TECHNOLOGY

New Drills Augur a Great Leap Downward

Using lasers and heat, researchers are designing new ways to delve deep into Earth and other planets

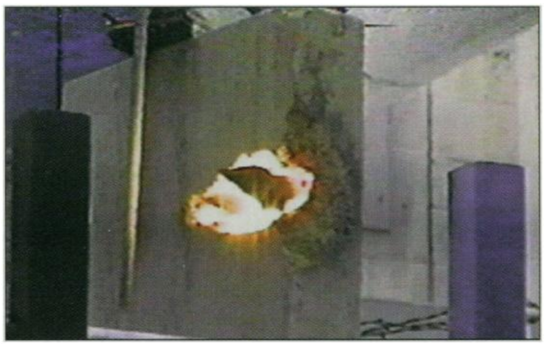
For more than 100 years, humans have dug deep holes with the same tools: dynamite and drills. Today's diamond-tipped machines routinely go thousands of meters down in search of fuel, minerals, geologic data, and deep microbes (*Science*, 2 May 1997, p. 703). But even they seem to have hit the wall at 10 or 12 kilometers—just 0.2% of the way to Earth's core—so there is no way to get at most of our planet. At shallower depths, new scientific and commercial enterprises are demanding cleaner, cheaper holes. So engineers are exploring what they call "revolutionary drilling," totally new ways to dig deep into Earth—or any other planet.

"We will need to design lightweight instruments and techniques that can drill at high speeds and extreme depth," NASA Administrator Dan Goldin said last week at a workshop on revolutionary drilling in Washington, D.C.* The scientists and engineers at the meeting offered a range of candidates already being tested on a small scale, including lasers, melting devices, and machines that pulverize rock with heat. With NASA setting its sights below the surfaces of other worlds, researchers are hoping for a big boost in interest and funding.

In theory, there is no limit to how far rotary drills can go. The world's deepest excavation—the 12.3 kilometer Kola Hole, in the former Soviet Union—was made with rotary drills. But after 20 years of work, by 1992 Kola was plagued by cave-ins, both physical and financial; it has since collapsed to 8.7 kilometers and drilling has stopped. The deepest U.S. hole was 9.6 kilometers, made by Oklahoma gas drillers in the 1970s. Ambitious projects to go deeper always hit the same basic limits: heat, pressure, and money. Temperature mounts quickly and wrecks equipment—at 9 kilometers down, the temperature reaches 260°C or more, and the pressure can crush the metal casings that line drill holes. Moreover, many holes that technically could be drilled just cost too much; the main obstacle to affordable geothermal power, for example, is the fact that it lies under hard igneous rocks that are costly to penetrate.

Much of the impetus and funding to develop new methods may soon come from NASA, which needs new tools to search for microbes below the surface of Mars and, later, below the icy crust of Jupiter's moon Europa. "We won't have the luxury of rotary drills," says physicist Geoff Briggs, head of NASA's Center for Mars Exploration. "They're heavy, complicated, and energy intensive."

One new technology that may be useful in space is the subterrene—an electrical resistor capped by a bullet-shaped ceramic tip that simply melts its way down. You just turn on the juice to heat the resistor and stand back, says James Blacic, a researcher at Los Alamos National Laboratory in New Mexico. Once the molten rock cools, it forms a strong, glassy lining for the hole, a result that may do away with cumbersome metal casing.



Rockbuster. A laser beam 5 centimeters in diameter carves a hole in sandstone.

Such a machine might be powered by solar energy and so could be useful on Mars. Planetary geologists think that traces of liquid water rather than ice—thought necessary for life—may start around 3 kilometers below Mars's frozen surface. Before going that far, NASA officials are planning a first exploratory hole of 200 or 300 meters, perhaps as soon as 2009. "That means we have to think about the digging method right now," says Briggs. Europa is also thought to harbor liquid water—an ocean of it, below perhaps 10 kilometers of ice. "Figuring out how to get at that has become even higher on the list than Mars," says John McNamee, project manager for the NASA Solar Probe.

Subterrenes may have earthly uses too. The Los Alamos researchers have already used it to make a drainage hole near an ancient kiva at nearby Bandelier National Monument in New Mexico; a conventional drill might have destabilized the structure. But this machine has its own limits. It currently goes only about a meter per hour—too slow for most commercial uses—and tests so far have sent it down only 30 meters.

For faster work, the U.S. Department of Energy (DOE) has already field tested a technique called thermal spallation. The idea is to heat rock so suddenly and severely that it expands and shatters, explains Jeff Tester, head of the Energy Lab at the Massachusetts Institute of Technology. The heat can be applied with many tools, including electric arcs, microwaves, and flames. And researchers already know it works: Back in 1988 a DOE team at the Rock of Ages granite quarry in Barry, Vermont, dug a 300-meter hole with what was essentially a rocket engine suspended in the hole like a plumb bob. The engine exhaust gets rid of the pulverized rock bits by blowing them to the top. "You don't want to hang your head over the hole—it's pretty aggressive," says Blacic. Spallation seems limited to rocks with big crystals that come apart in chunks, such as granites—but those are the kind that typically overlie geothermal sources.

Perhaps the sexiest new drilling technologies are spin-offs from Star Wars lasers, originally designed to blow enemy satellites out of the skies. Congress ordered Star Wars technology opened to peaceful uses in 1996, and now the Gas Research Institute (GRI), the scientific arm of the U.S. gas industry, is aiming the lasers at rocks in the lab. In one recent laboratory test, the Army's million-watt Mid Infra Red Advanced Chemical Laser at White Sands, New Mexico, cut through a 15-centimeter piece of sandstone in 4 seconds—10 times faster than a rotary drill. Other tests suggest that these lasers can cut granite, which is much harder than sandstone, 100 times faster than drills do. Lasers can pulverize, melt, or vaporize rock, depending on the intensity and duration of the beam. Says petroleum engineer Darien O'Brien, a GRI investigator, "You might see a hot light coming out of the hole, or sometimes just a white fluffy powder we call dust bunnies." Tests of a truck-mounted device that could be taken into the field may come within a year, says O'Brien.

However, lasers need lots of energy, so they may be best suited for small-diameter research holes on Earth rather than commercial operations or space missions. They may help, for example, to retrieve samples of deep microbes. Today, such samples are often plagued by contamination from surface organisms because drillers must circulate slurry up and down the hole to lubricate drill bits and carry up rock

* "Revolutionary Drilling Technologies," 27–29 January, sponsored by the National Advanced Drilling and Excavation Technologies Institute of MIT.

CREDIT: DARIEN G. O'BRIEN/SOLUTIONS ENGINEERING cuttings; the mud inevitably carries bacteria. Lasers and other high-temperature methods automatically sterilize the walls of the holes they make; small exploratory side passages could then be made to pick up biological samples, says microbiologist Thomas Phelps of Oak Ridge National Laboratory in Tennessee.

New digging methods such as a semirobotic thermal spallation device may also allow deeper mines with less risk to people—although working conditions won't be pleasant. The deepest mine in the world is the 3777-meter Western Deeps gold mine outside Johannesburg, South Africa, where the rock reaches 60°C; the only thing keeping the miners from cooking is cold air pumped from the surface. The veins may continue to 7 kilometers, but to keep expanding downward, companies must deal with daily earthquakes and high-pressure outbursts of rock. "We feel we can get further," says Ray Durrheim, head of deep-mining programs at the South African Council for Scientific and Industrial Research in Johannesburg. "Rock is rock. Further down is more of the same, just hotter and hotter." –**KEVIN KRAJICK**

New York journalist Kevin Krajick is writing a book about diamond prospectors.

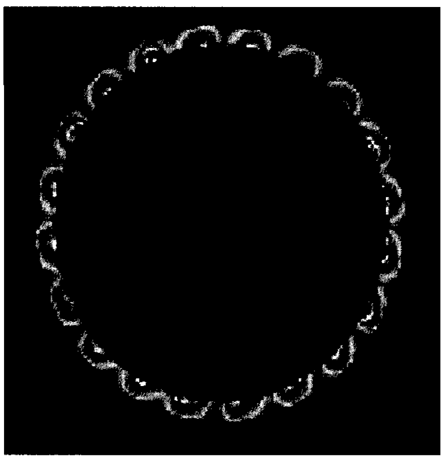
ASTRONOMY

Pulsar Weather Map Shows Storms on a Strange World

Flickers in the radio beam from a spinning neutron star may reveal a procession of compact, energetic storms marching around its polar cap

Two radio astronomers, peering at the polar cap of a dead star 3000 light-years away, have put to shame the weather report graphics that show cold fronts and low-pressure zones rambling across the earthly continents. The spinning, collapsed star, called a pulsar, could easily fit within the city limits of Chicago, and the astronomers may have mapped as many as 20 individual "microstorms"—each probably an explosive hail of gamma rays and subatomic particles—circulating around a region of the cap that is no more than 400 meters across. The storms appear as transient, drifting flashes within the beam of radio waves that emanates from the pulsar's cap.

Astronomers had puzzled over the flashes before. Now, by observing a pulsar with an especially regular sequence of them, Joanna Rankin of the University of Vermont, Burlington, and Avinash A. Deshpande of the Raman Research Institute in Bangalore, India, may have traced them back to features near the stellar surface—like keen listeners deducing the pattern of holes on a player-piano roll from the tune it plays. "This is the first time that any analysis of [the subpulses] has been possible to such remarkable accuracy," says Raman Institute astronomer V. Radhakrishnan. And some astronomers think the work, presented at an American Astronomical Society meeting in Austin, Texas, last month, holds a clue to precisely how and where pulsars generate their intense radio beams in the first place.



CREDITS: JOANNA RANKIN AND AVINASH A. DESHPANDE

Maelstrom. In this computer model, hot spots of radio emission form a ring that may be less than 400 meters across around the polar cap of a pulsar.

The spinning object at the heart of a pulsar is believed to be a neutron star, a superdense ball of matter left behind after an ordinary star explodes as a supernova. As gravitational forces crush the neutron star to roughly 20 kilometers across, its magnetic field gets compressed and amplified as well, becoming more than a trillion times as intense as Earth's.

The fields sprout like cowlicks from each cap, and as they are whipped around by the rapid spin, they act like the whirling dynamos in a terrestrial power station, creating electric fields that accelerate electrons, positrons, and other charged particles. Accelerated charges radiate, and somehow they act in concert to generate "lighthouse beams" of radiation. Because the caps are offset from the spin axis, the beams rotate through space like a lighthouse warning distant ships of a reef, and astronomers pick up blips of radio waves if a beam's orientation allows it to sweep past Earth.

That much seems clear, but not much more. "Pulsars have been around for a long time," says Jonathan Arons, a theorist at the University of California, Berkeley, "so people assume the problem must be solved." But theorists have struggled to explain the great intensity of the beams and debated whether they originate close to the surface or thousands of kilometers up, where the magnetic fields are whipping around at nearly the speed of light. And they have had even less success in explaining the subpulses that dance, drift, and disappear within the clocklike blips of the main radio emission.

Fitful signal. Intensity spikes in the pulses (rows) hold clues to the structure of the radio-emitting region.

One problem was the fickle nature of the subpulses, says Rankin. But she and Deshpande focused on a pulsar in the constellation Leo whose subpulse behavior, while complicated, was regular and reproducible. It was as if a dancer was going through the steps of a complicated waltz, then repeating them over and over. The team mapped this choreography in vivid detail with the 305-meter-diameter radio dish in Arecibo, Puerto Rico, then analyzed the results.

Rankin and Deshpande found that the data pointed to a train of radio-emitting hot spots, which were marching around the outside of the polar cap. The pulsar they chose, which spins on its axis once every 1.1 seconds, was ideal for analyzing such behavior, says Rankin, because its lighthouse beam just grazes Earth. Thus, each time the beam sweeps past, Arecibo observes a different slice through the slowly circulating train, allowing the full pattern to be mapped.

The map showed that a sequence of 20 hot spots, circulating about once every 37 seconds, remains stable for minutes at a time, then jumps to a pattern with just two spots (see www.uvm.edu/~jmrankin). "They've seen a pattern that they can follow all the way around," says Alice Harding, a theorist at NASA's Goddard Space Flight Center in Greenbelt, Maryland.

Rankin and Deshpande think they are seeing an effect first predicted by Malvin Ruderman of Columbia University and Peter Sutherland of McMaster University. In their theory, the electric fields generated by a pulsar's spin