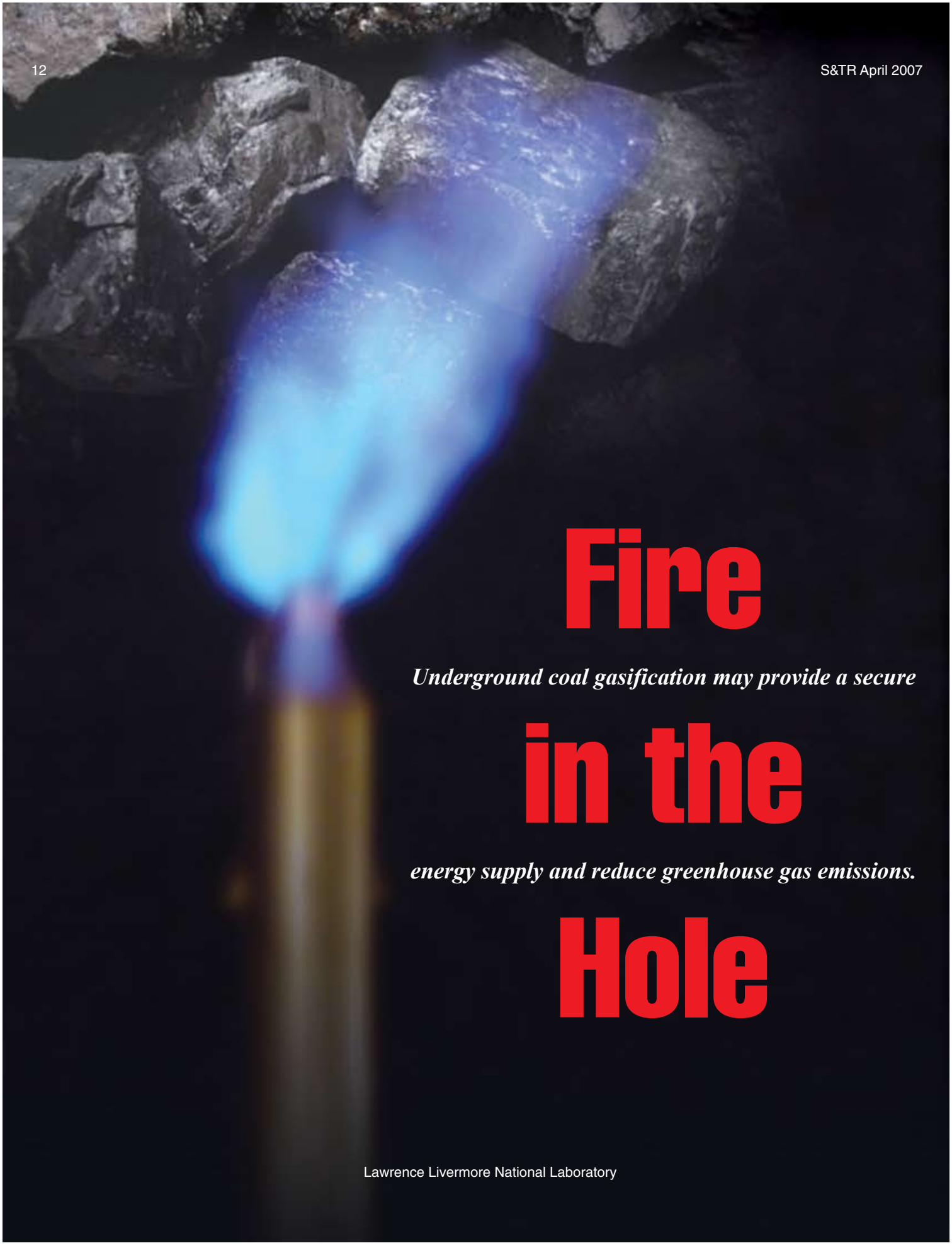


Fire in the Hole

Underground coal gasification may provide a secure energy supply and reduce greenhouse gas emissions.

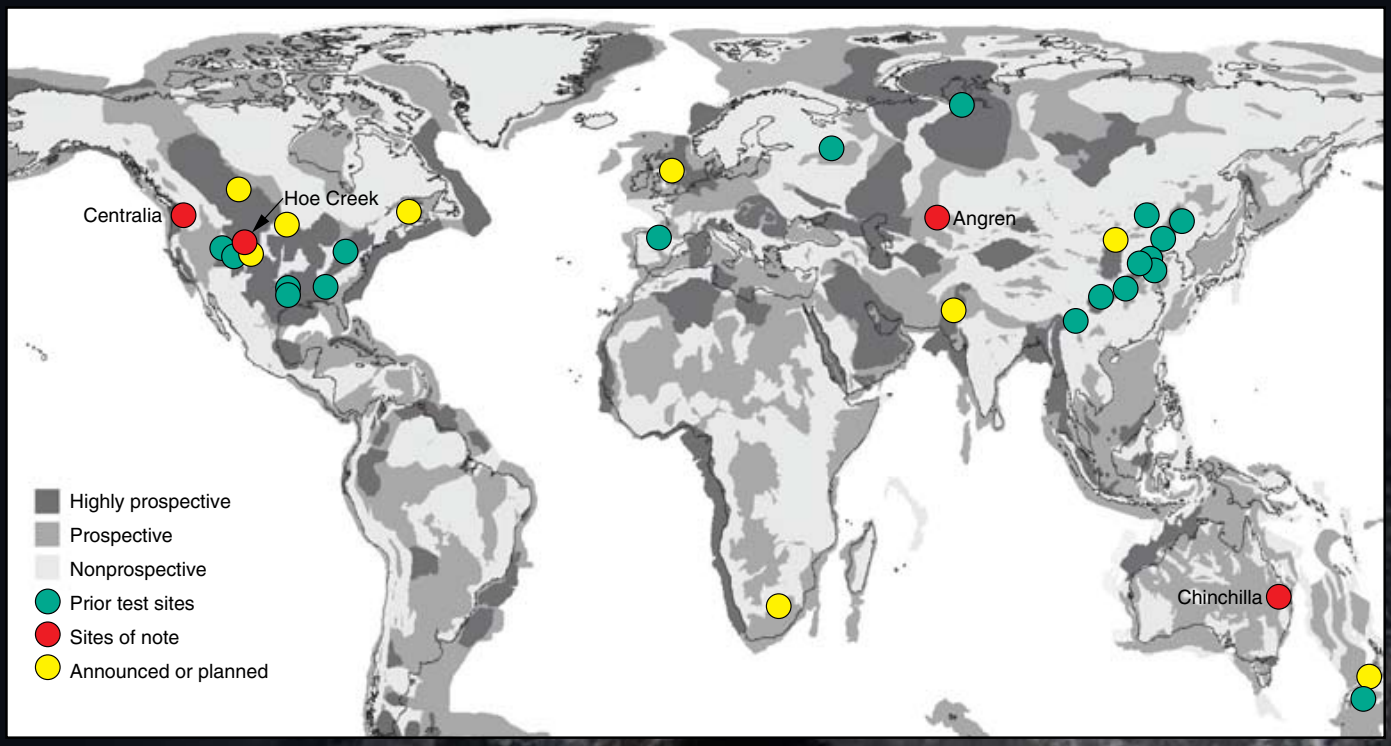
WORLDWIDE coal reserves are vast, over 10 trillion metric tons, but unless cleaner and cheaper ways can be found to convert coal to gas or liquid fuels, coal is unlikely to become an acceptable replacement for dwindling and uncertain supplies of oil and natural gas. Mining coal is dangerous work, coal is dirty to burn, and much of the coal in the ground is too deep or too low in quality to be mined economically. Today, less than one-sixth of the world's coal is economically accessible. However, Livermore is helping to revive an old technology that offers promise to substantially increase usable coal reserves and make coal a clean and economic alternative fuel. Known as underground coal gasification (UCG), this technology converts coal to a combustible gas underground.

In the early years of UCG, the technology gained an "ugly duckling" reputation in the U.S. The UCG process yielded gas of low heating quality with too much hydrogen, and it was considered an environmental risk. But as coal-rich countries now look to replace imported oil with secure domestic energy sources, make hydrogen fuels, and find ways to limit their greenhouse gas emissions, they are rediscovering the potential of UCG.

In the U.S., coal supplies about 50 percent of this country's electricity because it is the least expensive energy source. Coal can be gasified or liquefied to make transportation fuels, natural gas, or chemical feedstocks. Today, the U.S. has only one operating coal gasification plant and no commercial liquefaction operations. However, because of the nation's goal to produce secure and clean energy from its domestic coal reserves, coal-to-gas and coal-to-liquid conversions may become commonplace.

Applying improved UCG technology to gasify deep, thin, and low-grade coal seams could vastly increase the amount of exploitable reserves. The coal could be converted to gas for a variety of uses, and emissions of sulfur, nitrous oxides, and mercury could be dramatically reduced. "UCG could increase recoverable coal reserves in the U.S. by as much as 300 to 400 percent," says Julio Friedmann, who leads Livermore's Carbon Management Program. Another benefit of UCG is that hydrogen accounts for half the total gas product.

As with any hydrocarbon combustion process, UCG generates carbon dioxide



This map shows underground coal gasification (UCG) sites worldwide, including planned sites and prior pilot test sites. The sites of note are Centralia, Washington, and Hoe Creek, Wyoming, which are two Lawrence Livermore test sites; Chinchilla, Australia, where the longest pilot in the Western world was recently completed; and Angren, Uzbekistan, where a commercial UCG plant has operated for 50 years. The underlying gray shading shows potential areas for geologic carbon storage.

(CO_2), a greenhouse gas. Fortunately, potential sites for UCG operations correspond to locations where sites are plentiful for sequestering CO_2 in geologic formations underground. UCG also enhances the storage capacity of the coal seam itself to store injected CO_2. The generated gas, called syngas, would be taken from the ground and the by-products separated out. The CO_2 would then be returned downhole nearby.

Ups and Downs of UCG

The idea for coal gasification, either underground or in aboveground plants using mined coal, has been around for more than 150 years. The technology was first widely used in the U.S. during the late 1800s. Lamplighters made their rounds in many of our largest cities lighting streetlights fueled by "town gas," the product of early and relatively crude forms of coal gasification. Once vast fields of natural gas were discovered and pipelines built to transport the gas to consumers, the use of town gas disappeared.

From the 1930s through the 1990s, the former Soviet Union invested in developing UCG technology at numerous sites and was successful at the commercial scale in several locations. China has been developing the technology since the 1980s and currently has the largest operational UCG program. Their approach uses abandoned tunnels in conventional mines.

During the energy crisis of the 1970s, U.S. interest spiked in all forms of alternative energy, and the Department of Energy (DOE) invested billions of dollars to develop efficient coal-gasification technologies for power generation. Over 30 UCG pilot tests were run across the U.S. At that time, the hydrogen by-product of UCG was viewed as a liability, reducing the perceived quality of the gas. In addition, groundwater-contamination problems resulted at two sites.

The Laboratory, a pioneer in the study of UCG, developed two test sites—one in Centralia, Washington, and the other in Hoe Creek, Wyoming. Livermore researchers also patented a UCG process called Controlled Retraction Ignition Point, which was used in pilot tests performed in Europe during the 1990s. In the U.S., when gas and oil prices dropped in the 1980s and 1990s, efforts to commercialize UCG came to a halt.

Today, high prices have returned for all kinds of fuel, and uncertainties exist about political stability in the Middle East. A renewed U.S. interest in coal gasification is not surprising. Furthermore, hydrogen is now a welcome by-product because of the current interest in alternatively fueled vehicles.

The Majuba UCG Project in Mpumalanga, South Africa, is producing high-quality syngas for power generation. This photo shows the first flare on January 20, 2007, when the UCG plant successfully started operations.

UCG Revives

Four years ago, former Laboratory engineer Ray Smith, who led the Energy Program in the Energy and Environment Directorate, encouraged DOE to revisit UCG as a part of its program to develop hydrogen-from-coal technology. After Smith's retirement a year ago, his team of chemical engineers, geologists, and environmental scientists pursued the revival of UCG through Friedmann's Carbon Management Program. In February 2006, DOE commissioned the team to prepare a document evaluating the current state of UCG technology. *Best Practices in Underground Coal Gasification* was completed at the end of 2006 and is awaiting official release by DOE.

The document explores the UCG efforts that have been undertaken worldwide. Importantly, it also addresses the issues that were problematic in previous UCG operations by evaluating the potential application of technological advances in areas such as environmental risk assessment, combustion-process modeling, geologic subsurface characterization, and geomechanics.

Over the last few years, the number of activities throughout the world focusing on UCG has rapidly increased. The Chinchilla project, operating from 1997 to 2003 in Queensland, Australia, demonstrated the first long-term UCG pilot in the Western world. That project has now advanced to the stage of raising capital for a coal gas-to-liquids pilot that will make ultraclean diesel and aviation fuel. In South Africa, the electricity supply company Eskom is developing UCG at the Majuba Coal Field and achieved ignition in January 2007.

In the United Kingdom, the government undertook a five-year effort to review UCG and study the feasibility of using the technology for exploiting coal on land and offshore. A new UCG partnership, launched in the United Kingdom in 2005, draws its membership from more than

eight countries. The partnership hosted its second international conference in February 2007, and Livermore chemist and environmental scientist Elizabeth Burton delivered the keynote address.

In India, interest in the potential of UCG is particularly high. India is the world's third largest coal producer (383 million tons of bituminous coal in 2005) and uses coal for about 60 percent of its own energy needs. Although India has vast coal resources, much of it is low grade, with high ash content. In addition, the coal lies in steeply dipping deposits that are difficult to mine conventionally. India also has a shortage of natural gas.

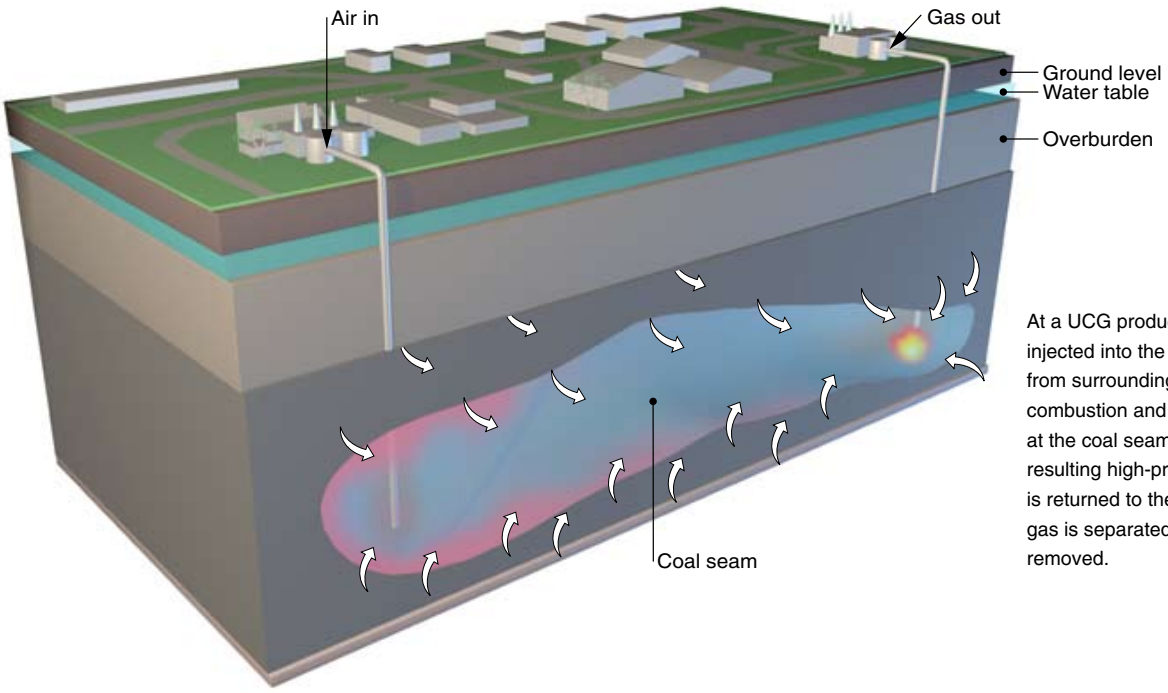
A November 2006 workshop on UCG, hosted jointly by the Indian Ministry of Coal and DOE, was heavily attended by representatives from India's coal industry. At least three pilot projects are now in the planning stages. Livermore, through DOE, is working closely with India on its UCG development. Ravi Upadhye, a chemical engineer who was involved in some of Livermore's early UCG projects, played a major role in organizing the workshop under the auspices of the U.S.–India Energy Dialogue Coal Working Group, with collaboration from governments within the Asian-Pacific Partnership on Clean Development and Climate. Burton represented the Laboratory and made technical presentations at the workshop.

Industry is reengaging with the Laboratory to pursue UCG. On March 30, 2006, Lawrence Livermore signed a memorandum of understanding with Ergo Exergy, which has licensed its proprietary Exergy UCG technology, or εUCG, to clients in Wyoming, South Africa, India, Australia, New Zealand, Canada, and Italy. The two organizations have agreed to cooperate in conducting research on UCG technology, specifically in the areas of process simulation and carbon sequestration, with an emphasis on evaluating the environmental performance of a large-scale operation. In addition, BP (formerly British Petroleum) recently executed an agreement with the Laboratory to develop simulations for optimizing the UCG process as well as tools for drilling, monitoring, and environmental management that are essential for field deployment of UCG.

The Powder River Basin is a massive coal and natural-gas deposit that spans the Montana–Wyoming border. It is the largest source of coal mined in the U.S. and is one of the largest deposits of coal in the world. GasTech, Inc., and the Wyoming Business Council recently completed a feasibility study showing UCG to be a better option with respect to cost, emissions, and environmental effects compared with conventional coal-fired stations and integrated gasification combined-cycle plants. New UCG field pilots are planned for the Powder River Basin. Ergo Exergy Technologies, Inc., will be involved in this test operation.

The UCG Process

In the UCG process, injection wells are drilled into an unmined coal seam, and either air or oxygen is injected into the cavity. Water is also needed and may be pumped from the surface or may come from the surrounding rock. The coal face is ignited, and at high temperatures (1,500 kelvins) and high pressures, this combustion generates hydrogen, carbon monoxide, carbon dioxide, and minimal



At a UCG production facility, air is injected into the cavity, water enters from surrounding rock, and partial combustion and gasification take place at the coal seam face after ignition. The resulting high-pressure syngas stream is returned to the surface, where the gas is separated and contaminants are removed.

Lawrence Livermore National Laboratory

amounts of methane and hydrogen sulfide. These products flow to the surface through one or more production wells. As the face is burned and an area depleted, the operation is moved to follow the seam.

Upadhye and chemical engineer Henrik Wallman from the University of California at Berkeley are developing improved combustion process models and a computational fluid dynamics model. Their goal is to optimize the design, operation, and control of UCG processes so that the composition of the product gas can be predicted and, despite variable subsurface conditions, constrained within acceptable limits. Gas composition affects the economic viability of the operation and must stay within the limits of the capabilities of the gas-processing plant at the surface. Thus far, they have developed the essentials of the process model and have integrated it with Aspen Plus, a commercial software package for simulating steady-state chemical processes.

Upadhye and Wallman's simplified model may work for some variables but not for all, as shown in the table below, which compares model results for UCG gas component levels to measurements made during the U.S. field tests in the 1980s. The model quite accurately predicts the hydrogen, methane, and water content of the gas. However, it predicts twice the actual level of carbon monoxide and about two-thirds the actual level of CO_2. "Verification of the model's accuracy can only be done with field experiments," notes Upadhye. "We cannot run laboratory experiments to verify the models. UCG takes place many hundreds of feet underground, and its results can be difficult to measure." Upadhye hopes to test and improve the model using field data from the UCG pilot tests that will occur throughout the world over the next few years.

Meeting Environmental Challenges

The new field pilots will also provide key data for the environmental models being developed by a team of environmental scientists led by Burton at Livermore. Although most of the previous UCG pilots did not produce significant environmental consequences, Livermore's 1970s test site at Hoe Creek, Wyoming, unfortunately resulted in contaminated groundwater, as did one pilot in Carbon County, Wyoming. At Hoe Creek, operation of the burn cavity at pressures higher than that in the surrounding rock strata pushed contaminants away from the cavity, which introduced benzene, a carcinogen, in potable groundwater. The contamination has required an expensive and long-term cleanup effort at the site.

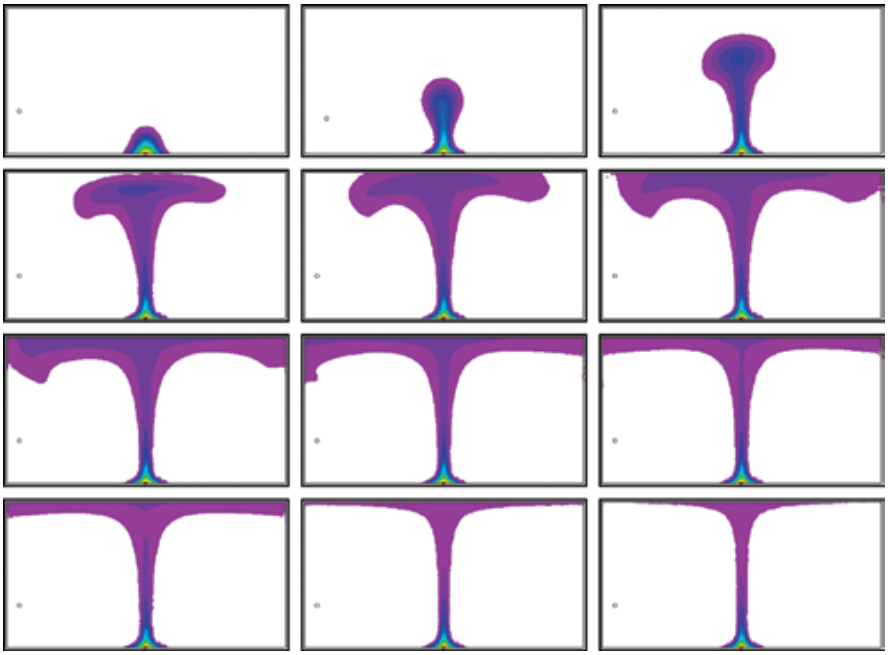
Since these problematic tests in the 1970s, environmental scientists have learned a great deal about the behavior and types of contaminant compounds produced by UCG as well as about contaminant transport and environmental risk assessment. Several steps can be taken to avoid groundwater pollution. One is balancing operating conditions to minimize the transport of contaminants from overpressurized burn zones. Another is to locate a UCG site where natural geologic seals isolate the burn zone from surrounding strata. Isolating the site from current or future groundwater sources and understanding how UCG affects the local hydrogeology are essential. This knowledge greatly benefited the Chinchilla project. "Chinchilla is an excellent example of how to plan a site and operate a UCG plant," says Friedmann. "The operators maintained negative pressure in the combustion cavity so that contaminants could not flow beyond the cavity."

Burton's team is creating the first detailed models of contaminant flow and transport specifically for UCG operations. "The standard types of hydrologic models used for environmental assessments do not consider the full effects of UCG operations," she says. UCG requires integrated simulations that capture the complex geochemical, geomechanical, and geohydrological processes occurring during a burn.

Initially, Livermore groundwater specialists Walt McNab and Souheil Ezzedine created and tested a modified version of the groundwater-modeling tool Flex to generate simple models of contaminant transport from UCG combustion. The models included thermal buoyancy effects on contaminant plume migration.

Model results for UCG gas composition compared with field measurements made during the 1980s Rocky Mountain 1 Controlled Retraction Ignition Point test.

Component	UCG model predictions (percent)	Field measurements (percent)
Hydrogen	27.2	27.3
Carbon monoxide	13.0	6.4
Carbon dioxide	19.4	27.2
Methane	7.4	6.4
Water	33.0	33.0



Groundwater modeling was used to simulate a hypothetical contaminant transport scenario in a subsurface homogeneous aquifer above a UCG coal seam. The model couples flow, heat, mass, and density to calculate changes in the temporal and spatial distribution of contaminants generated by the gasification process. In this simple case, the heat and contaminant sources are modeled for a stationary ignition point, and groundwater flow rates are minimized to highlight the buoyancy effects on the contaminant plume. The contaminant concentrations over time, from top left to bottom right, are shown (purple is lowest, red–yellow is highest).

These first simplistic models used a homogeneous subsurface. The layering and permeability contrasts that characterize natural rock sequences associated with coal seams were ignored. In this way, the researchers could isolate important thermal changes when predicting and assessing UCG environmental effects.

Another environmental concern is that the void created by gasification may cause the land surface to subside. Subsidence is likely to be more of a problem if gasification occurs in a shallow coal seam, closer to the surface. This phenomenon also often occurs above long-wall underground coal mines but is less of a problem if the seam is deep.

Managing Greenhouse Gases

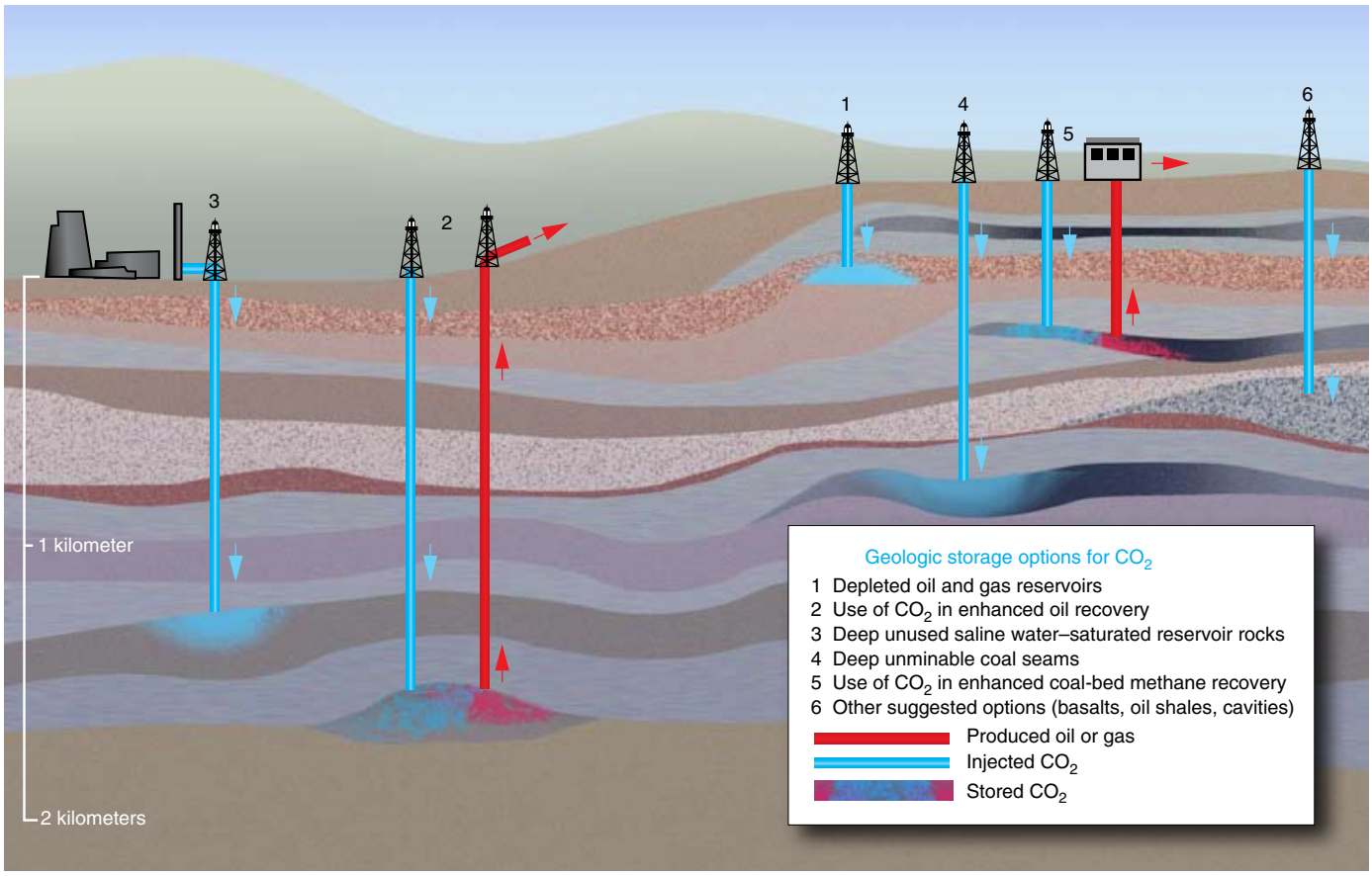
At the surface, the various combustion products are separated out to make the syngas usable. After cooling, the gas is filtered to remove ash and tar particles. Removal technologies are well established for hydrogen sulfide and ash products such as arsenic, mercury, and lead. These compounds are then disposed of safely. Hydrogen can be separated out for use alone, or it can be included as a component in the syngas, which is a mixture of hydrogen and carbon monoxide.

If the CO_2 is to be captured at the surface and sequestered, it must be separated from the syngas. The Laboratory is a leader in the field of carbon management and is developing a number of separation or "capture" technologies. (See *S&TR*, May 2005, pp. 12–19.) At a UCG production site, a significant percentage of the CO_2 would likely be sequestered in the void left by the burned coal seam. Ideally, remaining CO_2 would be sequestered in deep geologic formations nearby.

UCG processes cause thermal, geochemical, and geothermal changes to the surrounding rock reservoir, which may affect the reservoir's ability or capacity for CO_2 storage. Such changes include the effects of heating and quenching on fractures and rock properties. The reservoir may become more porous as acid leaches from ash, tars, char, coal, and rock minerals. Fluid densities in the reservoir may change because of high combustion temperatures. In addition, organic contaminants in CO_2 and metals in acid groundwaters may become more soluble because of UCG. "At this point, CO_2 storage in UCG zones comes with caveats," says Friedmann. Additional research is essential to quantify and characterize the effect of these processes before any CO_2 can be pumped back down near a UCG production facility.

If the CO_2 is not sequestered in place, it can be piped to oil fields. U.S. oil companies can then inject it underground to increase production from oil and natural gas wells, a process called enhanced oil recovery. The U.S. already leads the world in enhanced oil recovery technology, which represents an opportunity to sequester carbon at a lower cost compared with storing it in geologic repositories. Sales of the recovered oil and gas could generate revenues to help offset the expenses of sequestration. The only operating coal gasification plant in the U.S., at Beulah, North Dakota, has been piping its captured CO_2 to oil fields in Canada for years.

Livermore researchers have developed electromagnetic imaging and electrical resistivity tomography to monitor the CO_2 injected underground and ascertain its location over time. Electromagnetic imaging was originally designed as an aid in oil recovery. Electrical resistivity tomography was designed for environmental research but has since been extended for use in oil



Options for storing carbon dioxide (CO_2) in deep geologic formations are represented here. (Courtesy of Intergovernmental Panel on Climate Change, 2005.)

fields. When existing well casings are used as electrodes, electrical resistivity tomography is a nearly noninvasive and low-cost method for monitoring. Three-dimensional modeling at Livermore allows researchers to examine injection scenarios in detail, including those involving enhanced oil recovery, and to "test" monitoring tools in a virtual environment before expensive prototypes are built.

UCG for the Future

Although the potential of UCG as a transformational technology for coal has been rediscovered globally, its future maturation depends on the success of the pilot tests that are just beginning. The U.S. government has declared "clean coal" a critical goal for the near term, and the state of California and other government entities have mandated the reduction of CO_2 emissions. "Current plans are for an additional 120 coal-fired power plants around the world in the next decade," says Friedmann. "UCG could be used to power many of them." Success requires that the right tools are available to accurately assess the economic viability and environmental consequences of UCG in all phases, from planning to operations to site closure.

—Katie Walter

Key Words: carbon dioxide capture and storage, carbon sequestration, hydrogen production, underground coal gasification (UCG).

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