Hot Dry Rock: Problems, Promise

After a decade of hard lessons and limited success, tapping the enormous heat reserves in rock too dry to yield steam or hot water on its own faces more challenges

EARTH is a ball of hot rock, a storehouse of heat energy. Where coincidence brings together water, permeable rock formations, and heat, hot springs flow to the surface and drillers need only sink a well to tap this geohydrothermal energy.

Where nature has not obliged, some drillers are attempting to mine Earth's heat by not only drilling wells but also providing the water to carry the heat and creating the fractures in which flowing water can pick up the heat from the rock. During the energy crisis of the 1970s the enormous size of the heat reservoirs in hot but dry rock encouraged efforts here and in the United Kingdom to develop the techniques to extract this pervasive energy source.

But both the drilling of wells through hard, hot rock and the connection of those wells with enough fractures to form a heat-extracting circulation system have proved difficult. Just this month American researchers repaired nearly disastrous damage to their system. It awaits a long-term test scheduled for 1988 that turns on sufficient funds being in the budget now under consideration by Congress. A less powerful British system has now completed more than 2 years of testing. Both of these alternative energy projects are expected to require another 10 years or more to demonstrate commercial viability, but funding agencies have become far less receptive than in the alternative energy heyday of the 1970s.

There is no doubt that the large-scale extraction of energy from hot dry rock could have a significant payoff. Taking only the hottest areas of the United States, where the temperature increases 40°C or more with each kilometer of depth, Robert Hendron of the Los Alamos National Laboratory estimates that 430,000 quads of energy are in rock within reach of drilling. That is 100 million megawatt-centuries, or about ten times the heat energy of all U.S. coal deposits.

Most of that energy is heat lingering near young volcanic centers, such as in Hawaii, Alaska, and the western third of the conterminous states. In a few areas, such as the coastal region of the mid-Atlantic states, sediments blanket deep-seated granite intrusions containing considerable radioactive, heat-generating elements. Such granites are the prime target of hot dry rock efforts in the United Kingdom.

The heat is clearly there; getting it out in a practical way has been the problem. The first to take up that challenge was a group at Los Alamos working on a drill bit that would bore through rock by melting it. Looking for a way to dispose of the melted rock around the bit, they investigated pressurizing the melt until the surrounding rock fractured and took it up. Drillers have long used hydraulic fracturing, the injection of fluids at high enough pressures to crack the rock, to free up the flow of oil and gas.

In the early 1970s, the Los Alamos group envisioned a system including two wells drilled nearly parallel to each other into hot dry rock. Then hydraulic fracturing would connect the two wells by forming one or more pancake-shaped fractures. Cold water pumped down one well would pass through the fracture, where it would pick up heat, and rise through the other well to a power plant on the surface before returning to the injection well for another pass through the loop.

No one has figured out why some fractures open and others do not.

Conveniently enough, what seemed like a prime target for hot dry rock drilling, an old volcano, lies just west of Los Alamos. Nearby magma heats the rock at the Fenton Hill site to 240°C at a depth of 3.6 kilometers.

All went reasonably smoothly during construction of the world's first hot dry rock geothermal energy system, which was begun at Fenton Hill in 1974 and completed at its present size in 1979. Two wells were drilled more than 2.75 kilometers down and connected by a 0.3-kilometer-tall vertical fracture. Pumping through the completed loop produced 3 megawatts of thermal power. This research-scale power production was at best one-tenth the output required of a commercial system. The extraction of heat proceeded as intended, but it appeared that natural, preexisting fractures inclined 30 degrees to the vertical played a central role in carrying the heated water from the upper end of the vertical hydrofracture to the outlet well.

Although largely ignored in the next phase at Fenton Hill, which was to be a scale-up to a commercial-size system, preexisting fractures figured large in the hot dry rock drilling getting under way at a granite quarry near the tip of Cornwall, England. Anthony Batchelor, then at the Camborne School of Mines in Cornwall, headed the project until this year. He is a mining engineer who was familiar with deep, hot mines and the natural fractures that pervade crystalline rock. From early on, Batchelor assumed that, rather than create new fractures, preexisting fractures called joints had to be widened so that heat exchange could take place there. "Yes, there are going to be joints there," he recalls thinking, "so let's put them to use."

The other major difference between the American and British projects has been the more gradual approach British drillers have taken to the ultimate goal of a system hot enough and large enough to produce commercial amounts of power. To begin, they drilled four holes in 1979 and 1980 to only 300 meters in order to experiment with ways of encouraging circulation in the rock. Their next step was not a demonstration of commercial-scale heat extraction, but the intermediate target of completing a loop begun with two wells drilled in 1981 to 2100 meters, where the temperature was only 80°C.

This cooler, intermediate-depth drilling went smoothly, in part because British drillers and researchers had seen what problems hot drilling had caused their American counterparts. By mid-1980 the Americans had, with considerable difficulty, drilled energy extraction hole 2 (EE-2) to 4660 meters, where they encountered a temperature of about 320°C. That is as about as hot as any conventional geothermal well in the

United States. Its mate, EE-3, was already started in early 1981 when Los Alamos called in an ad hoc panel of drilling experts for advice.

The panel strongly recommended that the lab take a more conservative approach to drilling. Its report pointed out the obvious beating that the drill bit, the drill pipe rotating the bit, and the steel casing lining the hole had been taking. High temperatures, hard rock, corrosive hole conditions, and the 30-degree bend designed into the middle of each hole had taken their toll in numerous drill pipe failures, among other problems. The drillers should "overdesign for wear and corrosion" and institute a more conservative inspection program of operating equipment, according to the panel's recommendations.

The alternative to preparing for the worst, the panel warned, could be a catastrophic failure of the casing and a useless hole. The British, who stayed in close touch with the Fenton Hill operation, took all this to heart. "We have to give a lot of credit for our program's success here to Fenton Hill's being ahead of us," says Batchelor.

Once the two wells were successfully completed, with EE-3 nearly parallel to and 300 meters above the inclined EE-2, the next task was connecting them with a single vertical fracture. Pumps pressurized a deep section of EE-2. Nothing happened in EE-3. EE-3 was hydrofractured. Nothing happened in EE-2.

By mapping the three-dimensional distribution of microearthquakes during the hydrofractures, Fenton Hill workers could see that they were not making single, thin, vertical cracks at all. Instead, each hydrofracturing created great elliptical clouds of microseismic activity that presumably reflected the slippage of rock on a myriad of joints. As hard as they pushed the rock, it gave along preexisting fractures rather than forming new cracks.

The Los Alamos researchers, it seemed, had chosen between two schools of thought on hydraulic fracturing and chosen wrong. "For years we subscribed to the theory of fracturing as in the oil and gas industry," says Hugh Murphy, manager of the hot dry rock program at Los Alamos. When industry drillers hydrofracture a hole, they assume a few new fractures will form whose orientations are determined by the region's crustal stress. But, on the other hand, field studies and laboratory work in the 1970s suggested that preexisting fractures can control the behavior of rock, even at depths where no voids remain.

Compounding the problem of unexpected fracture behavior at Fenton Hill, the clouds of stimulated seismic activity failed to overlap. Instead of being vertical, they were inclined at an angle of about 30 degrees. The Los Alamos workers had assumed that the same stress field that had oriented the shallow-induced fractures vertically would do so at any depth. But the deep stress field had a different orientation than that nearer the surface, apparently due to the influence of the cooling magma chamber a few kilometers away. Despite a total of five hydrofracturing operations, the 300 meters between the two wells could not be bridged.

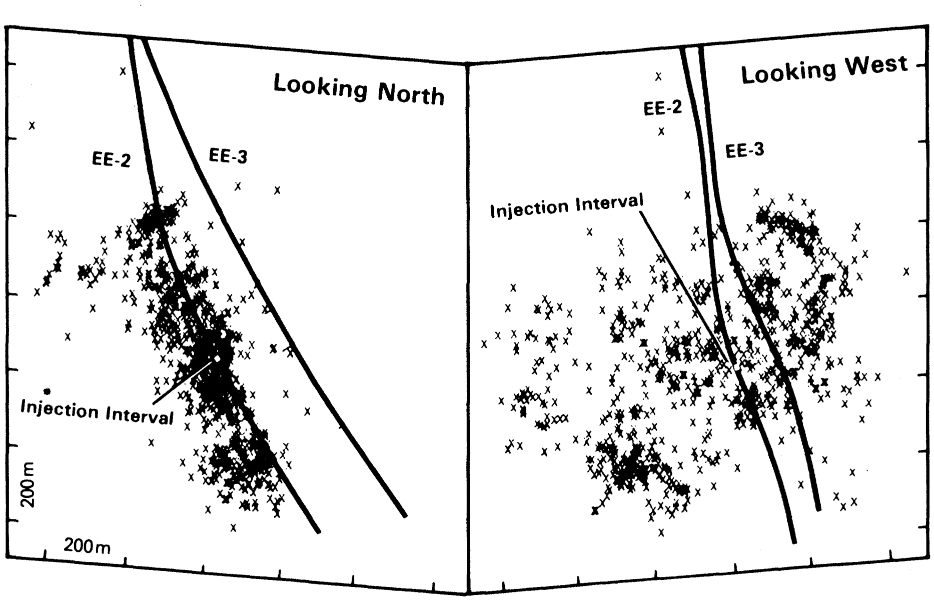
Meanwhile, the British were attempting to link their two wells by opening the preexisting system of joints between them. The stress field had already been determined in a shallow hole, and all looked well, but stress was redetermined in the bottom of the first deep hole, just to be sure. The results gave Batchelor a rude shock. Instead of being equal in orthogonal directions, as expected, the stress was almost three times as great in one direction as in the other.

Despite their best efforts to deal with the effect of this anisotropic stress field, hydraulic fracturing in the deep well stimulated the opening of preexisting fractures mostly below the holes. A loop existed, but it was a small, leaky one, losing more than 60% of the water injected. Failing with two wells, drillers sank a third well that spiraled to a point within the cloud of fractures 600 meters below the first two wells. No improvement. Finally, in mid-1985, a thick gel instead of water was injected at high pressure so that more tensile stress, which would tend to open fractures, and less shear stress, which only slides rock along fractures, would be produced. That did the trick. The resulting loop has been operating for 2 years now, producing 5 megawatts of thermal power. Water loss is down to about 20%.

In the end, a third well, of a sort, proved necessary at Fenton Hill too. In March 1985 drillers created a second leg for EE-3, redirecting a hole from part way down the well into the stimulated fractures 150 meters from EE-2. That yielded a small connection that enlarged with further stimulation, although the high temperature prevented the use of hydrofracturing gels. Deepening of the sidetracked well and three more stimulation operations produced only one more set of connecting fractures, despite the clear overlap of clouds of fracture slippage stimulated by hydraulic fracturing. Obviously, fractures can just slip and not open, and no one has yet figured out exactly why some open and others do not.

Of the world's two hot dry rock reservoirs, the British one is physically larger, but the hotter American system can still extract heat energy faster. According to Batchelor, the system in Cornwall probably has a heat-exchanging surface area three to four times that at Fenton Hill. After 2 years of operation, the British system is producing 5 megawatts of thermal power by injecting cold water into 100°C rock. About 20% of the 24 liters per second of injected water does not return. A 30-day flow test at Fenton Hill demonstrated a thermal power production of 9 megawatts from 240°C rock. The water loss rate was about 30% and dropping.

In terms of goals set before drilling began, however, the British have the better record. They have achieved their intermediate goal



A failure to connect. *Instead of the expected vertical fracture that would complete the circulation loop and provide a heat source, pressurization of the "injection interval" stimulated the slippage of preexisting fractures. Even this ellipsoidal cloud, visualized here by the plotting of microseismic activity, failed to intersect the other well.*

of creating a reservoir at a modest depth and temperature. The cost has been modest as well, about $40 million. The next step could be a pilot plant that would generate electricity from 220°C rock at 6 kilometers.

The recent American attempt to go from a shallow system to a large, hot loop powerful enough to drive a commercially viable electric generator has failed. A half dozen vertical fractures connecting the lower inclined sections of the first two wells were projected to yield 35 megawatts of thermal power. The holes reached the intended 200°+ temperatures, but the small fracture systems opened between the holes limited output to one-quarter of the intended power. To date, $150 million in U.S. federal funds have gone toward hot dry rock research at Fenton Hill plus a total of $30 million from Japan and West Germany.

The next step at Fenton Hill would be a 1-year flow test to determine just what the reservoir can do over the long term. Before that, extensive damage to EE-2 must be repaired. During a hydrofracturing operation in December 1983, an overworked flange gave way, which eventually created a towering geyser that spewed 10 million liters of hot water during the next 36 hours.

This failure created the worst-case conditions that the expert panel had warned about. EE-2's ruptured casing and other problems have just been sidestepped by sidetracking the hole starting above the problem areas. The long-term flow test now depends on the fiscal year 1988 budget, which is still being worked out in Congress.

Hot dry rock has proved to be a recalcitrant, even devious foe, demanding greater respect and subtlety of design than pioneers in the field imagined. Still, interest is growing. Other programs are under way at sites in Japan, the Alsace region of France with European Community and West German funding, Sweden, and the Soviet Union. What may help as well is a new perspective. "We believe that hot dry rock has a future," says Batchelor, "but you have to look at it strictly in the long term. It is wholly unrealistic that a novel technology could compete with 1984 power plants," as post-energy crisis politics seemed to be demanding. Industry involvement is probably necessary, too, if hot dry rock is to meet its potential in the 21st century, says Batchelor. ■

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ADDITIONAL READING

A. S. Batchelor, "Development of hot-dry-rock geothermal systems in the UK," *IEE Proc.* **134** (part A), 371 (1987).

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Coral Bleaching Threatens Atlantic Reefs

Unexplained changes are occurring in some of the most productive ecosystems on the planet, the Caribbean coral reefs

BENEATH the clear, still waters of the Caribbean something is amiss. From the Florida Keys to St. Croix, the rich brown reef-building corals have turned a startling, snowy white, an indication of environmental stress. The severity of this "bleaching" episode, as it is called, cannot yet be assessed, but many Caribbean researchers fear it could profoundly disrupt the ecology of the Atlantic coral reefs—some of the richest, most productive ecosystems on the planet. Earlier this month Senator Lowell Weicker (R–CT), a strong supporter of oceanographic research, held a hearing to try to assess the extent of the problem and likely causes.

Bleaching occurs when corals expel the symbiotic algae that reside within the corals' soft tissues. In exchange for nutrients, these photosynthetic algae provide energy and oxygen, thereby boosting the rate at which corals grow and secrete their calcium carbonate skeleton that makes up the stony framework of the reef.

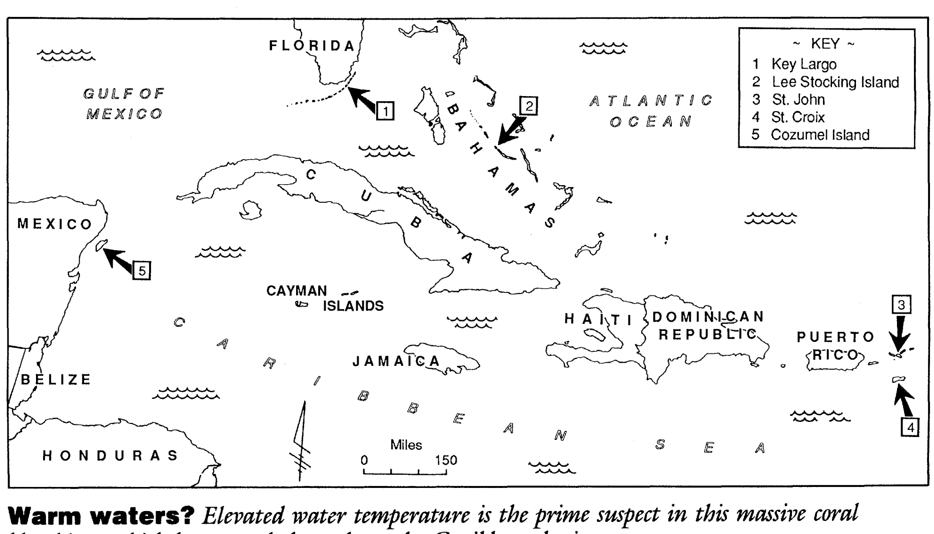
For some unknown reason, in response to environmental stress, corals expel the algae, known as zooxanthellae, which leaves the corals weakened and may lead to death. It is called bleaching because without the brown algae, the denuded corals are white.

Isolated instances of bleaching commonly occur in response to heavy rains, pollutants, decreased salinity, or other local stresses. But never before has bleaching occurred almost simultaneously across such a wide swath of the Caribbean, researchers say.

An even more extensive bleaching episode—followed by mass mortality—swept through the tropical eastern Pacific in 1983, brought on, it is believed, by the unusually warm 1982–83 El Niño, the strongest in a century. Reefs off the coasts of Costa Rica, Ecuador, Panama, Colombia, and the Galápagos Islands were devastated.

What caused the Caribbean bleaching is not known, but suspicions center around elevated water temperatures there, too. Nor is it clear what this bleaching episode portends. The bleaching, most of which was detected just last month, seems to be spreading both in geographic scope and in intensity, according to E. H. Williams of the University of Puerto Rico. Some of the corals are beginning to die, but it is too soon to tell whether the bleaching is a precursor to mass mortality, as it was in the Pacific, or whether the corals are likely to recover. If corals die and stop laying down their calcium skeleton, reef growth halts and reefs themselves are more vulnerable to erosion and physical devastation.

It seems to have started in mid-July in the



Warm waters? *Elevated water temperature is the prime suspect in this massive coral bleaching, which has spread throughout the Caribbean basin.*