is unknown which of the three will be the frontrunner.

CIGS has achieved the highest laboratory efficiency of nearly 20 percent; however, amorphous silicon, with laboratory efficiencies around 10 percent, is presently the material with the greatest production capability.

The goal in solar cell development is to find a balance between the cost associated with manufacturing and efficiency. Although thin film technologies are not any more efficient than crystalline silicon, they have the potential to be significantly more cost effective.

Some of the most promising approaches explored at Mines involve spraying or printing various layers of thin film cells, plasma processing cells and fabricating tandem amorphous silicon/nanocrystalline silicon cells. Researchers also are exploring alternative materials such as organic solar cells and cells that are known as "third-generation" such as silicon nanodots and nanowires.

Various tools help understand the absorption of light by the films and probe the structure of the cells on an atomic level to better determine the effects of defects or inclusions. Additionally, the thin films are sometimes unstable and degrade with exposure to sunlight.

"Understanding this degradation process on an atomic scale is a major emphasis of our research here at Mines. If we could find a way to eliminate these metastabilities, the efficiencies of solar panels could be dramatically improved," said Taylor.

Mines students involved in solar research have the unique opportunity to take advantage of the close collaboration between Mines and NREL. Many conduct a significant portion of their research at NREL, giving them access to a greater range of equipment and resources.

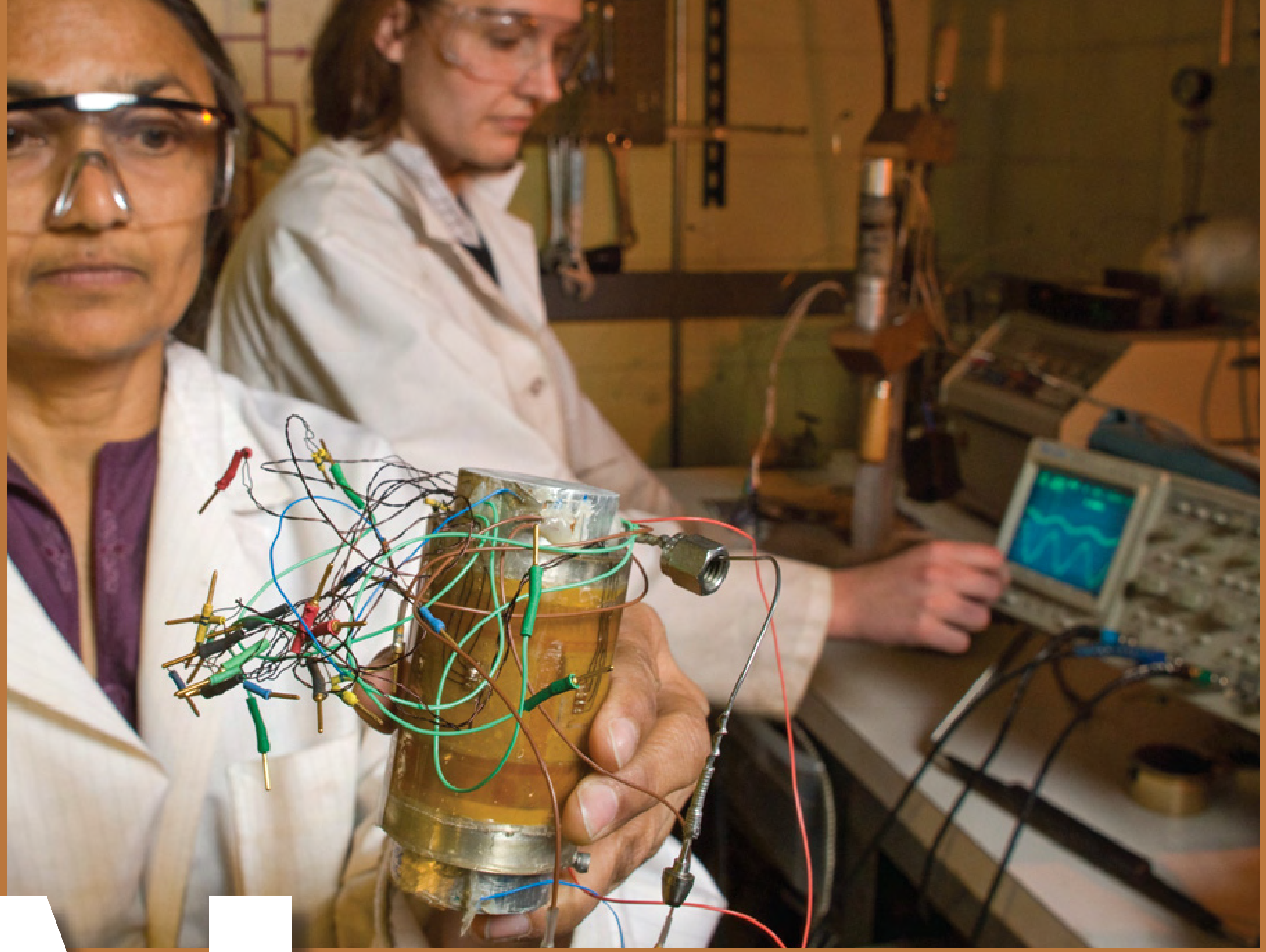


"Although we have made progress, much more needs to be done before solar panels can provide an inexpensive alternative to the energy generated from traditional fossil fuels"

*—Craig Taylor*

Researchers make remarkably accurate predictions about a region by applying pressure to rock samples—and "abusing" them in other informative ways

# HIGH-TECH Rock Abuse



By Nick Sutcliffe
*Mines* magazine, Winter 2008

Geophysicists are masters of uncertainty. Armed only with theories, algorithms, and a few snippets of information about the rock they are studying, they interpret sound-wave data and formulate highly-detailed predictions about the subsurface. By and large, these predications are remarkably accurate, but geophysicists are rarely 100 percent certain until a hole is bored into the ground and samples are brought up for analysis. More often than not, there is a degree of guesswork that goes into interpreting seismic data, leaving room for uncertainty.

Manika Prasad, Mines professor of petroleum engineering, and Marisa Rydzy, graduate student in geophysics, in the Rock Abuse lab.

Mike Batzle, who heads up Mines' Center for Rock Abuse (CRA), explains: "Predictions from seismic data are based on theories. But theories have adjustable knobs. If you don't know where the right settings are, then you have to make a guess." Batzle is the Baker Hughes Professor of Petrophysics and Borehole Geophysics

The CRA is helping provide the right "settings" to geophysicists by analyzing rock samples in the lab. Taking a fist-sized column of rock, they can calibrate changes in seismic signature under a variety of different conditions—this is where the "abuse" comes in. "We will often squeeze the rock, exerting pressures that mimic the sample's native environment. Then we inject either a liquid or a gas and calibrate the speed that sound moves through the sample under those conditions," says Batzle. "Then we'll inject a different gas or liquid and test again. We might do this with methane, carbon dioxide, water, oil or a mixture of two or more of these, each time registering the change in seismic signature."

With the CRA's results in hand, geophysicists can be much more certain of their predictions. "They can point to a given signature and be pretty certain of what that signal means—whether the rock transitions from natural gas to water, or natural gas to oil, or oil to water, or even water to a mixture of carbon dioxide and petroleum."

The lab's results are not only useful for interpreting seismic surveys from the region where the sample originated, they can also be used to interpret seismic data from any area where a similar rock is found. Manika Prasad, the lab's co-director, points out that with each new kind of rock they test, they add to their database. "With some rocks we get in, we can simply go to data from previous tests of similar rock. As our database of seismic signatures grows, we can extrapolate more and more."

In addition to seismic analysis, the lab also tests porosity, permeability and strength of samples. This can provide valuable baseline information for predicting how fast fluids and gas will flow under certain conditions, how much gas or oil is contained in a given formation and how best to fracture rock to increase flow rates.

In addition to calibrating rocks, the lab also analyzes liquid and gaseous hydrocarbons in isolation. "There is a lot of interest in heavy oils right now because they are so plentiful," says Batzle. "But they are thick and hard to extract. Heating the oil-bearing strata can lower its viscosity, allowing oil to flow more easily. When this is done, seismic imaging can be used to monitor the production process remotely, but to do this accurately—to translate seismic wiggles into materials and conditions—the seismic signatures of the various materials must be known. That's what we can provide."

The laboratory is home to eight graduate students, one full-time technician and several visiting scholars. Much of the work is done in collaboration with other departments and universities, particularly the Rock Physics Lab at the University of Houston.

Indicative of their high profile, the CRA's client list includes a raft of blue chip oil and gas corporations and service companies from around the world, including Anadarko, BP, British Gas, Chevron, Encana, Shell, Petrobras, StatoilHydro, ExxonMobil, Devon, Japan Oil and Minerals, Chinese National Oil, Schlumberger, CggVeritas, Paradigm and others. Batzle says, "There aren't many other labs doing what we do. We've got a lot of toys and can recreate just about any kind of underground condition. It's fun. We get paid to play, and we're building up a very valuable database of information."



Colorado School of Mines | RESEARCH PROFILES


## Eileen Poeter

Eileen Poeter, director of the International Ground Water Modeling Center (IGWMC) and professor of geology and geological engineering, has earned the esteem of students and colleagues alike.

The National Ground Water Research and Educational Foundation (NGWREF) honored Poeter in 2006 when she was selected by a panel of scientists and engineers to be the 2006 Henry Darcy Distinguished Lecturer. Each year, an outstanding ground water professional is chosen to give the Darcy Lecture Series and share their research with peers and students. The series, established in 1986, now reaches more than 50,000 ground water students, faculty and professionals.

Through the lecture series, Poeter presented her research on ground water modeling in 11 countries on five continents in a lecture titled "All Models are Wrong, How Do We Know Which are Useful?"

Poeter's research focuses on ground water modeling and resource evaluation. The models are used to predict ground water conditions under alternative management scenarios. Her research is unique in that rather than developing a single model for a given ground water system, she develops multiple conceptual models effectively capturing more of the uncertainty in the system. Poeter then helps hydrologists evaluate the models to estimate the uncertainty of their predictions. This provides ground water decision-makers with more information and helps them to achieve a sustainable system.

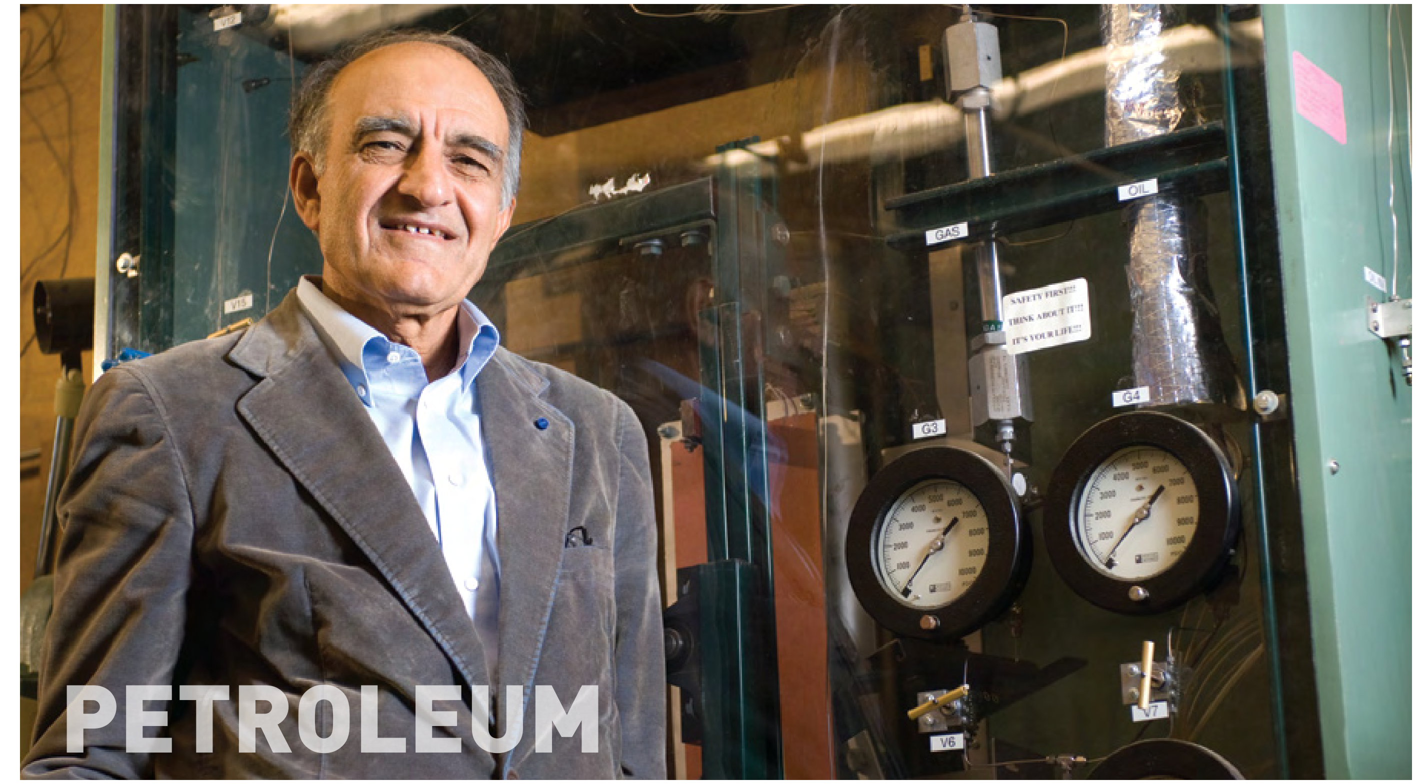
According to her students, Poeter takes education very seriously. "As a teaching assistant for Eileen, I was amazed at how much time and effort she put into each of her classes," said graduate student Stephanie Schmidt.

"The material is challenging so the class can be intimidating, but that is exactly what makes it fun — because she is encouraging and will answer any question," said Lacy Jones, one of Poeter's students. "I really respect Dr. Poeter and enjoy her class."

Master's degree student Clint Carney called Poeter one of the "most influential people in my life."

"She has challenged me to be a better hydrologist and to see problems from many different angles," Carney said.

"It is a joy to be immersed in a population of young people. Each day the projects present new challenges. It is often said that that to be happy in life, one should find a job that requires doing what one loves to do. I have been fortunate enough to have such a job."




## Hossein Kazemi

The most challenging aspect of being both an educator and a researcher is developing "top-rated students who will go into the business world with enthusiasm to serve, will demonstrate integrity of purpose, and will provide community, business and technical leadership," said Hossein Kazemi, co-director of the Marathon Center of Excellence for Reservoir Studies and the Chesebro' Chair in Petroleum Engineering at Mines.

Kazemi's research interests stem from 37 years working in industry and 31 years at the Marathon Oil Technology Center in Littleton, Colo. Since joining the Mines faculty in 1981 and now in his second year as the Chesebro' Chair Professor, Kazemi has worked to increase the efficiency of oil and gas production from petroleum reservoirs through an improved understanding of both the large and small scale physics of flow and the associated reservoir and geological issues.

The average oil and gas production efficiency is approximately 33 percent, with almost two-thirds of the world's oil and natural gas supplies trapped in porous materials.

"There is a great need, as well as a great opportunity, to produce more of the remaining oil. But, to be able to produce 10 to 15 percent of the remaining two-thirds, we have to work harder and a lot smarter," said Kazemi.

Well-respected in his field, Kazemi has earned many honors and awards. He was appointed to the National Academy of Engineering, earned an Honorary Membership to the American Institute of Mining, Metallurgical and Petroleum Engineers, was named a Distinguished Member of the Society of Petroleum Engineers, and won the 2006 Improved Oil Recovery Pioneer Award. In addition, Kazemi received the 1995 Everette Lee DeGolyer Medal, the 1987 John Franklin Carll Award, the 1980 Henry Mattson Technical Service Award, and earned the SPE Distinguished Service Award in 1991.

"As a researcher, one can only point to the petroleum literature to see that Kazemi is a giant," said Mohammed Al-Kobaisi, petroleum engineering graduate student. "As a teacher, he is as good as it gets and I am so fortunate to be one of his students."

Kazemi works hard to tie his research efforts into his teaching through classroom discussions about both the research projects being conducted at Mines and his own personal experiences in research and in industry. Kazemi often assigns small research projects as the term project in his classes to give students a broader base of exposure. According to Kazemi, some of the term projects have led to more substantial research projects outside the classroom.

"Any improvement in oil and gas recovery would buy the future generation time to find an eventual solution to energy needs and demand."


## David Matlock

A member of the National Academy of Engineering, David Matlock has built a world-class research center and a worldwide reputation for his vast contributions to mechanical properties research, as well as his outstanding teaching.  Matlock is the director of the Advanced Steel Processing and Products Research Center (ASPPRC) and a Metallurgical and Materials Engineering professor.

Matlock joined the Mines faculty in 1972, and along with colleague George Krauss, founded ASPPRC in 1984. The center has since been recognized as one of the most successful centers of its kind, and draws an annual budget of more than $1.5 million. The majority of the center's funding comes from industry support.

"Research in the center is unique because it brings together competing companies as well as suppliers and customers to work together on research projects that are mutually beneficial to a variety of companies that do not normally work together," Matlock said.

The center's research focuses on microstructural development and the effects of microstructure on the mechanical properties of steel.

One important area of research is the development of new advanced high strength sheet steels for use in affordable lightweight automobiles. The drive to reduce fuel usage and maintain safety propels this critical research, developing new steels and steel processing methodologies to bring to market strong, lightweight steel products.

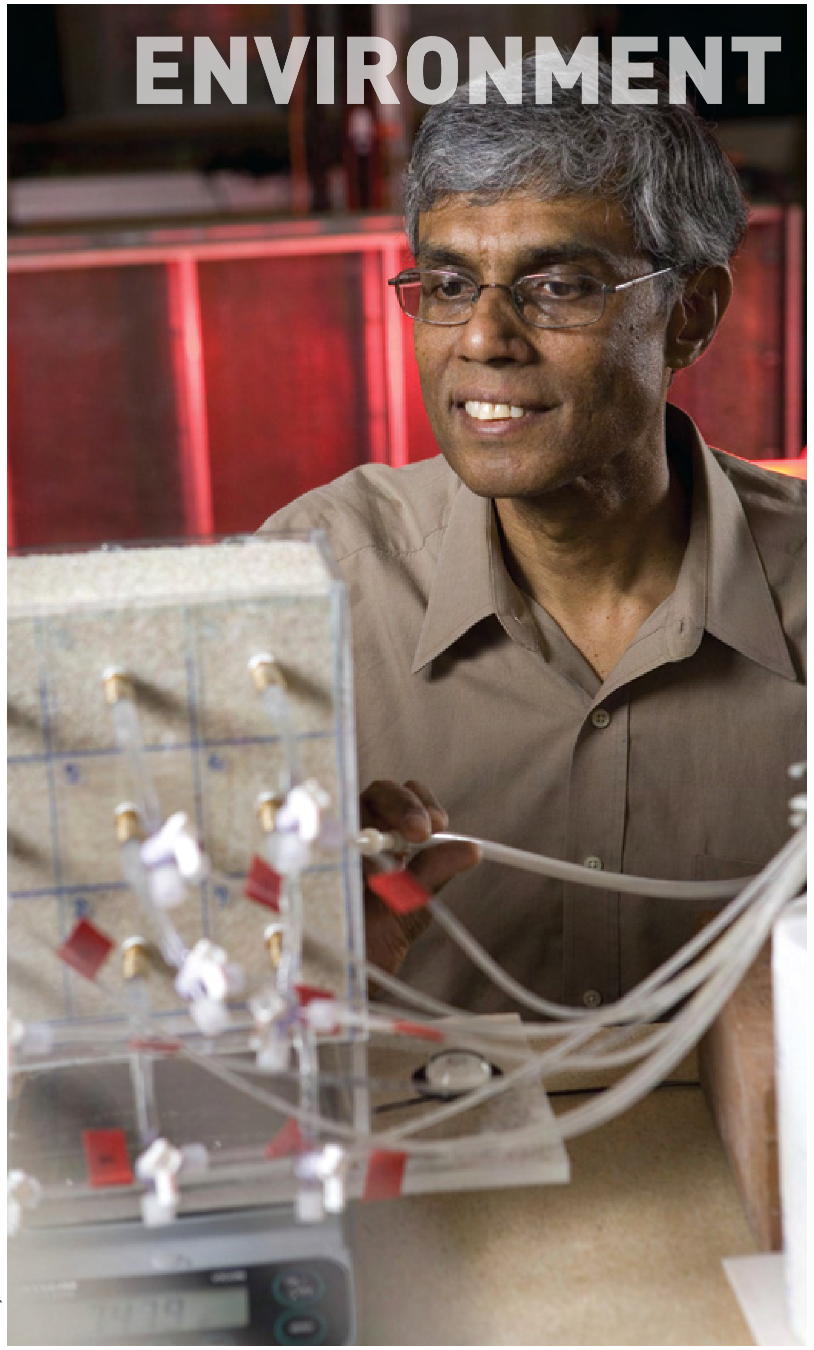
Development of high-strength pipeline steels for the oil and gas industry is a second area of energy-related research, driven by the need to produce either oil in deep-sea locations or natural gas from remote locations. New pipelines will require steels with significantly improved mechanical properties. Improvements based on ASPPRC research efforts will impact oil and gas production and "in some cases make previously unavailable energy sources viable," said Matlock.

To support the extensive research conducted by members of ASPPRC, Matlock has developed first-rate mechanical testing laboratories, including a high strain rate mechanical system. Extremely rare in a university laboratory, this system has the capability to simulate material behaviors in a car crashing into a concrete wall at 35 miles per hour and then assess the damage and properties of automotive structural steels.

Matlock's laboratories are also available to students through many lab-based classes. Matlock says he likes having  "the opportunity to continually learn and where possible, pass on the information to students."

"Professor David Matlock is easily the best instructor I have ever had. He instills in his students the capacity to learn and understand difficult concepts and start thinking about the next step," said Mark Richards, a Ph.D. candidate.

> "Research, teaching and education are, in my view, inseparable. Research results continually provide new information that can be incorporated into conventional classroom and laboratory classes."




Tim Ryan

> "I enjoy the opportunity to mentor and teach future engineers and scientists in areas dealing with protecting the water and the environment."

## Tissa Illangasekare

According to his students, Tissa Illangasekare is a demanding professor who sets high standards. Illangasekare is the AMAX Distinguished Chair and Professor of Civil Engineering at Mines.

"I felt challenged every day, but once I was done with my thesis I felt very proud to have worked at Tissa's side and in his great research group," said Lisa Porta, M.S. student in Environmental Science.

Illangasekare's research is aimed at protecting water resources and the environment through the study of flow and transport in porous and fractured media. This translates to the development of models that simulate the flow of water (most specifically groundwater) and transport of chemicals to gain an improved understanding of the processes that control these phenomena. The applications for Illangasekare's research include management of surface and subsurface water, remediation of subsurface systems that are contaminated with petroleum and organic waste, effects of natural disasters on groundwater, arctic hydrology (as it applies to sea-level rise), and dam stability analysis.

In conjunction with his teaching and research, Illangasekare has published numerous book chapters and more than 200 technical articles in refereed journals and proceedings. Illangasekare is also the director of the Center for the Environmental Study of Subsurface Environmental Process (CESEP), a collaborative center between several universities, national laboratories, and industry partners.

Illangasekare receives his funding from federal, state and industry sources and has collaborated with scientists and engineers from Denmark, the United Kingdom, Spain, Sri Lanka, Sweden, Korea, Japan, the Czech Republic, Germany, and Australia. He has also offered many workshops and seminars to students around the world.

In 2006, Illangasekare was elected a Fellow of the American Association for Advancement of Science for his significant contributions to understanding flow and transport processes in soils and groundwater. In 2005, Illangasekare was elected a Fellow of the American Geophysical Union in recognition of his contributions to understanding the behavior of organic chemicals in a heterogeneous subsurface. Illangasekare was also elected a Fellow of the American Society of Civil Engineers in 2005. In addition to his honors, Illangasekare is registered as both a Professional Engineer and Professional Hydrologist, and is a Diplomate of both the American Academy of Environmental Engineers and the American Academy of Water Resources Engineers. Illangasekare is also the current director of Hydrologic Sciences Program at the National Science Foundation.


## David Marr and Jeff Squier

David Marr and Jeff Squier offer undergraduate and graduate students the unique opportunity to not only learn about but also apply important and developing technologies in state-of-the-art laboratories. Both Marr and Squier enjoy bringing their research efforts into their teaching. "Seeing students in my course grasp and apply new technology is exciting and gratifying," said Squier.

Marr emphasizes hands-on learning in his undergraduate/graduate level microfluidics class where students learn to fabricate and test microfluidic devices of their own design. According to Marr, the best aspect of being both a researcher and an educator is "the freedom to investigate what I want in an environment populated by vibrant engineers-in-training."

Focused on health care, the research projects conducted by Marr and Squier are both collaborative and complementary. They are co-directors of the Center for Microintegrated Optics for Advancing Bioimaging and Control at Mines.

Marr's research focuses on employing external optical, electrical and magnetic fields in micro-sized geometries to control and direct cellular and colloidal systems. The techniques utilized by Marr allow the construction of micron-scale devices like pumps and valves, photonic (light activated) materials, and optical-based separators that are capable of isolating and manipulating individual cells for bio-analysis. The development of this research would allow doctors to obtain analysis of a biological sample nearly immediately, speeding diagnosis and treatment processes.

Marr collaborates with a broad range of researchers from academia, industry and health clinics. These collaborations include the Universität Stuttgart in Germany, the University of Maryland in Baltimore County, the Laboratory for Malaria and Vector Research, NIAI, the National Institutes of Health, the National Flow Cytometry Resource at Los Alamos National Laboratory, and the Invasive Cardiology Department at the University of Colorado Health Sciences Center. Collaborative projects have ranged from applying magnetic fields within microfluidic systems to create microdevices, to modeling cell mechanical properties based on deformation of cells via applied optical forces, to using optical forces to develop new cell counting and sorting techniques.

Much of Marr's research is closely tied to Squier's area of expertise — lasers. As the head of Mines' Photonics and Ultrafast Laser Science (PULSE) laboratory, Squier builds lasers that are capable of documenting events that occur in the femtosecond (less than one-trillionth of a second) time range. The PULSE laboratory at Mines is one of the "most comprehensive ultrafast optical laboratories in the world," said Squier.

The technology developed by Squier has potential to significantly impact many fields including health care and renewable energy. Potential applications for the PULSE lasers include ultra-fast x-ray and spectroscopy imaging, ultrafast pulse measurement, and micromachining. Squier uses his expertise in laser optics to aid Marr's research by making microfluidic devices more compact and useful. Specially designed micromachining lasers are used to make the microfludic devices. For example, to make bio-analysis devices, the lasers cut micrometer-sized channels in the surface of a chip, creating pathways that direct cells to testing areas allowing for nearly immediate bio-analysis feedback.

Squier has also cultivated extensive collaborations with various departments on the Mines campus, as well as many universities and national laboratories. These collaborations include the University of Colorado, JILA, the National Institute of Standards and Technology, the University of Colorado Health Sciences Center, the National Renewable Energies Laboratory, the University of California San Diego, Georgia Institute of Technology, the University of Toronto-Mississauga, the University of Amsterdam, Colorado State University and Cornell University. Squier also collaborates with industry researchers from Preision Photonics, Alpine Research Optics and Translume.

"We are exploring a broad range of phenomena over unprecedented spatial and time scales. This research is aimed at improving our understanding of fundamental physical, chemical and biological processes."

*—Jeff Squier*

## SUSTAINABILITY
# for Life

By Jonathan Meuser

**It was 1988 and I had just started the third grade when I discovered the multitude of ways our resource utilization is destroying the natural systems upon which we depend, and I knew the unidirectional use of finite resources was a disastrous end game. These were dismal realizations for a child, and today a new generation of children is burdened with even more concrete evidence and greater awareness of the problem.**

In my adolescence, I embarked on a life experiment to see what one person could do to affect change. The answer is conceptually simple: to promote transformation of our means of production from linear to infinitely cyclic systems powered by no more energy than we can harvest from the products of real-time solar flux.

Solar energy is clearly the most abundant renewable energy source. Photosynthesis provides the energy requirements of almost all life on earth. Currently fossil fuels are still relatively cheap, but soon photosynthesis may play a special role in the production of transportation fuels. I earned an undergraduate degree in plant biology at the University of California at Davis to learn everything I could about harnessing photosynthesis to produce renewable fuel.

In 2000, researchers at the National Renewable Energy Laboratory (NREL) made an important discovery. Employing a metabolic trick, they could coax algae to produce hydrogen directly from photosynthesis for days at a time. Algae can also produce many other useful products, from oils for biodiesel to pharmaceuticals. A summer internship brought me to NREL, introducing me to Colorado School of Mines. An invitation to continue working with the NREL team through the Environmental Science and Engineering Division at Mines was the perfect opportunity for me to answer scientific questions with the potential for revolutionary application. Since my second year at Mines, I have been funded by a NASA graduate student fellowship to study the vastly unexplored diversity of algae and cyanobacteria.

However, as a citizen-scientist, sustainability is more than an academic pursuit. It is a way of life for me. An interest in biodiesel led me to work with a Senior Design team to build a mobile biodiesel processor that can make biodiesel from restaurant grease—a valuable portable teaching tool that I use for instruction and producing my own fuel. Because of my combined knowledge in plant biology and small-scale biodiesel, I was recently invited to work with farmers developing dry-land rapeseed crops for biodiesel feedstock without irrigation. Additionally, this summer will be the third year I have co-organized the Biodiesel Collective Conference, which brings participants from around the world to Mines to learn about grass-roots biodiesel production.

I have also worked to promote the sustainable practices on the Mines campus to improve recycling, mandate green building, provide a student bus pass and promote green purchasing. In the spring of 2007, I received Mines' first Arthur B. Sacks Award for Environmental Sustainability, an award that will continue to honor a graduating Mines student each semester.

Led in 2004 by Arthur Sacks, who was then associate vice president for academic affairs, students, staff and faculty came together to form an institutional Sustainability Committee, approved by the Mines Board of Trustees. Campus culture has since reflected an explosion of interest in sustainability. Today any new construction built with student funds must meet LEED Silver Certification. Due to a student fee passed by an overwhelming majority, students now enjoy an unlimited pass on local and regional buses. Last year, Mines celebrated Earth Day for an entire week with lectures and demonstrations during the School's first Climate Action Days event. Almost weekly, academic lectures feature esteemed experts on environmental sustainability, including recently Hunter Lovins, Jared Diamond and Thomas Prugh. From fuel cells to biopolymers, the research on campus is increasingly reflecting world-class work to address society's need to achieve energy and resource balance.

Though I am still concerned about the future of humans on our planet, I no longer feel alone. Across the globe, people are doing their part to improve the way our needs are met. Mines specializes in the utilization and preservation of the world's resources. To survive the inevitable energy and materials revolution, Mines must continue to evolve to match changing resource constraints with a scientific awareness of real consequences, from climate change to fertilizer shortages. Today society is far from living in balance within the relatively closed system of Earth, but the path towards sustainability and the technological innovation required to get there will provide challenging questions for Mines students and researchers to answer for years to come.

Jonathan Meuser is a Ph.D. candidate at Mines in the Environmental Science and Engineering Division.



## ECONOMIC ANALYSIS
# through a Kaleidoscope of Events

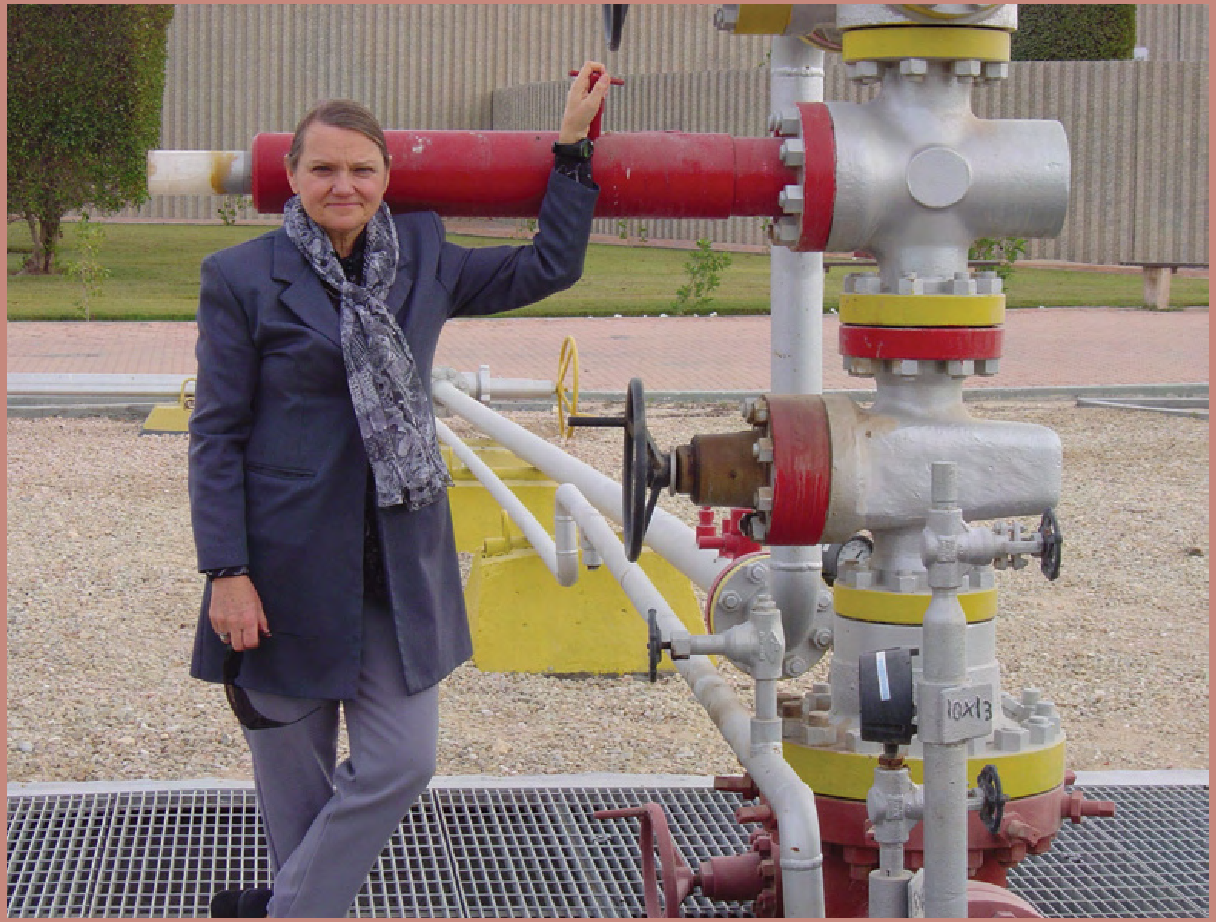
By Carol Dahl

**It was 1973. As oil prices rose, tempers flared. Lengthening lines at gas stations pointed out our vulnerability to foreign sources of energy and piqued my interest in international energy markets and energy policy. I chose gasoline demand as my Ph.D. dissertation topic in Economics at the University of Minnesota, a decision I have never regretted.**

My topic on gasoline demand and its responsiveness to income, price and other variable changes led to an internship at the Federal Energy Administration (the precursor to the U.S. Department of Energy) and a thesis fellowship from the Washington D.C. think tank, Resources for the Future, with the thesis eventually published in the series "Outstanding Dissertations in Economics."

The years since have been marked by periodic energy crises – a constant source of real-world problems for me and my students to analyze. World recession and a world oil glut followed the first crisis, but revolution in Iran renewed the crisis in late 1978. Once again, governments considered policies such as gasoline taxes and auto fuel efficiency standards while multinational oil companies wanted to know gasoline demand response to these price changes in the near term and the long run. My work was in the spotlight and queries came in from oil companies, the White House, Congressional staff and others.

Energy markets remained weak during the 1980s with an oil price collapse in late 1985. I continued my work on gasoline demand and refinery choice for several years and applied it to a variety of policy issues including gasoline taxes, gasoline tariffs, energy price decontrol and emergency allocation schemes. Later in the decade, events at Three Mile Island and Chernobyl devastated the world nuclear power industry in many countries. In conjunction with a summer job at the Central Bureau of Statistics in Norway, I




Carol Dahl visited the site in Saudi Arabia where oil production began in 1938—Damman, Well Number 7.

did some modeling of the European gas market and the effect a phase-out of nuclear power would have on it. I also began to do survey work on energy models and gasoline demand models.

The excitement continued in the 1990s when the industrial world went to war in the Gulf over oil. Environmental concerns over fossil fuel use, the move toward energy deregulation, collapsing economies in Eastern Europe and the former Soviet Union, and increased opportunities for foreign investment in energy-exporting developing countries provided many opportunities and research challenges. Prices remained low and consumers were optimistic. With the Asian economic crisis in 1997, oil prices plummeted even further. Early in the decade, I moved from Louisiana State University to Mines and developed a course in energy economics, which I still teach. My demand and supply survey work continued and was expanded to include all energy products in a project commissioned by the U.S. Department of Energy. This work further enhanced my global reputation as an expert in energy market analysis.

In the current decade, energy has come full circle. Markets are again tight. High natural gas prices brought down California's electricity deregulation and have been spurring a surge in the global liquid natural gas market. An unexpected surge in the world economy, particularly in the U.S. and China starting in 2004, coupled with political turmoil in oil-producing countries have kept oil prices high and volatile in recent years. Hurricanes, sulfur regulations on transport fuels, refinery bottlenecks and shortages of skilled personnel and equipment both up and downstream have tightened markets and added to price volatility.

All these events have increased the demand for my work. Material from my energy course was expanded into my recent book, *International Energy Markets: Understanding Pricing, Policies, and Profit*, which was published by Pennwell Press in 2004. It broadened my portfolio of expertise to include coal, electricity regulation and restructuring, natural gas markets, energy futures and options markets. Pennwell wants to publish a second edition in 2008, and I plan to include new material on renewable energy and carbon sequestration as ways to reduce carbon emissions.

Carol Dahl is a professor in the Mineral Economics program at Mines.



Colorado School of Mines | RESEARCH

# Research CENTERS

Colorado Fuel Cell Center Director Neal Sullivan and George R. Brown Distinguished Professor Robert Kee

# Fueling Electricity's Efficiency

Fuel cell technology has the potential to significantly reduce fuel consumption and increase electrical efficiency, making it a potentially viable component of the U.S. energy portfolio.

Research conducted at the Colorado Fuel Cell Center (CFCC) at Mines is focused on integrating the technology into the existing energy infrastructure by overcoming the initial high costs of fuel cell systems and the perceived need for a hydrogen-fuel infrastructure.

Conventional electricity production hinges on converting the chemical energy in a fuel (like coal) into thermal energy (heat) by burning the fuel. This heat is then converted into electricity through a number of additional steps, each with associated inefficiencies that lead to an overall low efficiency of conversion from chemical energy to electricity.

By contrast, fuel cells directly convert chemical energy to electricity, reducing the number of conversion processes and significantly increasing efficiency. Due to the direct conversion achieved by fuel cells, the same amount of energy can be produced from half the amount of fuel — reducing dependence on foreign energy sources and increasing energy security.

Research at CFCC has a broad scope, addressing development of both Polymer Electrolyte Membrane (PEM) fuel cells and Solid Oxide Fuel Cells (SOFCs). The Center features a new 3,600-square-foot laboratory where PEM- and SOFC-development is conducted under a single roof, promoting collaboration between researchers.

Significant work also is underway regarding the processing of hydrocarbon and biomass fuels for use in these types of fuel cells. Research projects involve an interactive combination of experimental and theoretical approaches to understand the fundamental physical, chemical and electrochemical processes underway during fuel cell operation. CFCC studies span from the investigation of atomic-level interactions to cell development to system integration.

Due to the multidisciplinary nature of fuel cell research, CFCC is composed of researchers from several Mines departments including Robert Kee, Mark Lusk, Marcelo Simoes, Kevin Moore and Neal Sullivan of the Engineering Division, Anthony Dean and Andrew Herring of the Chemical Engineering Department, and Ryan O'Hayre, Ivar Reimanis and Nigel Sammes of the Metallurgical and Materials Engineering Department.

"The interest, creativity and energy between faculty and students across these departments, in both research and teaching, are what make the CFCC a success," said Sullivan, CFCC director.

CFCC research aims to solve a number of technical problems facing fuel cell systems. These issues include fuel cell operation on readily available hydrocarbon and biomass fuel streams (rather than hydrogen, which is comparatively scarce), improvement of fuel cell reliability by widening the range of operation through development of advanced fuel cell membranes and integration of fuel cells with fuel reformers and other system components.

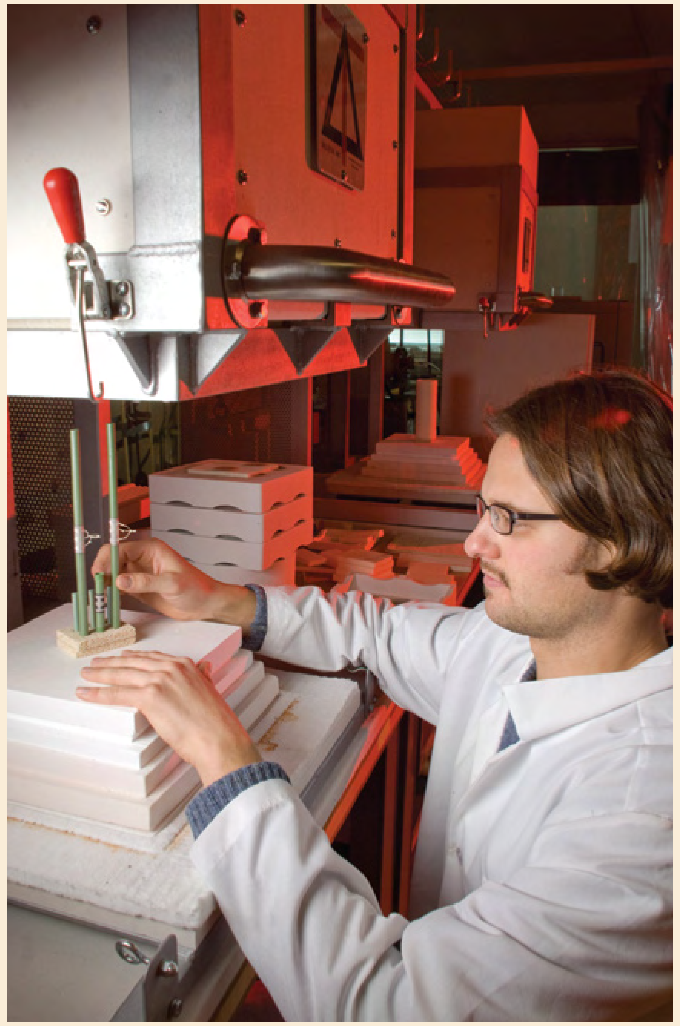
Cutting-edge modeling efforts, led by Kee and Dean, work in close concert with the Center's experimental investigations. The modeling work bridges the gap between atomic-level chemistry and system-level engineering. Kee notes that "the development and optimization of cells and systems are accelerated and improved with the fundamental understanding afforded by physically based models, representing the complex interactions among fluid dynamics, thermal transport, gas-phase chemistry, catalytic chemistry and electrochemistry."

The CFCC also has strong educational goals, and is "intimately involved in the development of a trained fuel cell workforce through traditional undergraduate and graduate courses in fuel cells and through student design projects," said Sullivan. This is further evidenced by the fact that O'Hayre, one of the newest members of CFCC, wrote the leading fuel cell textbook, *Fuel Cell Fundamentals*.

The training afforded students through CFCC helps support the local and national fuel cell business clusters — establishing Colorado as the center for fuel cell product development.

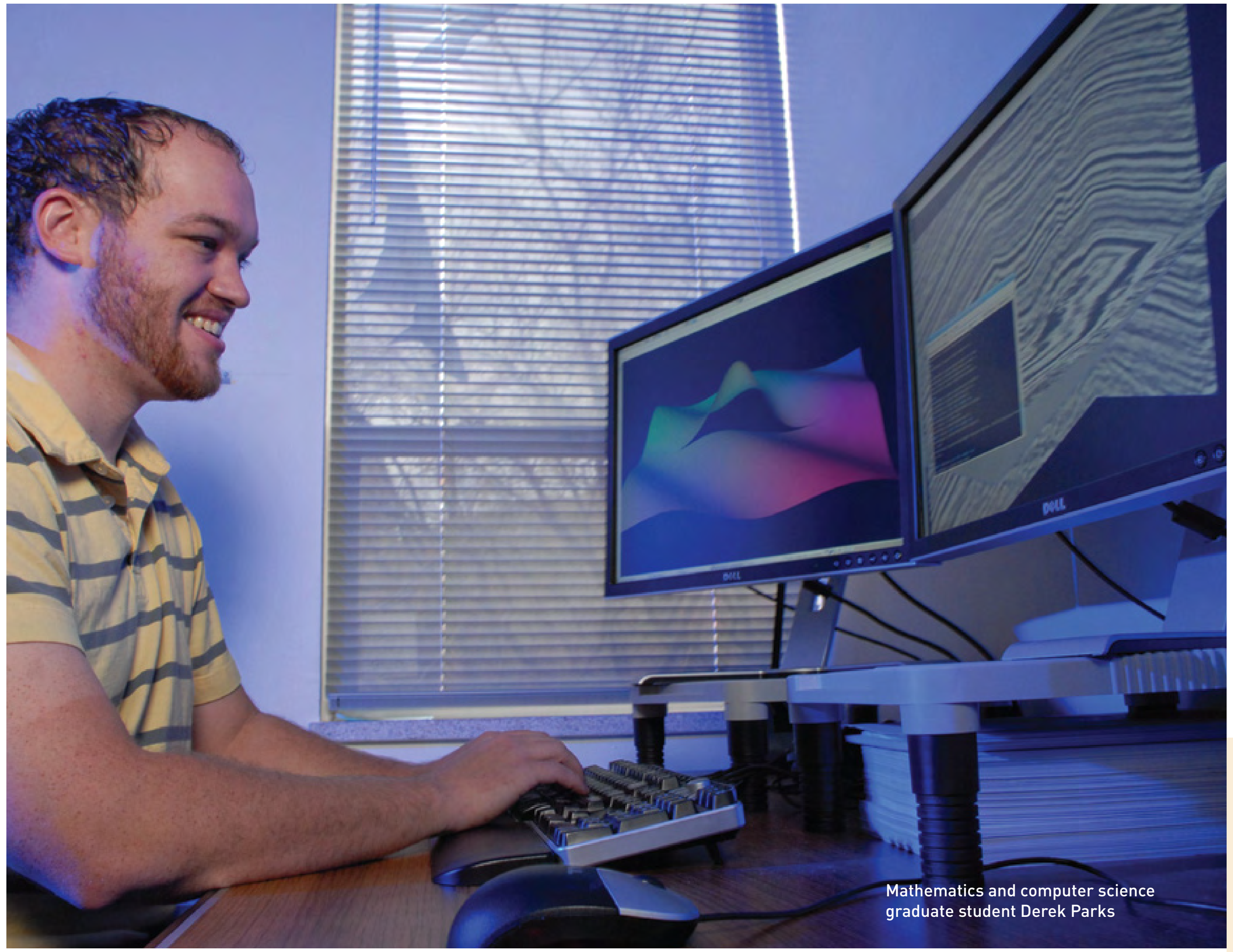
CFCC researchers collaborate with researchers at the National Renewable Energy Laboratory, Caltech, the University of Maryland, Northwestern University, Case Western Reserve University and the University of Karlsruhe in Germany. Many industrial researchers also partner with CFCC including researchers from CoorsTek, Protonex Technology Corporation, TDA Research, VersaPower Systems, Barber Nichols, Inc., 3M Company and the Gas Technology Institute in Illinois.

The Center receives most of its funding from government and industrial partners. Close collaboration with these partners allows the CFCC to address and overcome critical technical challenges.



## Students Fuel Research

Student involvement in CFCC is extremely important to advancing the research of the Center. Ph.D. student Dan Storjohann has been instrumental in turning the new CFCC laboratory into a functioning research and development center, initiating the fabrication of Solid-Oxide Fuel Cells at Mines. Storjohann integrates his materials science background with mechanical- and chemical-engineering disciplines to study the interaction of hydrocarbon and biomass fuel streams with the fuel cells to which they are exposed. This crosscutting work serves as an excellent example of the multidisciplinary work under-way at CFCC. Storjohann said that working in the CFCC "has been a remarkable experience for me. In only two years, the evolution of the laboratory space and capabilities has been substantial, starting from an empty room with cement floors and evolving to an impressive lab with complete fuel cell fabrication and testing."


Mathematics and computer science graduate student Derek Parks

# Making Waves in Efficient Energy

For 25 years, the Center for Wave Phenomena (CWP) has been on the forefront of applied seismology and today it continues to serve as a force in the development of more efficient petroleum-based energy technologies.

CWP is a research consortium that strives to maintain a portfolio that is both cutting-edge and relevant to collaborative partners, while also supporting a premier graduate-level research and education program in applied seismology.

"CWP is dedicated to providing graduate students with an in-depth knowledge in applied seismology and opportunities to participate in original, high-quality scientific research. We foster a close-knit environment that encourages creativity and freedom of exchange between students and faculty," said CWP Director Ilya Tsvankin.

The center, which was founded in 1983, collaborates with the petroleum industry, government agencies, and academic institutions to carry out research in seismic exploration, monitoring and wave propagation. Originally formed by applied mathematicians, CWP conducts research combining mathematical rigor and computational sophistication with realistic representation of subsurface formations.

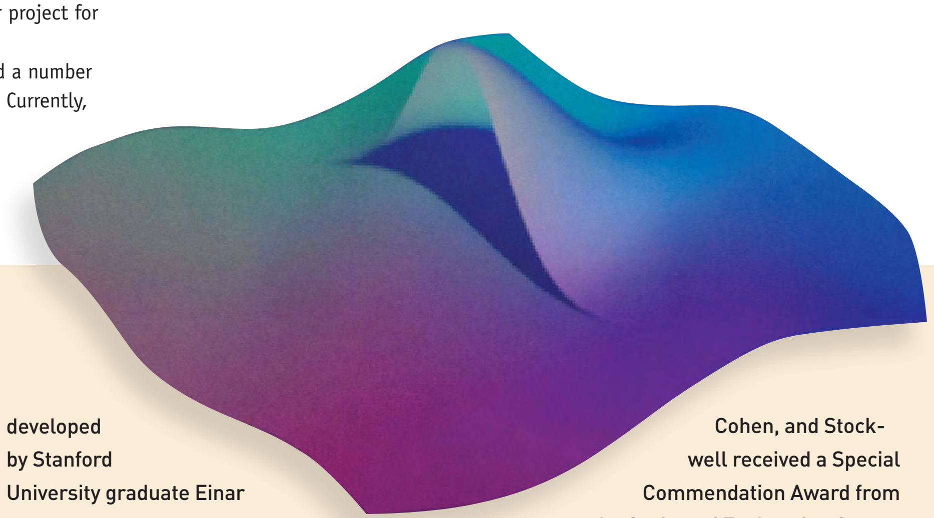
CWP is devoted to the development of theoretical and computational methods for imaging the earth's subsurface to detect and monitor hydrocarbons. The main focus of the consortium is inverse wave-propagation problems and seismic data processing for complex subsurface models. Active CWP research topics include seismic imaging and velocity estimation using wave-equation techniques, seismic interferometry, anisotropic velocity analysis and imaging, multicomponent seismology, fracture characterization and image processing.

A combination of industrial and government support provides a diversified and stable financial base for the center. The CWP Consortium Project on Seismic Inverse Methods for Complex Structures is currently supported by 25 companies in the hydrocarbon exploration industry. CWP also receives funding from the U.S. Department of Energy, National Science Foundation, Petroleum Research Fund of the American Chemical Society, U.S. Geological Survey, ExxonMobil, Landmark Graphics, Shell and Statoil.

The industrial collaborations established by CWP also allow faculty and graduate students to work on joint projects with their sponsors. A recent industry collaboration between Mines' Roel Snieder and ExxonMobil employees, Mike Payne and Anupama Venkatarama, focused on using induced seismicity to monitor the steam behavior in a heavy-oil reservoir. Through the support of ExxonMobil, CWP attracted Masatoshi Miyazawa from Kyoto University in Japan to work on the heavy-oil reservoir project for one year.

Additionally, CWP faculty members have organized a number of high-profile international meetings and workshops. Currently, Tsvankin and professor Ken Larner, along with James Gaiser and Edward Jenner of GX Technology, are organizing the 13th International Workshop on Seismic Anisotropy planned for August 2008, in Winter Park, Colo.

CWP faculty members also provide the program with breadth and professional recognition: Larner earned the Petr L. Kapitsa Gold Medal, the highest award given by the Russian Academy of Natural Sciences and the Maurice Ewing Medal, the highest award for lifetime achievement of the Society of Exploration Geophysicists (SEG); Norm Bleistein, CWP founder, received an honorary membership from SEG; Tsvankin and Dave Hale have both received the Virgil Kauffman Gold Medal, the highest scientific award of SEG; and Paul Sava has been honored by SEG with the Reginald Fessenden Award for his work on wave-equation imaging. SEG also has recognized several former CWP students and post-doctoral fellows with the J. Clarence Karcher Award for outstanding young scientists.



## Seismic Software

A free seismic processing software package that allows users to transform raw seismic data into scientifically meaningful images of the earth's subsurface has taken off since its inception in the late 1980s with more than 3,700 installations across the globe.

Seismic Un*x (SU), consisting of more than 300 modules, is used worldwide by academics, government researchers, small independent geophysical contractors, and large oil and gas companies for seismic processing and modeling. The applications of SU go beyond petroleum seismology and include near-surface seismic and ground penetrating radar data.

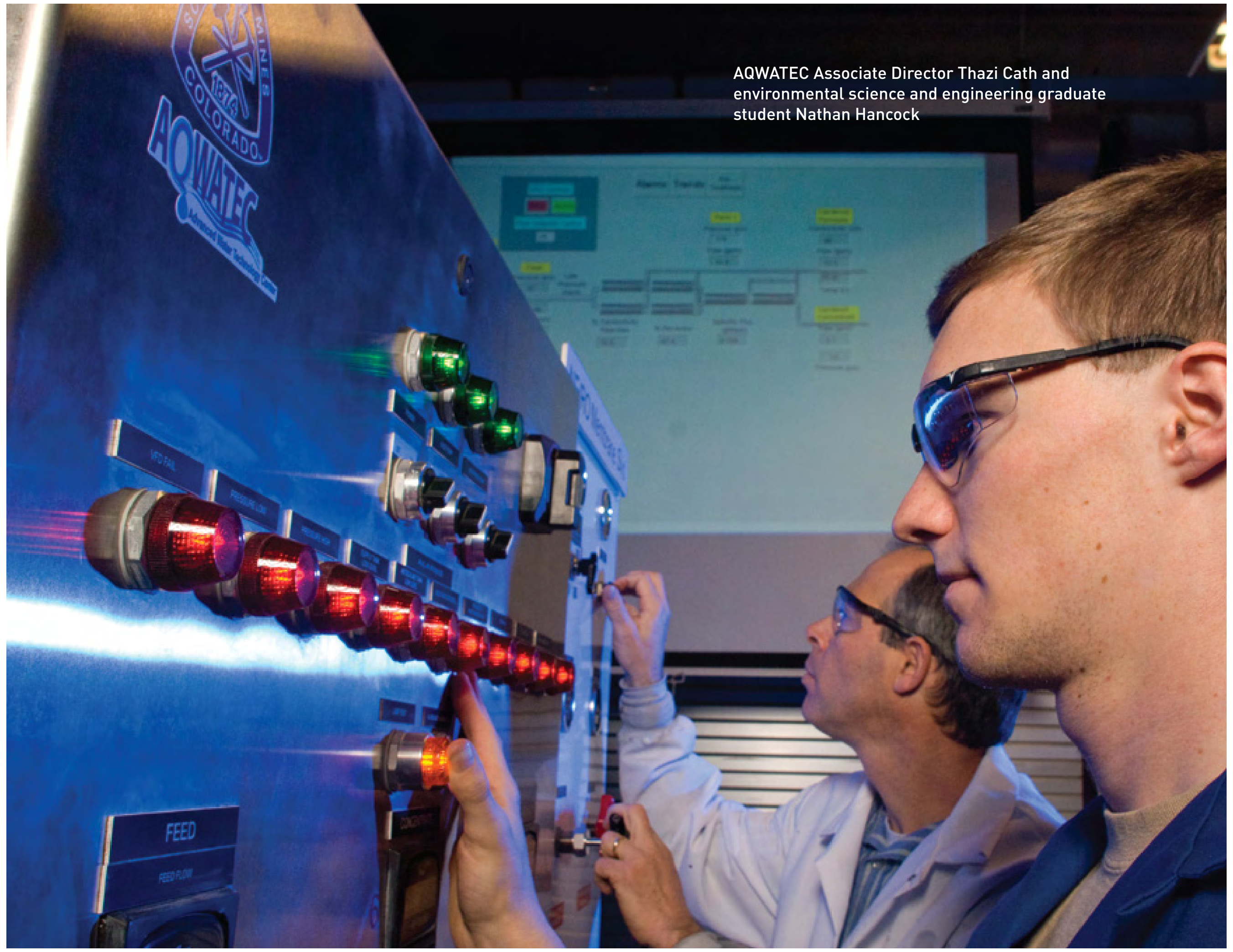
The software package provides the user with "an instant seismic research and data processing environment," according to John Stockwell, principal investigator for the SU project.

SU began as a small collection of programs developed by Stanford University graduate Einar Kjartansson. These codes were brought to Mines by geophysicist Shuki Ronen, also a Stanford graduate. Ronen and Jack K. Cohen, one of the founders of Mines' Center for Wave Phenomena (CWP), decided to create a seismic processing package for open use, which evolved into SU.

In the late 1980s and early 1990s, Cohen and Dave Hale expanded SU considerably. Stockwell became involved in 1989, making the package more transportable and easier to install. In 1992, the first Internet version of SU was released. In 1994, Cohen and Stockwell received the University to Industry Award from the Technology Transfer Society for their work with SU. In 2001, Kjartansson, Ronen, Cohen, and Stockwell received a Special Commendation Award from the Society of Exploration Geophysicists for their work with SU, which has more than tripled in size using code written by students and faculty of CWP as well as outside contributors.

SU has become a fixture in the exploration geophysics community. During its 21 years of existence, SU has been installed at sites identified by 68 Internet country codes. There are nearly 700 active researchers in the SU e-mail list-server group; however, these numbers likely underestimate the actual size of the user community.

The software is provided free of charge at the SU website at www.cwp.mines.edu/cwpcodes.




AQWATEC Associate Director Thazi Cath and environmental science and engineering graduate student Nathan Hancock

# Water Technology Future

In anticipation of society's future water needs, Mines researchers are developing novel and integrated treatment processes in hybrid systems, advancing sustainable and energy efficient utilization of impaired water sources and enhancing the education of young scientists and engineers.

The Advanced Water Technology Center (AQWATEC), which launched in August 2007, focuses on improving existing water processing systems and developing new technology to address the increased demand for water.

AQWATEC research covers a broad spectrum of water treatment techniques for various water sources including surface water, groundwater, seawater, reclaimed water, industrial wastewater and water generated during oil and gas production. The cost and energy demands associated with production of high quality water from these resources are motivating factors in developing more efficient and cost-effective methods.

"Water is not the same everywhere. It is an ever-changing aqueous solution of different chemicals, some of which can be hazardous, and may contain biological activity of pathogenic microorganisms. When we are challenged with a problem in a certain source of water, we always look for a multidimensional solution that must take into account complex chemistry, biology, physics, engineering and ethics," said AQWATEC Associate Director Tzahi Cath.

"This is undoubtedly exciting and particularly rewarding if you can find an efficient and elegant solution to the problem. And most importantly, it always makes an impact on people and the environment," he added.

The goals of AQWATEC are well-aligned with the water needs of the future. As populations grow and economies expand, more stress is imposed on existing water resources. Climate change also places strain on these sources. Because demand continuously grows, more water resources must be utilized. And as conventional water resources dwindle, people turn to researchers to develop unconventional resources.

AQWATEC researchers are exploring how to improve existing water processing in the area of subsurface and soil-aquifer water treatment. For example, the focus of the Prairie Waters project with the City of Aurora, Colo., is to develop a filtration system that can remove organic contaminants from river water making it available for city use.

The center also is conducting research in novel membrane processes such as membrane distillation, forward osmosis and capacitive deionization.

A future challenge facing AQWATEC is advancement in desalination applications. There is a push in science to achieve extremely high recovery of water and minimize the concentrated waste stream.

According to Cath, "one of our great challenges is to achieve recoveries higher than 95 percent (from brackish groundwater) at low cost and low energy demand."

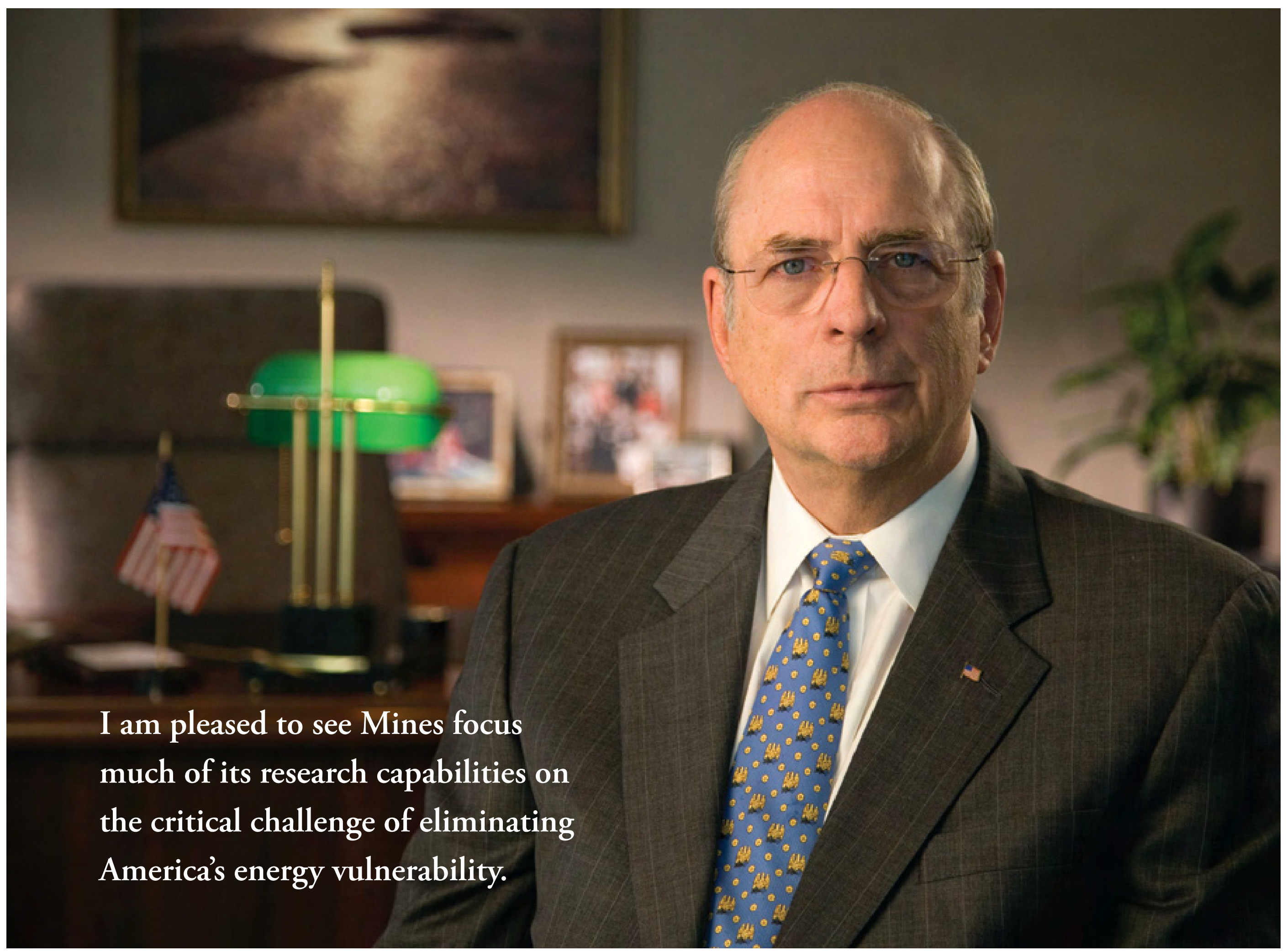
AQWATEC collaborates with researchers from other universities and with institutes and water agencies from around the world including partnerships with the Southern Nevada Water Authority, UNESCO-IHE in the Netherlands, University of California-Berkeley, University of Nevada-Reno, Yale University, Colorado State University, the University of Poitiers in France, the University of New South Wales in Australia, the University of Edinburgh in Scotland, the University of Hokkaido in Japan, Gwangju Institute of Science and Technology in Korea, and the University of Technology Dresden in Germany. In addition, the center's scientists collaborate with many water utilities in Colorado, California, Arizona and Nevada.

AQWATEC research is funded by federal, state and research agencies and foundations. The U.S. Bureau of Reclamation, the Awwa Research Foundation, the WateReuse Foundation, the California Department of Water Resources, the National Renewable Energy Laboratory, the City of Aurora, the Water Environment Research Foundation and the National Science Foundation also provide project funding.

# A MESSAGE FROM Norman R. Augustine

When invited to write a message for Colorado School of Mines' research publication "Energy and the Earth," I was quick to say "yes" because the opportunity would allow me to address three of my life's passions in one short piece: First, Colorado, as the place where I was born, continues to hold a very special place in my heart. Second, one of this nation's truly great institutions is Colorado School of Mines, a university from which, I am proud to say, I hold an honorary degree. Third, the research being conducted by scientists and engineers at Mines, particularly in the areas of energy and the earth, is not only exciting and exemplary but promises to help solve some of the most difficult problems facing humankind.

Research projects highlighted in this publication address a critical theme of my recent monograph for the National Academies, "Is America Falling Off the Flat Earth?" I argue that the United States must greatly increase its efforts at creating new scientific and engineering knowledge if it is to maintain a position of strength, overall prosperity, and constructive leadership in an increasingly competitive world. As the monograph notes, the choice is straightforward: In the 21st century, a developed nation can either innovate or evaporate. It can invest in the future, or it can enjoy the present until the present becomes the past.




In the monograph I draw upon the work of the National Academies "Gathering Storm" committee, which I chaired, to offer some answers to the question: How does a nation achieve success in innovation in science and technology? There are at least four prominent ingredients in the process. The first is to generate a supply of brilliant scientists capable of producing new knowledge. The second is to invest sufficient funds to support the research of those scientists. The third is to provide a cadre of engineers who have a solid understanding of the fundamental laws of the universe yet are capable of the unconstrained, imaginative, creative thought that translates newly discovered scientific knowledge into products and services. And the fourth is to create an environment that is highly conducive to innovation.

Mines clearly supports such an environment as well as provides the caliber of talent that can survive in it. I am particularly impressed with the interdisciplinary nature of much of the university's research. In this interactive environment, creative people identify and pursue synergistic cross-cutting technologies to produce world-changing innovations. Diversity pays dividends.

Finally, I am pleased to see Mines focus much of its research capabilities on the critical challenge of eliminating America's energy vulnerability. The "Gathering Storm" committee's report recognized the urgency of the energy challenge and made it the centerpiece that drew together a series of 20 specific recommendations. There were several reasons for making this connection. First, the availability of a sustainable supply of reliable, clean, affordable energy is critical to the nation's economy and physical security and to the natural environment. Second, an attack on the energy-security problem happens to draw heavily on the same science and engineering fields that are currently in the greatest need of increased attention from a competitiveness standpoint: physics, chemistry, mathematics and engineering. Third, an assault on energy vulnerability provides focus, much as the Apollo program to put humans on the moon provided cohesiveness to the national research and education reforms that followed the Soviet launch of Sputnik in 1957.

So I salute Colorado School of Mines for its progressive research efforts and its contributions to the creation—and application—of new knowledge centered on energy and the earth, and its long enduring commitment to excellence in all that it undertakes. The work of Mines faculty and students will help assure that future generations—in Colorado, the nation and the world—enjoy stability, security and a high-quality standard of living.

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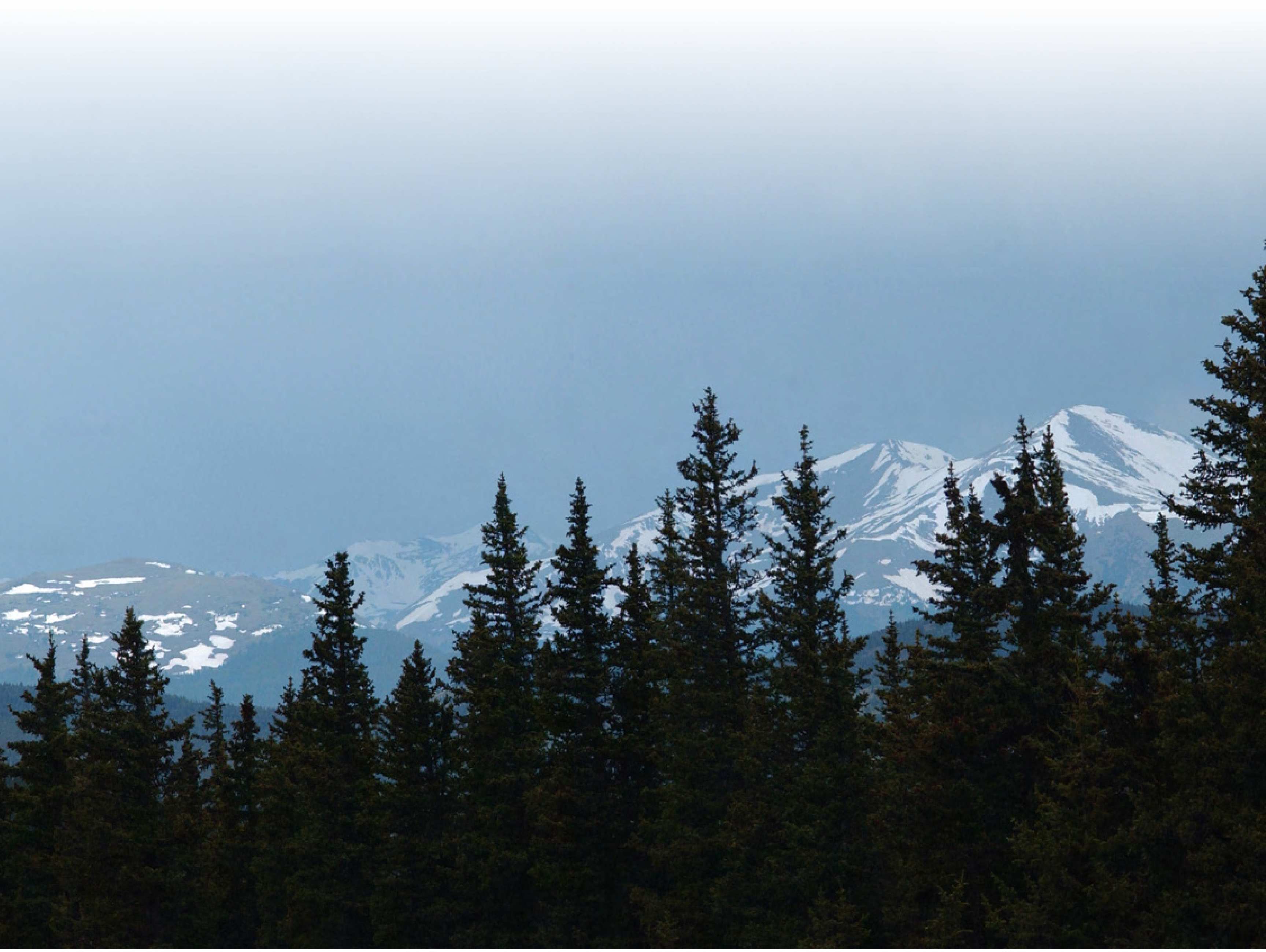
Mr. Augustine is retired Chairman and Chief Executive Officer of Lockheed Martin Corporation and Chair, National Academies Committee on Prospering in the Global Economy of the 21st Century, which issued the report "Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future."



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