Geothermal energy development

Research needed to hasten the use of the little-tapped but extensive heat energy of the Earth includes devising sensors to operate in the hot, corrosive underground environment and improving surface geophysical measurements.

John C. Rowley

The interior of the Earth represents an enormous reservoir of energy. Most of it, with the exception of the relatively thin surface-crust material, is at a temperature either close to, or above, the melting-point range for the rock and metallic alloys that make up the mantle and core. Yet this great energy reservoir is not at present a generally useful resource, being currently tapped only in a few small areas where surface conditions permit an economic yield. What are the problems limiting the development of geothermal energy to its full potential?

The difficulties include: Poor accessibility of the most promising source regions (and, conversely, the relatively low temperature of the more easily accessible regions); the lack of established, economic technologies for conversion and utilization of the heat, and the high risk inherent in exploring for promising new fields, together with high costs both for exploration and the development of extraction technologies.

Geothermal heat could become a significant contributor to our energy needs, with relatively little environmental damage, but it will take some new ideas, the application of much ingenuity, and a lot of hard scientific and engineering effort. As an example, figure 1 shows one of the so-called "integrated thermionic circuits" recently developed to operate at the high temperatures of geothermal wells. Let us take a look at those areas where physicists and materials scientists could make a contribution.

The story so far

The first extensive commercial use of geothermal energy was at the beginning of this century, when natural steam from wells was piped to two small low-pressure turbogenerators at Larderello, Italy.[1] Since this early success, a number of significant developments have been carried out around the world, the better known fields being located in New Zealand, Iceland, Japan, Mexico and the US. These efforts were often inspired, encouraged and supported by the technological expertise of the United Nations, which has sponsored two international geothermal symposiums[2,3] reviewing all aspects of geothermal development.

The general status of the development of geothermal energy is summarized in figure 2, which gives the electric output of the major electric-power installations and locates these on a world map. We see that a total of about 1200 megawatts of electrical energy is generated—the capacity of one large fossil-fuel or nuclear power plant. This figure also shows the non-electric uses of the world's geothermal resources. The direct utilization of geothermal heat for industrial processing, spas, greenhouses and agriculture, and space conditioning (both heating and cooling), has been estimated[4,5] at ten times that of electric power production.

Not apparent from this map is the recent expanding growth rate of geothermal development, especially during the last five years. Exploration activities, in particular, are accelerating rapidly throughout the world. At the world's largest power-producing field, The Geysers in northern California, extensive new wells are being drilled and plans are to increase the capacity by approximately 100 MW(e) yearly over the next decade, to a total of about 1500 MW(e). The projected increments of 100 MW(e) are significant because they relate to the economics of scale for such developments, for which an optimum has been found in the 50–100 MW(e) power-plant size.

Geothermal energy has been developed until now only in local regions where the geologic setting is such that the heat flow from depth is transported close to the surface by the convective circulation of steam or very hot water. These geothermal systems are usually referred to as "hydrothermal reservoirs." There are two subtypes, "vapor dominated" and "liquid dominated." The vapor-dominated type produces dry steam, and the world's two largest geothermal power producers, The Geysers and Larderello, are of this type. Such reservoirs are especially easy to exploit. A steam or hydrothermal reservoir is often very leaky and has surface expressions in the form of hot springs, fumaroles or geysers. These formations are relatively easy to find, drill and pipe the steam to turbines, *but they are extremely rare.* The liquid-dominated type of hydrothermal reservoir, which contains superheated water, are more abundant, by perhaps two orders of magnitude, but are harder to find and to exploit. The geofluids in these reservoirs (often termed "brines") are difficult to utilize—witness the long period of development of the extensive hot-brine fields in the Imperial Valley–Salton Sea area of southern California.

Types of resources

Three further categories of geothermal systems exist: "geopressurized," "dry hot rock," and "magma" systems. Geopressurized reservoirs contain high-pressure, hot fluids (brine plus methane), and they

Basic amplifying element (magnified 20 times) being developed at Los Alamos for use in hot geothermal wells. The interdigitated fingers form the cathode (darker) and grid; the circular pattern is a sputtered-tungsten heater on a sapphire substrate. Figure 1

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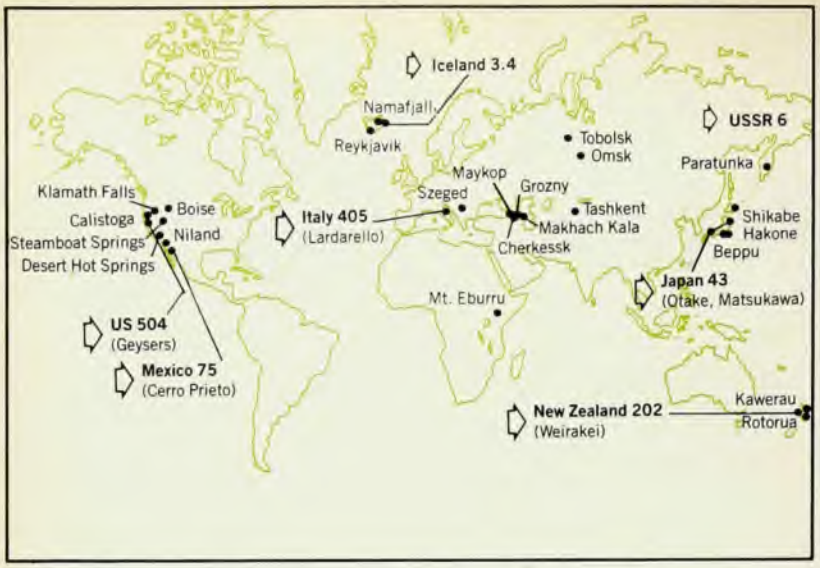


Current world status in the development of geothermal resources. Sites of direct heat utilization are marked with black dots; electric power plants (see arrows) are shown with their total generating capacity, by country, indicated in megawatts of electric power. Figure 2

owe their higher-than-normal temperatures to low conductivity, shale layers and/or exothermic geochemical transformations. The US Gulf Coast and certain regions in Hungary are recognized as potentially valuable thermal-energy sources of this type. Dry-hot-rock hydrothermal systems have more than half of their heat stored in the reservoir rocks, and this heat exists even if no fluids are present. In many places hot rocks exist at shallow depths, but the methods of providing sufficient heat-transfer surface in these rocks and circulating water to extract the heat are only in the stages of initial experiments and development. Los Alamos Scientific Laboratory has been engaged intensively in this area of research for the past four years. Lastly, lava pools and magma chambers are known to be associated with volcanic systems. Access to these regions and injection of a practical heat-exchanger system into them are major problems. Yet these extremely large reservoirs of high-temperature heat are an attractive target and deserve serious research attention. The table on page 41 summarizes all these geothermal reservoir types, their location and potential.

Each resource type has problems associated with its development, some specific to that type, others common to all types. For example, all geothermal reservoirs require well drilling for their exploration, development and production. The fluid-extraction technologies, on the other hand, are quite different—yet even here the surface equipment can be similar, depending most strongly on the desired use, and constrained mostly by the temperature and salinity of the geofluid.

One common feature that all resource types *do* share is that nearly all the elements of each system are capable of improvement or advancement by appropriate materials research.

We could organize the discussion of these materials problems in several ways—by research discipline areas, for example, or by specific resource types and their special problems. Here, my approach will be to proceed through the elements of the geothermal energy system and then take up some special topics. It is important to note that many of the required solutions could affect the economics of the development significantly, provided we note that in this context, improvements (or cost reductions) of 10% are considered "significant" and that a 50% improvement would be judged a "breakthrough."

Exploration

It is suspected that there are still a significant number of hydrothermal reservoirs yet to be found—a small number of additional steam fields and perhaps enough hot-water reservoirs to triple the present total magnitude. The geophysical and geochemical techniques and measurements now used to develop models of the subsurface could benefit from improvement. Even in areas where surface hot springs are present, the results of careful (and expensive) geophysical exploration often leave considerable uncertainty in the (very expensive) decision of where to drill the first exploratory well. The recent application[6] of cryogenic magnetometers, which use extremely sensitive solid-state quantum detectors,[7] has made a significant contribution to the accuracy and flexibility with which electric-resistivity, magnetic and electromagnetic measurements of subsurface properties can be made in the field. This is perhaps a classic illustration of the direct application of a solid-state research result to an improvement in geothermal development.

Measurement, from the surface, of the electric properties of the subsurface rock is a valuable tool in detecting the absence or presence of water contained in rock pores; however, higher-temperature rocks are also lower in resistivity, and therefore the results are not unambiguous. Thus, a need exists for research toward additional geophysical measurements in the field to improve the definition of rock, fluids and porosity in relation to the depth, and at increased resolution.

A complement to these endeavors would be the establishment of improved solid-state models of rocks that would include the influence of the cracks, porosity and contained fluids on the physical properties of multicomponent materials. An essential feature of such research is the establishment of high-pressure geophysics laboratory facilities that can contain large samples, so that grain-size distribution effects are evaluated and transport properties can be measured at conditions simulating those *in situ*. These laboratory data are needed to coordinate the model predictions, which can then be used in the interpretation of field measurements.

Let us move from local exploration needs to a broader research area. It is clear that geological and geophysical research results that provide understanding (on a regional or continental scale) of the thermal and physical regime of the lower crust will in turn yield valuable insights into the terrestrial heat flow on a regional basis. Improved and extensive deep magnetic sounding might be one component of such a study, which should help focus exploration efforts on local regions without obvious surface manifestations of geothermal activity. Such an effort could be especially valuable in prospecting for potential dry-hot-rock reservoirs—hot rocks near the surface with no significant fluid-convection systems.

Drilling

Present drilling-technology limitations represent a major constraint on geothermal energy development.[8,9] Drilling is required for nearly all elements of the work, and may typically constitute around 40–80% of the cost.

The magnitude of the problems in geothermal drilling is illustrated in figure 3, which compares the costs, at 1972 prices, of wells about 1.5 km in depth. Note that Imperial Valley geothermal wells are about twice as costly as oil and gas wells, even though both are drilled in similar sedimentary geological formations. The cost increases are nearly all due to the high temperatures encountered in the drilling.

Several components of the rotary drilling system are affected by the elevated temperatures; corrosion, erosion, early fatigue failures and other life-limiting effects degrade the properties of materials and lead to the higher costs. The approximately four-fold increase in cost shown for The Geysers drilling is partly due to these high-temperature effects, although it also reflects the harder, volcanic rocks and difficult terrain in that field. A considerable incentive therefore exists to provide the improvements in rotary drilling that will increase the efficiency and reduce the cost.

A number of current research and development activities seek to improve various components of the equipment, and the majority of these require materials upgrading to provide improved properties at higher temperatures (generally to about 300°C). Some of the necessary improvements and related materials problems are:

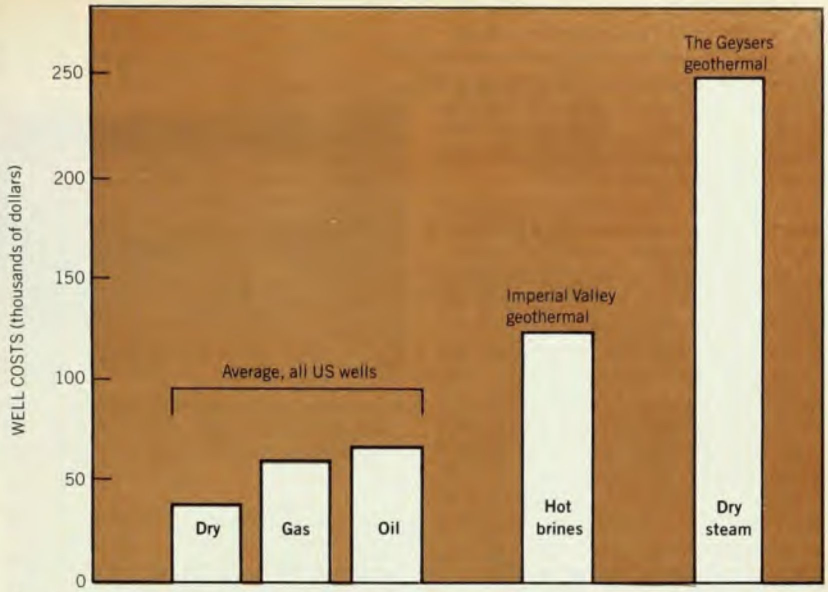
- Making drilling data from the hole available at the surface.[10] This requires rugged transducers, reliable electronics and, especially, satisfactory data transmission to the surface. The downhole components must be temperature- and corrosion-resistant (or protected from the corrosive fluids).
- Improved materials for the fabrication of rotary drill bits and for seals and bearings are needed to increase equipment lifetimes and penetration rates in the hot formations.
- Prevention of drill-string corrosion and metal fatigue is a major problem because drill-pipe twist-offs are common in geothermal drilling and represent a large expense.
- Improved high-temperature rubber-based materials or elastomers are needed for hoses and seals.

In addition to incremental improvements in our present rotary drilling technology, there is also the possibility of exploring advanced methods of drilling. Although many of the rotary-drilling improvements may be expected to come from the results of industrial R&D, the higher-risk longer-term approaches will be initiated by research in universities and national laboratories. Many drilling schemes, using a wide variety of physical and chemical processes, have been proposed as new methods of hole making.[11] Most of these ideas have been restricted to laboratory experiments because a fundamental limitation was discovered, because the method was too difficult to extend to a practical downhole tool or because the expense of field development was too great.

There are some exceptions, however, and three examples may be cited to indicate how materials science has played a role:

Water-jet-augmented rotary drilling If high-pressure jets are included in the bit so that water impinges on the rock face being cut, a considerable weakening effect occurs. (In fact, water jets alone can be, and have been, used to cut rock.) This technique increases bit life and penetration rate. However, the materials of the jets are eroded by the cuttings in the circulating fluid (mud) and so must be made of special materials. In addition, costly high-pressure seals and pumps are needed in the drill string and at the surface. Field tests are in progress,[12] and it seems likely that where an economic advantage is found (such as in very hard formations or in offshore drilling) this technology will be utilized.

Rock melting The Los Alamos Scientific Laboratory has been working (under NSF-RANN and ERDA sponsorship) to perfect a drilling system based upon the fusion of rock.[13] Figure 4 shows the result. An electric heater supplies energy to heat a refractory-metal "bit" (pene-



The costs of geothermal wells, in 1972 dollars, in comparison to typical costs of conventional oil and gas wells. The wells are approximately 1.5 kilometers deep. Figure 3

Types of geothermal reservoirs

Reservoir type	Status of technology	Estimated US resource base (quads*)	Typical sites or regions
Hydrothermal (to 3-km depth)			
Dry-steam	Well developed	100	The Geysers; Larderello, Italy
Liquid-dominated	Developed	3000–10 000	Imperial Valley; Wairakei, New Zealand
Geopressurized (to 10-km depth)	Initial reservoir tests	44 000–132 000	US Gulf Coast; Hungary
Dry hot rock (to 10-km depth)	Extraction and exploration in R&D stage	48 000–150 000	Regions surrounding recent volcanism and those with high heat flow and shallow depth to basement
Magma (to 10-km depth)	Research topic	52 000–150 000	Near surface magma chambers, Hawaii

See US Geological Survey Circular 726 (1975).
*1 quad = 10^{18} J = 10^{15} BTU; equivalent to 270 × 10^6 barrels of oil or 50 × 10^6 tons of coal.

trator) that is thrust into the rock or soil. The search for bit materials (such as molybdenum) to withstand the 1200–1400°C melting temperatures and deep formation pressures, for thermal insulators (such as pyrolytic graphite) and for heater elements (graphites and pyro-graphites) has been successful in part.

Preliminary field tests have indicated that bit lives of over 300 hours are possible, but additional materials improvement could extend this significantly. Such a hole-making tool would be inherently temperature resistant—indeed the performance improves with higher formation temperature—and may prove to be an excellent approach to drilling for deep-lying hot rock formations.

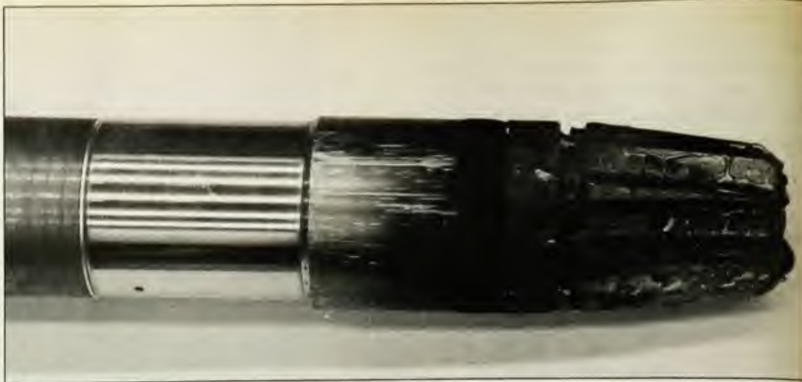
Electric spark disintegration Discharge of a high-energy, high-voltage spark in the mud at the rock interface causes a cavitation "bubble" to impinge on the rock, chipping it away.[14] Researchers at Sandia Laboratories have shown that considerably higher energy can be delivered to the rock with this approach than with mechanical chipping by a rotary bit. Early problems in selecting a suitable electrical insulator were solved, at least for short-time operations, which can be used to perfect and optimize the technique. The method appears to be insensitive to high temperature and therefore holds promise for geothermal applications.

Whether these concepts, as well as others being worked on, can be developed into practical new geothermal drilling systems remains to be seen. But if the technical problems can be solved—particularly in the area of materials—geothermal development (as well as oil and gas drilling) will benefit significantly. The problem of creating a bore hole in deep hot-rock formations is a challenging one, which deserves far more attention than the scientific community has given it until now. Although drilling is a critical factor in geothermal development and might warrant such attention on that basis alone, it is, it should be remembered, a several-billion-dollar-a-year activity in the US; yet it has experienced only incremental progress for the last 25 years.

Reservoirs—natural and manmade

An important element in the development of a geothermal reservoir is flow testing the producing zone in a well bore. Such tests determine the productivity of the field and provide the data to estimate the ultimate economics of the venture. These reservoir-evaluation tests require downhole high-temperature packers (pressure seals), which can be set in the bottom hole to control pressures and isolate separate portions of the formation. Elastomers that will seal into the borehole walls and hold high pressures for extended times are needed for this purpose.

More detailed knowledge of rock properties obtained from the surface geophysical measurements mentioned above would also aid in evaluating the results of the reservoir tests; they would provide a better understanding of the extent and nature of the fluids contained, as well as the size, porosity and permeability of the producing formation at depth.



Rock-melting bit used in making holes in basalt formations. The bit has an electric heater to generate a surface of about 1400 K and flow holes to remove the melt. The part shown in the photo is about 32 cm long. Bit lives over 300 hr are possible. Figure 4

Development of natural hydrothermal reservoirs would be speeded by the introduction of pumps capable of operating efficiently in the corrosive high-temperature downhole environment.[15] Use of such pumps—several types are now under development—will avoid the current practice of allowing a sufficient pressure drop to occur in the well bore so that the superheated water boils ("flashes," as it is usually termed). After pumping to the surface, the low pressure steam–liquid column is led to steam–water separators. The unfortunate consequence of the pressure reduction required to produce boiling is the reduced solubility of certain minerals, mostly the carbonates. As a result they precipitate and often plug the producing formation or the well bore. The development of the needed pumps depends directly on finding or developing suitable materials for the required high-temperature seals and bearings for the downhole motor or turbine-pump drives.

The development of the so-called "dry-hot-rock reservoirs" is in the early stages of field experiments. This concept visualizes "mining" the heat content in hot rock formations that do not have sufficient fluid content, or are otherwise restricted, to support a convecting system. The concept is illustrated by the experimental system under development at Los Alamos, shown in figure 5.

An initial borehole is drilled to a depth where a useful temperature level (about 200–250°C) is reached, and a large hydraulic fracture is produced at the bottom of the hole. We accomplish this by setting packers and pumping in water under sufficiently high pressure to fracture the rock. This results in a vertical crack with a thin cross section, which, however, can be extended outward with continued pumping. After mapping the fracture to determine its size, shape and orientation, we drill a second well in a direction such that it will intersect the fracture in an appropriate location.

Cold pressurized water is then injected into the first well. It sweeps the exposed heat transfer area of the fracture, is heated and finally flows (as a liquid) by the outlet well. The heat is removed by a heat exchanger, and the energy is either used directly or transformed into electricity. Simulation models of such a system[16] indicate that useful "artificial" reservoirs of the dimensions shown will deliver about 100 MW(t) for reasonable lengths of time.

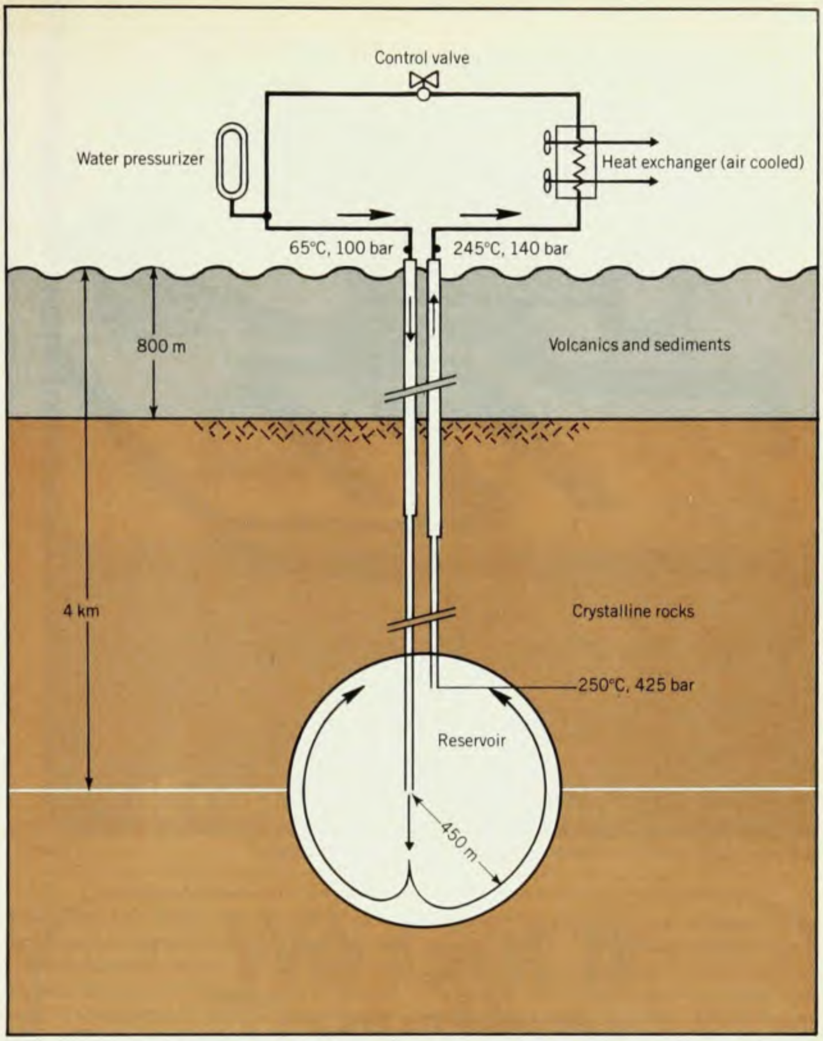
The success of such systems clearly depends upon the development of fracture systems of the sort depicted, which requires an understanding of the properties of the hot rock and its fracture behavior. Our present understanding is quite limited, both in the practical setting and as to appropriate theoretical models of fracture initiation, propagation and stability. Experimental verification of much of the rudimentary theory that has been developed is also lacking. The physical models of how such cracks grow under pressurization, how the *in-situ* and injected fluids influence the propagation, and how the stress controls the direction of fracture have been largely unexplored.

The stability of such a fracture system—Does it grow under prolonged pressurization at levels below that required to produce the fracture?—also needs to be studied. These questions remain unanswered even though hydraulic fracturing of oil- and gas-producing formations is a common commercial practice and has been for many years.

Our approach has been to drill two deep holes about 3 km deep into hot granite (about 200°C) at the site, near Los Alamos, seen in figure 6, and to attempt to produce hydraulic fracture systems. We have succeeded in this endeavor, and are now doing flow and pressurization experiments of the fracture system that we created. It is evident to us that the actual system is more complex than the simple models and theory have predicted. Whether or not we succeed in extracting heat in the next few months, it is obvious that there is need for research into the fundamental processes of rock fracturing if such systems are to be predictable and their development optimized.

We have begun to map the fracture system with downhole acoustic detection packages (geophones), which listen for the microseismic events that occur as the fracture system is expanded under pressurization. This approach is similar to that used to detect the microseismic events preceding rock bursts in mines. While these methods are perhaps adequate for our initial experiments, complementary and more definitive field techniques to determine the extent, shape and character of the fracture systems would be most valuable.

The most commanding and impressive demonstration of the intense heat contained in the interior of the Earth is evidence provided by active volcanos. A large number of imaginative schemes have been proposed to tap this energy. However, practical extraction of the heat from the lava pools left from volcanic eruptions or from the deep magma chambers is a long way off in the future—if it is ever achieved. The most promising ideas[17] appear to be those that envisage the introduction of a heat exchanger into the liquid melt and circulate a heat-transfer fluid in a closed system to a conversion system at the surface. Obviously severe materials-compatibility and -protection problems will have to be solved if the heat exchanger is to survive for any extended period of time. Drilling into the magma will be a difficult and exciting adventure!



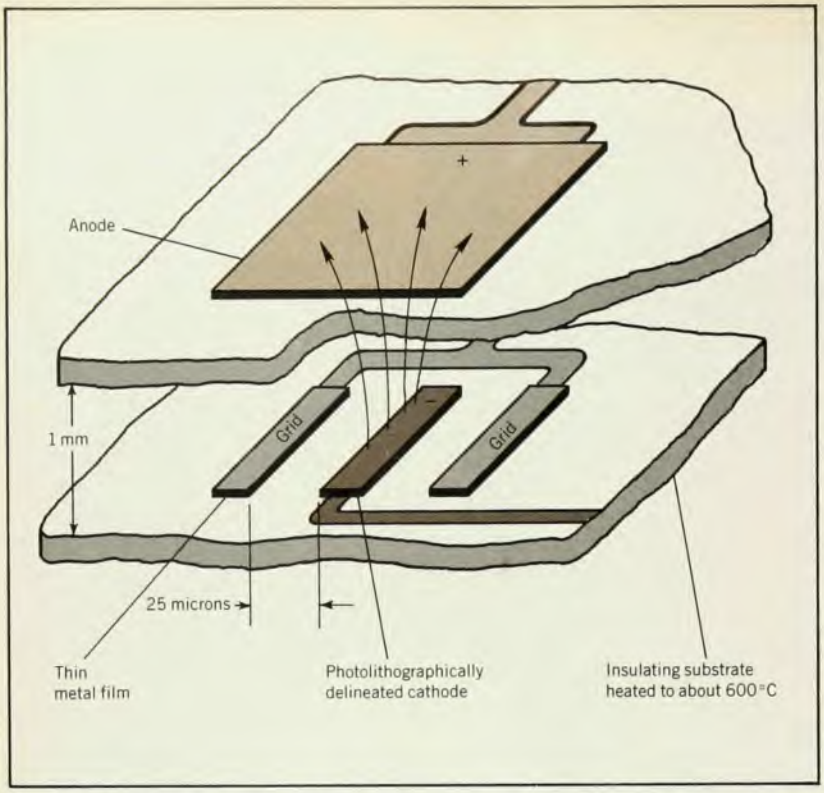
An experimental system developed at Los Alamos for "mining" heat from dry hot rocks. A reservoir, created in crystalline rock by hydraulic fracturing, heats water circulated by a pump through a pressurized, closed-loop system. The temperatures and pressures at three points of the system are indicated. The water flows through at a rate of 130 kg/sec, yielding at the heat exchanger 100 megawatts, which can be converted to electric power or used directly. Figure 5

Site of geothermal experiments near Valles Caldera, N.M. Small drill rig is over the first hole (about 3 km deep); the larger one is in process of drilling the second borehole. Figure 6

Corrosion of surface equipment

The corrosion and scaling problems associated with the use of natural hot-water reservoirs have imposed major restraints on the developments of these potentially large energy sources. Highly saline and mineral-laden brines result from the fact that solubility of most minerals increases with the temperature of the water in the reservoir.[18] Water hot enough to be valuable for commercial exploitation is usually highly mineralized and so is highly corrosive to most common metals that would ordinarily be used to construct surface piping and conversion equipment. Furthermore, the fluids can deposit large quantities of silica, carbonates and other compounds as their thermal energy is removed.

These problems are considerably aggravated when—as in the Imperial Valley reservoirs—the porous rocks of the res-



Geometry of the high-temperature gain device shown in figure 1. Integrated thermionic circuits will have applications in high-temperature geothermal-well logging. Figure 7

ervoir contain very high concentrations of very soluble materials. These brines contain up to 30 percent dissolved solids, by weight. Although corrosion and scaling of boilers, and fouling of sea-water equipment, have been common problems for over a hundred years, research in these areas is still being carried out at a very low level. Although there are some excellent workers in the field, the time-honored solution approaches are still being applied. These involve the testing of the high-temperature-resistant metals and alloys that are commercially available in the specific brine of a geothermal field.[20]

This approach will often find candidate materials—titanium appears to be a favorite choice for the Imperial Valley—but surface equipment fabricated from such materials may be very expensive. It seems almost certain that research effort on the fundamental physics and chemistry of solid surfaces would illuminate much more clearly the mechanisms of corrosion, and sort out the causes of stress–corrosion cracking, pitting and general etching, lower fatigue life and embrittlement.

A recent review article[21] stressed the influence of adsorbed surface-active species at regions of local stress concentration in the fracture behavior of solids. This type of research has clarified to some extent the mechanisms of liquid-metal embrittlement of metals and indicated directions toward the solution of practical problems. It also seems likely that inhibition of the growth to critical size of subcritical cracks in components is possible by appropriately controlling the chemistry of their operating environments. Perhaps more directly applicable to the geothermal corrosion problem would be an adjustment of the metal's surface composition so that, on its dissolution, preferentially-adsorbed, non-embrittling species are formed.

Liquids can produce adsorption-enhanced fracture in nonmetallic-material surfaces and thus facilitate drillability of the crystalline solids in rocks.

In any event, the practical control of corrosion effects by geothermal brines will have a large positive influence on the development of geothermal energy. It is a field of real and worthwhile challenge for R&D scientists.

It is interesting to note that the dry-hot-rock system allows in its operation, conceptually at least, the control of fluid chemistry. This is due to the facts that

- the system is of the closed-loop type,
- the chemistry of the initial charge of water can be controlled and
- the rock–water interaction *in-situ* is a "virgin" situation; that is, the dry hot rock has not been in contact with large quantities of water.

This may mean that control of corrosion, erosion and scaling can be achieved to some extent by surface treatment of the fluid.

High-temperature electronics

Let us conclude this brief overview of materials science needs in geothermal-energy development by an example in which physics has made continuing contributions. That area is in measurement technology, mainly involving electronics. At a recent workshop on "Geophysical Measurements in Geothermal Wells," sponsored by ERDA and the US Geological Survey, held in Albuquerque[22] last fall, representatives of the geothermal industry, well-logging companies and researchers met to define the problems of making measurements in very hot wells. They concluded that the problems are formidable and largely unsolved.

While it is possible to obtain some temperature-hardened sensors, and to temporarily protect—that is, thermally insulate—some signal-conditioning and preamplifying equipment, we really need an array of suitable sensors and electronic components that can survive at 300–500°C for extended periods of time. Los Alamos has initiated research on a solution to the electronics problem,[23] applying a concept first proposed at the Stanford Research Institute.[24] The devices under development, integrated thermionic circuits, utilize integrated circuits fabricated by photoresist processes. These, in conjunction with older vacuum-tube technology, produce a device that is essentially a microminiaturized vacuum tube. The grids, cathodes and anodes are thin refractory-metal films sputtered on to an insulating substrate of sapphire or quartz. The configuration is illustrated in figures 1 and 7.

Even with the development of suitable temperature-hardened electronics, there is still a need to extend the temperature capabilities, develop new ideas and discover new techniques to sense the downhole parameters needed for geothermal well logging and experimental monitoring in their high-temperature, corrosive environments.

Needed: data, devices, ideas

In these times when "crises" in food, energy and pollution are threatening us worldwide, it is a welcome sign when a large group of physicists and materials scientists apply their special knowledge and training to some of the immediate problems that beset us. Many of the large-scale engineering problems of geothermal-energy development can be tackled and solved directly in the field. However, many solutions and economic optimizations may be found by research in the scientific areas sketched above. Certainly, the engineer requires the scientific information, the data, the devices and the *ideas* that the physics community can develop.

The work described in this article was performed under the auspices of the US Energy Research and Development Administration.

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