HOT DRY ROCK IS WHERE YOU FIND IT

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Because the earth's interior is very hot and the upper crust is a poor thermal conductor, the heat stored in crustal rock at practical drilling depths represents by far the largest supply of usable energy that is accessible to man. At least to me, it seems inevitable that -- as our limited supplies of fossil and nuclear fuels dwindle and become more expensive -- this vast reservoir of thermal energy will eventually be exploited to mankind's benefit all over the world. Much of its use will be direct -- for space heating, processing foods and chemicals, and a wide variety of other low-temperature applications. However, where relatively high temperatures are encountered at reasonable depths, it will of course also be used to generate electricity.

Some small fraction of this geothermal energy -- probably much less than 1% -- is stored in hydrothermal reservoirs, representing a useful and economical, but limited, energy resource. The rest is in the rock itself, and it is with this "essentially inexhaustible" energy supply that the Hot Dry Rock (HDR) Program is concerned.

In principle, naturally heated crustal rock can be of any type and in any physical condition -- and a means can be proposed for extracting heat from it in almost every conceivable geologic situation. For example, the Soviets propose to recover large quantities of low-grade heat by a water-flooding operation in a highly permeable sandstone. Gunnar Bodvarsson proposes forced circulation through natural fractures in fault systems, within or adjacent to dikes, or along the interfaces of successive basalt flows. The British and the French propose to circulate through reopened natural fractures in old, weakly sealed, crystalline rock. Some years ago, Robert M. Potter proposed forced horizontal circulation between vertical hydraulic fractures in formations with low but significant matrix permeability. These and a variety of other HDR concepts appear worthy of serious investigation.

At Los Alamos, however, we have so far concentrated on only one type of HDR environment and one method of heat extraction. We have assumed that, at depths and temperatures of geothermal interest in regions undisturbed by recent large-scale earth movements, the normal situation at depth is hot rock with very low initial permeability and free-water content. This is ideal for containing a pressurized-water heat-extraction loop, but construction of such a loop requires creation of flow passages in the rock with large surface areas for heat transfer. For loop construction, we have concentrated on the use of hydraulic fracturing to connect two vertically separated wellbores.

Conceivably, in a deep sedimentary basin, the low-permeability HDR thermal reservoir might be a massive body of shale or dolomite or limestone, or even an initially permeable formation tightly sealed by alteration products or mineral deposition. However, the better choice in general has seemed to us to be the crystalline basement. Once this has been penetrated to a sufficient depth to reach a usefully high temperature and desirably low permeability, one is reasonably assured that the thermal reservoir is large both horizontally and vertically -- with the advantage that if a higher temperature is required, one need only drill a little deeper.

For some reason that I do not understand, a mystique has developed that it is somehow more difficult to locate and characterize an HDR thermal reservoir than a hydrothermal reservoir. As a nonexpert in geothermal exploration, it seems to me that the opposite must be true. It appears that it should certainly be easier to demonstrate the absence of a hydrothermal reservoir than to demonstrate its presence. As I understand it, aside from obvious surface manifestation, the principal evidence for existence of hot water at depth is low electrical resistivity. Since this may result from other causes than the presence of hot water (e.g., permeation by a highly saline brine, mineral alteration to clays or zeolites, a layer of shale, or a mineral deposit) it is not definitive, and a shocking proportion of dry holes has resulted from drilling where the experts predicted the presence of hydrothermal reservoirs.

In exploring for hot dry rock, the obvious first approach is simply to locate those hot dry holes (which of course we have already done, so far as we could). In their absence, or if they are found only in areas already leased, one should probably resort to fairly conventional exploration techniques but avoid areas where there are high-conductivity anomalies at depth. Conceivably this could ultimately result in drilling into a steam field (which would be a scientific but not a financial disaster), and this constraint may be overly conservative since it would eliminate from consideration areas where the anomaly represented something other than hot water. However, there appear to be enough really good HDR areas so that we can afford to pass up the doubtful ones.

If the energy system is to be developed by hydraulic fracturing and operated as a recirculating pressurized-water loop, it is desirable that it be constructed in a large, shallow body of hot rock with very low matrix and fracture permeability. The lateral extent of the area should be not less than several square kilometers, to provide for construction of a group of parallel systems. (This can of course be put in terms of an investigation of the nature of the heat source.) To avoid extending the fracture system to the surface or to overlying permeable formations, it is important that the top of the fractures be not less than a few hundred meters below the top of the reservoir formation. Otherwise, the shallower the better, primarily to minimize drilling costs but also to reduce overburden stress and pumping pressures required to create and extend hydraulic fractures.

In our present state of knowledge, we believe that the most desirable type of reservoir formation is the crystalline basement, whether volcanic, plutonic, or metamorphic. Since we would like to reach a high temperature at shallow to moderate depth, a high conductive geothermal gradient, persistent with depth, is obviously desirable. Because crystalline rocks are relatively good thermal conductors, this is favored by the presence of a few hundred meters of poorly conductive sediments or volcanics above the basement -- so long as there is no significant cooling by active ground-water circulation. (If you prefer, this can be put in terms of conductive and convective heat transport, and internal heat generation may also be important.) For predictability of fracturing behavior, it would be useful if the reservoir formation were reasonably uniform and isotropic, and very helpful if the stress condition at depth were known. Natural fracture systems are to be avoided, because of the dangers of excessive leakage from the pressurized-water loop and of triggering earthquakes by injecting a pressurized fluid. All of this requires (1) a careful temperature-gradient (or heat flow) study; (2) detailed geological, hydrological, and geophysical investigation of the area; (3) identification of any currently or recently active faults; and (4) review of the seismic history of the area.

In the absence of an existing deep hole, information at this point will necessarily be limited to that collected at the surface and from shallow holes, and little will be known about hydrology at depth and basement rock structure. The next step, therefore, should be to drill a slim hole that penetrates the basement rock by at least a hundred meters and preferably more than that, and is left uncased in the basement section. That section should if possible be cored continuously and the cores examined for chemical, mineralogical, physical, and mechanical properties, altered zones, and sealed and unsealed fractures. The entire hole should be logged for temperature, and geophysical logs run in the uncased basement section to learn as much as possible about the rock around the hole and in any uncored intervals. The borehole wall should be examined with a televiewer for initial structure and reexamined after a series of hydraulic-fracturing and pressure-flow tests. By drill-stem or other tests, permeability should be determined locally wherever there are indications of fluid loss, unusually high drilling rates, or altered or fractured zones.

All of this is expensive and time consuming, but much less so than drilling a deep, full-size hole in the wrong place.