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GEOTHERMAL ENERGY — AN OVERVIEW

> *There are more things in heaven and earth, Horatio,*
> *Than are dreamt of in your philosophy.*
> *Hamlet, I, v, 166*

Geothermal energy, although not strictly speaking a renewable resource, can substitute for fossil fuel in important applications and can be available for an indeterminate time in the future. Its source is largely the still-hot interior of the earth. Considerable technical difficulty persists, but is slowly being overcome, in geothermal reservoir discovery, in proper engineering of the withdrawal and reinjection wells (for hydrothermal waters), and in the economic application of the heat. By far the most abundant resource available at depths down to 3 km or so is of relatively low temperature, below about 185°F, and thus is basically useful for space heating of commercial, industrial, and residential buildings. Used in this mode, there are some environmental problems to be expected, but none looms of such serious consequence as cannot be overcome with straightforward engineering.

INTRODUCTION

As little as ten years ago who, except for a mere handful of earth scientists, had ever heard of geothermal energy? But now, in sharp contrast the incessant and continual discussion and polemics relating to energy, fuels, and environment have made it, if not exactly a household phrase, at least moderately familiar. People now see geothermal energy as one of our better candidates for new energy technology. Along with direct solar radiation, wind, waves, tides, ocean thermal, and biomass as sources of renewable energy, geothermal will displace its appropriate share of fossil fuels. Although not as obvious and pervasive a source as the sun's rays, geothermal energy technology is a far better proven one. Together then, energy from the earth and energy from the sky represent the two basic legacies from the genius who created the world.

Hot springs, fumaroles, and geysers are as well known as any geologic features on earth since the days of antiquity. About 85 years ago in Italy, near Pisa, an underground steam field was discovered and, after being originally exploited to make boric acid from the boron compounds contaminating the steam, the spewed vapor was turned into a steam supply for the fledgling electrical generating industry. The fields at Larderello are still producing 2.5 million lb[1] of steam per hour for generating 190 MW of electrical power.[2] Other steam systems have been discovered and are driving turbines in the volcanic islands of Iceland and Japan, but the largest natural supply of steam now being utilized surges out of the ground at The Geysers in California, where commercial electric power has been produced since 1960. Here the Pacific Gas and Electric Company currently generates over 600 MW of power (about half the needs of San Francisco) and will expand to probably 1900 MW in the decade of the 1980's. Current usage of steam is 8 million pounds per hour. A complex system of underground faults and fractures is thought to provide deep passageways for water to circulate from the surface down to where it comes into contact with very hot rock and is thereby vaporized and superheated.

Dry steam fields are the exception rather than the rule. More commonly, the geothermal resource consists of a hydrothermal (hot water) system that derives its thermal energy either by conduction from the earth's mantle (the layer between the molten interior — the core — and the "cold" crust), or from an intrusive crystalline granite body (called a "pluton") that contains minute amounts of radioactive uranium, thorium, and potassium and is being heated continuously by the α-particle emission or fission decay of these unstable elements. To the extent that the overlying sediments are porous, contain water, and are permeable, water can be pumped from them. These moderately hot hydrothermal resources turn out to be far more extensive and ubiquitous than the steam fields. Such hydrothermal resources heat buildings in the USSR, Hungary, Iceland, France, and several other countries. Just south of the Imperial Valley of California, in Cerro Prietò, Mexico, a 100 MW electrical generator runs from hydrothermal resources and El Salvador is on the verge of similar installations; so are a number of other countries.

A third, exotic form of energy is stored in the earth in the so-called "geopressured" zones, most prominent in Texas and Louisiana. At relatively great depths (12,000 to 15,000 ft) zones are encountered where the ancient water-rich sediments have been sealed off by beds of impermeable shale. In such zones the pressure has risen to considerably more than the hydrostatic pressure appropriate to that depth, in fact, to the pressure necessary to sustain the total burden of the sediments above. As a consequence the fluid has not only heat energy appropriate to that depth, but also the mechanical energy stored in the excess geopressure. This mechanical stored energy makes a geopressured well risky to drill and unpredictable to develop. Oil and gas drillers intensely dislike a geopressured zone.

One of the most intriguing features of a geopressured well is that it often contains saturated quantities of methane dissolved in the hot saline water. When the fluid pressure is relieved upon well completion, the methane comes out of solution as a gas of pipe-line quality. Amounts up to 70 ft^3 of methane per barrel of water have been observed, but generally the content is between 20 and 40 ft^3. If widespread, this methane itself could extend U.S. gas reserves manyfold.

Finally, the hot dry rock at depth is always a potentially recoverable source of energy. Heat flows continually from the mantle to the surface to be radiated into space. This heat flux is so diffuse, however — an order of magnitude less than the energy from the sun — that it simply cannot be captured and put to use. Some method of storing the heat for long times — eons — is needed to bring both the flux and the temperature to the point where practical use can be made of the energy.

The storage is effected by the relatively low thermal conductivity of the rocks of the earth. Just as in an electrical resistor the voltage rises toward the source of electricity, so in the earth the temperature rises the deeper one goes. The normal temperature gradient (25°C/km depth) suggests that very useful temperatures will be found at quite modest depths (say 2 to 4 km), but frequently anomalies can be found with gradients in the neighborhood of 35°C/km, or even higher. At a depth of 3 km, for example, temperatures well above the (sea-level) boiling point of water (100°C) will be reached. If the rocks are nonporous and dry, they can be cracked in various ways, such as by hydraulic fracturing, and surface water can be circulated through the crack to absorb the stored heat and convect it by natural circulation to the surface. Thus the almost unbelievably huge heat content of the upper basement rock of the earth's crust can be tapped, at least in principle. Since the heat stored in the topmost 3 km of the crust of the United States is 3×10^6 quads (one quad $= 10^{15}$ Btu), in principle a resource base of this type could supply the country's needs for tens of thousands of years.[3] Whether the energy from hot dry rock is economically recoverable is another matter, to which we shall return later on.

Thus, in summary, the geothermal resources in nature consist essentially of:

dry steam,
convective hydrothermal systems,
geopressured systems,
hot dry rock.

This classification[4] implies that the energy extraction is basically different for each. The order in which they are listed also appears to be in ascending order of available energy content, the most prolific resource being the hot dry rock.

BASIC AND SIMPLISTIC GEOLOGY

The interior of the earth is so hot that most matter there is in the molten state, with densities from 10 to 11 times that of water (Fig. 1). "Floating" on this fluid is the mantle, with a specific gravity ranging from 3 to 6. Next lies a relatively thin sliver of rock that has solidified from the melt. The average density of this continental crust is 2.7. Still moving outward, we find what is, on the scale of the earth's size, onionskin-thin layers of detrital material deposited by eons of weathering, that is, by chemical and physical alteration of crystalline rock. This top layer is generally termed "sedimentary." It may also contain remnants of marine plant and animal life. The lower part of the sediments may have been converted by heat, pressure, and geologic time to hard material ("sedimentary rock") and various sequences of

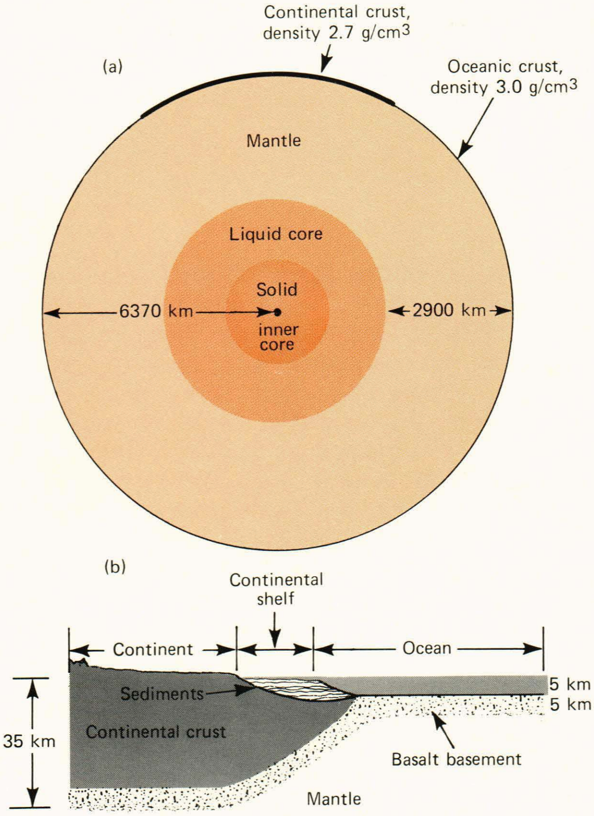

Fig. 1—Crust, mantle, and core of the earth (after Bullard, *Geothermal Energy*, UNESCO 1973).

(a) Schematic cross section. The mantle is composed of a strong lithosphere near the surface of the earth, resting on a weaker asthenosphere. At some 3000 km depth the temperature reaches the melting point of rock, and the interior becomes liquid. Under increasing pressure (millions of pounds per square inch) in the interior, below about 4500 km, the liquid undergoes another phase change and becomes solid. "Floating" on the mantle is a thin (35 km) continental crust and an exceedingly thin (5 km) oceanic crust of sedimentary material.

(b) A cross section through a typical continent-ocean boundary. The continental crust blends smoothly via the continental shelf into the much thinner oceanic crust. The boundary between continent and ocean is covered by successive deposits of sediments, each typical of a distinct geologic era.

heating, cooling, and reheating may have altered this sedimentary rock to form mixtures, foliations, and alterations, termed "metamorphic rock". In an imprecise but visualizable terminology, the metamorphic rock and the older crustal rock (granites) represent the "basement" of the sedimentary layer.

By the inexorable dictate of thermodynamics, heat must flow from the interior of the earth to the cooler surface, where it is conducted, convected, or radiated away. The worldwide average of this normal heat flow is about 1.5 μcal/cm^2-s (or, in the literature, 1.5 HFU [heat flow units]). By contrast, the peak solar flux at the equator is about 0.01 cal/cm^2-s, or 7000 times as much. As mentioned earlier, this geothermal energy flux is far too small to be captured and put to practical use (although essential for the heat balance of the earth). Most rocks are poor thermal conductors. Since the steady state demands equal heat flux per unit area through all layers from the interior outward, elevated heat transport must be associated with higher temperature gradients. Therefore, we look for anomalies in the heat transported upward from below, that is, an area of unusually high and useful temperature gradient. Such places do exist.

The sources of the anomalies, apart from oceanic rifts, in general terms are three: intrusions of magma, that is, granite at a temperature that renders it plastic; frictional heat due to plate interference; and heat generated by radioactive decay (Fig. 2).

In certain regions, magma has floated up along some rift line or through denser material and has settled down and cooled near the surface. Although perhaps tens of millions of years old, its temperature is still significantly higher than its surrounding country rock. Volcanism is an obvious manifestation of a magmatic abnormality; the volcano is essentially a conduit between the surface and the molten material beneath the crust.

Theories of plate tectonics envisage the crust of the earth as subdivided into a number of huge plates that are in constant motion. In some regions one plate dips below another — called "subduction." Although excruciatingly slow on human time scales — rates of the order of a few centimeters per year — the gigantic scale of the frictional resistance of one solid body sliding on another manifests itself as local heating and melting. Consequently an upwelling magma produces an elevated region of heat flow. Finally, the molten state of the interior

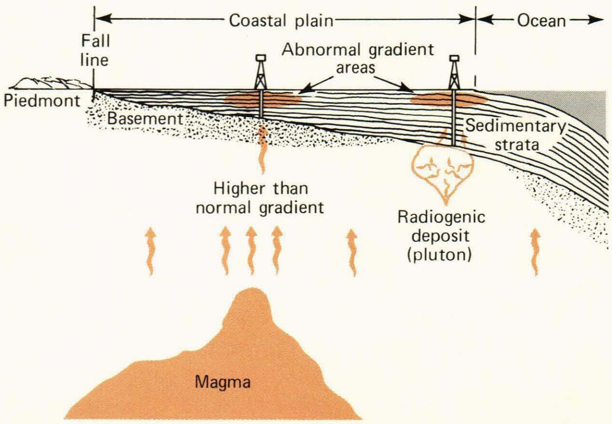

Fig. 2—Concept of a hydrothermal system on the Atlantic Coastal Plain. Eons of weathering of the Appalachian Mountains have laid down successive sedimentary strata on the coastal plain and the continental shelf. The normal heat flux from the interior can be concentrated either by an old magma intrusion (which, in the case of the geologically old eastern region, has probably lost much of its original excess heat by thermal conduction) or by a younger granitic intrusion heated by the decay of minute deposits of radioactive elements.

of the earth, it is generally believed, is maintained by the radioactive decay of unstable elements, notably uranium, thorium, and potassium. It has been established in recent years that certain masses of granite have intruded to near the surface (as the magmas mentioned above) and subsequently cooled off. Containing an excess of up to twenty times the normal amount of uranium, thorium, and potassium found in average crystalline rock, these "plutons" are a local source of heat produced by the radioactive decay of its uranium and thorium (the contribution of potassium is generally ignorable). Although extremely minute (about 10^{-12}cal/gm-s or 4 mW/kg), this energy over millions of years, if suitably insulated by poorly conducting sediments, can lead to rather high temperatures (Fig. 3). From heuristic arguments, Costain has shown[5] that the heat flow at the surface is augmented according to $q = q_0 + DA_0 \exp(-z/D)$, where q is surface heat flow, q_0 is heat flow in the absence of a pluton source, D is the depth of the sedimentary insulating layer, A_0 is the heat production term, assumed to be uniform within the pluton, and z is depth. Figure 3 illustrates a typical case.

Examples of all these locally anomalous heat sources abound throughout the world, but as usual the "log normal distribution of values" prevails: the hotter, more accessible the resource, the fewer in number. Although the anomalies contribute only marginally to the world's total recoverable geothermal energy, the usefulness of a resource with from normal to twice-normal temperature gradient is clear and undeniable.

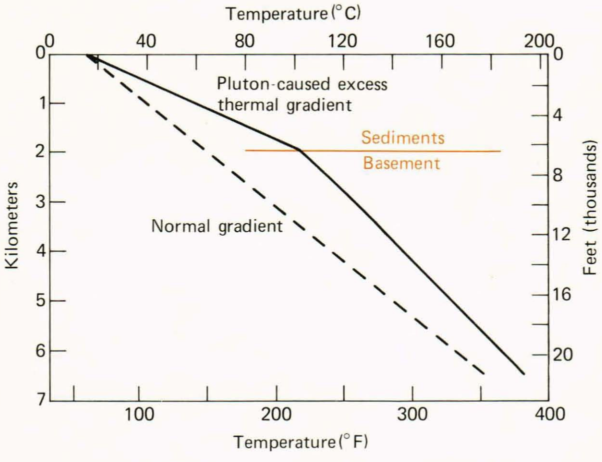

Fig. 3—Calculated temperature above a radioactive pluton (after Ref. 5). The surface temperature is assumed to be 18°C. A "normal gradient" of 25°/km is shown (dashed line). The uniform heat production from radioactive decay is 10^{-12} cal/cm^3-s. The pluton exists in the basement, with assumed thermal conductivity of 7×10^{-3} cal/cm-s-°C at a depth below 2 km and is overlain by sediments with assumed thermal conductivity of 3.5×10^{-3} cal/cm-s-°C. The solid curve gives the calculated temperature as a function of depth. The elevated temperature at a given depth is the basis of keen interest in the existence and location of radioactive plutons.

Another way of classifying geothermal resources is in terms of how the energy arrives at the surface. There are a few dry-steam sources (such as The Geysers); there are mixed steam and water sources (such as Cerro Prieto); there are hydrothermal resources (such as the Paris Basin); and there is hot dry rock (such as on the edge of Valles Caldera in New Mexico). Little or no uncertainty in the future use of dry or wet steam stands in the way of commercial exploitation of geothermal energy. The greatest unknown is how to exploit the ubiquitous hydrothermal resources and thus we shall limit the balance of this discussion mainly to these resources.

TECHNICAL ISSUES

Certain technical issues, none really formidable, confront the widespread employment of the hydrothermal brand of geothermal energy. They include reservoir discovery, reservoir engineering and management, chemical management of hot brines, drilling technology, conversion of thermal energy to electrical energy (where applicable), development of economical heat exchangers, district or community heating/cooling system problems, and environmental issues. Only a few of the more important of these topics will be briefly discussed.

Reservoir Discovery

Without a doubt the most serious technical problem is finding the anomalous heat source. Occasionally a hot spring, a fumarole, or a geyser will indicate subterranean thermal resources, but in the vast majority of cases the existence of a hydrothermal asset or of an anomalous heat production zone must be inferred from indirect indicators. These indirect techniques include: gravity surveys, magnetic surveys, electrical resistance measurements in a variety of ways ranging from 0.01 to 100 Hz, and chemical thermometry. The final proof, of course, lies in drilling and *in situ* thermometry.

The existence of plutons can sometimes be inferred from gravity lows. Intrusive granites are of slightly lower specific gravity than the surrounding country rock (e.g., 2.7 versus 3.2); this shows up as a reduction in the observed acceleration of gravity of from a few to a few score milligals (1 milligal = 0.001 cm/s^2) in a precision gravity survey. Furthermore, there is geologic evidence that magnetite (iron oxide, Fe_3O_4) is often precipitated out preferentially on the boundaries where magma intrusions cool and solidify; this exhibits itself as rings of magnetic highs in precision surveys of the earth's magnetic field. The coincidence of the two (i.e., gravity low, magnetic high) obviously lends credibility to the hypotheses mentioned above and permits some confidence in assigning the term "anomaly." Generally speaking, to be economically useful, the source location needs to be one to a few kilometers below the surface since the sedimentary or alluvial cover must be thick enough to insulate the source sufficiently for the temperatures to rise to economically attractive values.

In the case of hydrothermal resources, the deeper they are, the more saline or ionic they are in general, and the electrical conductivity is noticeably affected. When a bounded volume or stratum possesses sufficient porosity (say 15%), the resistivity is substantially lower than that of surrounding rock (say, 1 versus 10 Ωm). The most effective indirect measurements of the electrical conductivity of deeply buried strata come from the so-called "magnetotelluric" techniques. Natural sources of electric energy (lightning strokes) provide vertically descending electromagnetic waves of frequencies from 0.01 Hz upward. Large coils, sensing the magnetic field on the earth's surface, see the combined effect of the incident field and the secondary field scattered by a buried conductive body. With considerable manipulation (and uncertainty) a conductivity model that gives a measure of the extent and quality of the resource can then be adduced.

Another advantage can be taken of the high salinity of deep hydrothermal waters. The relative concentration ratio of several ions (sodium/potassium, for example) is related to the temperature, as is also the fraction of dissolved silica. If evidence of a resource reaches the surface by virtue of a spring, for example, analysis of the water can imply the temperature at depth.

Correlating with the techniques described above, and generally superior to them, the most reliable indication of a true source is to measure the thermal gradient itself. For this purpose, a technique that has been pursued by the Virginia Polytechnic Institute and State University is currently in favor. Typical plutons on the East Coast of the United States are about 10 to 20 km in extent. Slim holes are drilled where other information (gravity, magnetic, geologic) suggests that plutonic intrusions with elevated radioactive content may occur. These so-called gradient holes are cased and cemented to a depth of about 1000 ft and allowed to come to equilibrium, whereupon a temperature log is run to an accuracy of a millidegree. At the time of drilling, a core (or cores) is taken, sliced into cylinders, and the thermal conductivity of the rock measured in the laboratory. A variety of rock types — arising from compaction, metamorphism, intrusion, etc. — is found, and the temperature correlates usually inversely with the thermal conductivity, as it should unless unsuspected convection is taking place. From the two measurements, temperature and thermal conductivity, heat flow is calculated from $q = k\nabla T$, where q is the flux of heat, k is the thermal conductivity, and ∇T is the temperature gradient. Identifying high values of q (or ∇T) lends strong confirmation to the idea that an anomalous heat source exists below. Worldwide "normal" temperature gradients run 20 to 30°C/km; gradients of superior interest for geothermal energy in the eastern United States run to 40 to 60°C/km (Fig. 4), while extraordinary gradients, up to 200°C/km, are found in rare cases (Iceland, El Salvador, etc.). The boundary between normal gradient and "hot dry rock" is hazy, but is now conventionally taken to be 40°C/km. The desirability of high gradients is obvious: the highest available temperature in a hydrothermal zone is obtained at the greatest depths, down to the basement rock. Thus $T_{max} = T_0 + (\nabla T \times D)$, where T_0 is the surface temperature and D is depth to basement. The basement depth is generally a slowly varying function of the local geography, whereas an anomalous ∇T is found only in restricted local regions. More generally, the higher ∇T, the less drilling is required to reach a desired temperature.

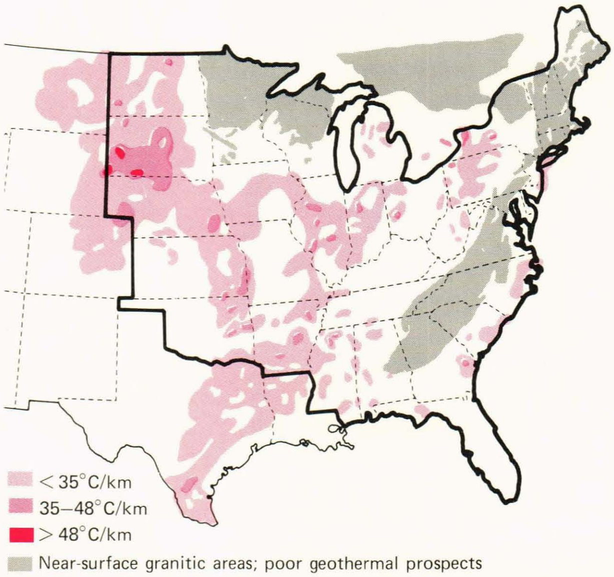

Fig. 4—Potential resource areas in the eastern United States (from geothermal gradient maps of the American Association of Petroleum Geologists and the U.S. Geological Survey).

While an above-average temperature gradient might support a strong case for a hot dry rock installation (see below), it does not of itself guarantee a useful hydrothermal resource. Thermal power (often expressed as Btu/h) = $\dot{m}\Delta TC_p$, where C_p is the specific heat of water, ΔT the temperature difference between the source and sink, and $\dot{m}$ is the mass rate of fluid production. In practice, therefore, large amounts of water are needed. Whether or not the quantities are adequate is connected with the porosity of the medium, the permeability (or resistance to flow), the confinement or extent of the water-bearing stratum (the "aquifer"), and the natural pressure exerted by either the weight of the overburden or the hydrostatic head (if the aquifer reaches the surface at some distant horizon), or something intermediate.

Reservoir Engineering and Management

Of most significance, but as yet only rather poorly understood, are the intricacies of hydrothermal reservoir engineering and management. The discussion to follow is somewhat simplistic in order to point up the issues of importance. However neither the technology nor the interpretation of data is by any means simple or predictive. In short, geothermal reservoir engineering and management is emerging as an exacting technical discipline, where substantial improvements can be expected in the near future.

Reservoir Engineering — As has been stated earlier, the geothermal aquifer is characterized by geometrical boundaries — pinchouts, where it comes to an end; fault zones, i.e., rock displacements that may be fluid conduits; impermeable layers — and by such physical parameters as porosity (or interstitial fluid content), piezometric head (the driving pressure), transmissivity, and permeability. (The last two terms are intimately connected, as mentioned below.) Porosity is defined as the fraction of the consolidated material (by volume) occupied by water; typical values of interest run from 10% in competent (hard) rock to perhaps 25% in sandstones and limestones. The deeper one goes, in general, the lower the porosity, as the lithostatic pressure compacts the rock lattices and expels the fluid. One should recall in this connection that at, say, 3000 m depth, the lithostatic pressure may be as high as 15,000 lb/in^2 or, if there is access to the surface, the hydrostatic pressure may be greater than 4000 lb/in^2.

The piezometric head is nothing more or less than the hydrostatic pressure in an unconfined aquifer (one with access to the surface) or the lithostatic pressure, if completely confined. Artesian wells are those where the piezometric head exceeds the hydrostatic pressure at the well outlet, so that they flow freely. In general, artesian wells are scarce, occurring where a recharge area exists in neighboring hills or high ground. Most wells must be pumped to bring the water to the surface.

The permeability of a medium is directly related to the transmissivity and has an engineering definition (Darcy's Law) which states that $v = -D\nabla p$, where v is the volume flow rate through a cross-sectional area A, ∇p is the average pressure gradient, and D is the Darcy constant. (Note the similarity to Ohm's Law.) For v in cm^3/cm^2-s and p in atmospheres, D (which is a measure of permeability) is denoted as "darcys." Darcy's equation is an empirical one, related to viscous flow in small channels. (If $v = 1$ cm^3/cm^2-s and $\nabla p = 1$ atm/cm, then $D = 1$ darcy for water at 20°C, where its viscosity is 1 centipoise.) The term D is physically given by k/η, where k is the permeability of the medium, and η is the viscosity of the fluid. Typical values of D run from 10 to 20 millidarcys in semi-hard rock, to several hundred millidarcys in permeable sandstone, and up to darcys in limestone.

The maximum rate of withdrawal of water, therefore, depends primarily on the permeability of the aquifer and the pressure available (piezometric head), augmented by the pressure applied by either a downhole or a surface pump. At equilibrium the resulting effective source of the fluid becomes in the ideal case an inverted hyperbolic cone of revolution with the well bottom at the apex.[6] The depth of the apex of the cone at the well below the static water surface is called the "drawdown" and physically it is the level at which the fluid stands in the well while fluid is being withdrawn. Figure 5 illustrates the point. If the drawdown is high (at a given rate of withdrawal), then the downhole pump must be sized for considerable lift. (Pumps of 100 to 400 horsepower are by no means uncommon in large, deep wells.) If the drawdown increases with time, the only solutions are to increase the depth and power of the pump or to decrease the rate of withdrawal. Therefore the drawdown of the well is a critical engineering parameter.

Permeability and porosity data are generally obtained from core sampling as the well is drilled. Additional formation data on these quantities *in situ* come from well-logging, a complex subject in itself that we have insufficient space to discuss here.[7]

The drawdown data are derived from permeability data by means of pump tests (Fig. 6). In principle, if one pumps a well at a constant rate of water flow, the level of water in the well will initially fall, approaching an equilibrium value. If pumping ceases, the well will recover, that is, the water will rise in the well. Both the rate of recovery of level and the rate of fall are directly related to the permeability of the aquifer (or to the transmissivity, which is the permeability multiplied by a

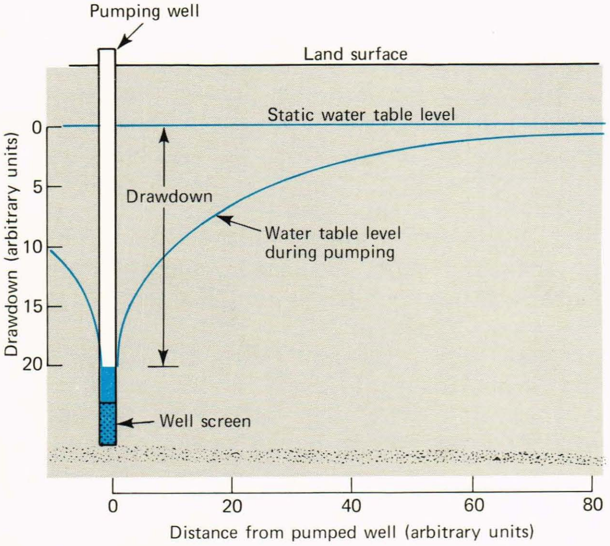

Fig. 5—Typical drawdown during pumping of a water well. The water table level becomes ideally a hyperbolic cone of revolution asymptotic to the static level. The drop in the water level during pumping, called the drawdown, is a function of the porous water-bearing formation parameters and the rate of water withdrawal.

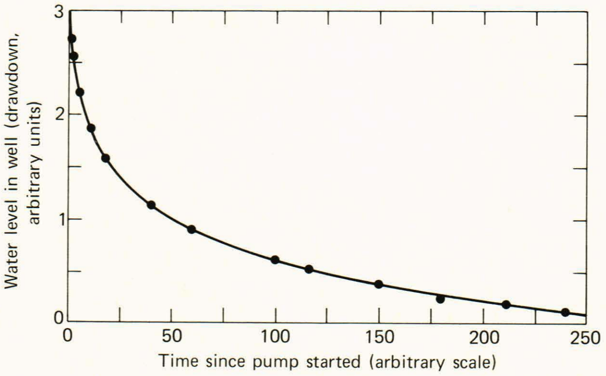

Fig. 6 —Typical pumping test data. Water is withdrawn from the well at a constant rate. The drawdown is initially small but increases with time, eventually approaching an asymptotic limit (for an aquifer of infinite extent). The formation transmissivity and storage coefficient can be obtained by adjusting the porous medium parameters in a model of the aquifer to match the observed curve.

geometric factor to account for the size of the water-producing stratum). With more-or-less complicated models of the reservoir (derived from geological, seismic, or electromagnetic surveys, from similarity to neighboring aquifers, and from intelligent intuition), a fairly satisfactory set of reservoir parameters useful for reservoir management can be derived.[8]

Reservoir Management — Given that the reservoir model is accurate, then reservoir management is not a difficult task. There are two aspects. First, the withdrawal rate must be controlled so that the lifetime of the reservoir is compromised neither by reduction of water flow nor by reduction of temperature (see below). Second, since after use the water withdrawn from the well must, in general, be reinjected somewhere else for environmental reasons, the reinjection stratum must be chosen geographically[9] so that the chilling thermal pulse from the (relatively) cool reinjected fluid does not intersect the producing reservoir until some span of time, perhaps 25 to 50 years. Recalling that the migration of the cool water from reinjection point to production point usually involves some reheating by conduction from the country medium through which it passes, one has a nice, but soluble, problem in convective/conductive heat flow.[10,11] Reservoir management largely revolves around this solution, in making enough and proper measurements to keep up-to-date. The references are recommended to those who wish to delve further.

Reservoir Quality — A word should be said about the quality of the reservoir. First and foremost, of course, the quality of a reservoir is a strong function of its temperature. The First Law of Thermodynamics yields an inadequate measure of temperature "quality," namely, the number of Btu's per unit mass per unit time available from the hydrothermal resource. It is a measure of the ability of the resource to supply heat irrespective of the temperature at which it is used. The Second Law of Thermodynamics, however, assigns great value to large temperature differences, providing a measure of the capacity of the resource to do mechanical work or generate electricity. Thus the temperature of the resource plays a dual role: it measures the energy available, and it also determines what use can be made of it. In general, generation of electricity is not attractive for geothermal resources below 150°C.

A totally different aspect of quality of the well output relates to the dissolved gases and solids. Usually the deeper the source, the hotter the fluid and the higher the pressure. Consequently, from extensive and lengthy leaching and eroding processes, considerable amounts of gases and salts are dissolved in geothermal water. Indeed the generic term for geothermal water is "brine," virtually a chemical storehouse with a host of elements in varying concentrations. The dissolved sodium chloride and calcium chloride content may vary from very little up to over 30% dissolved solids. In addition, dissolved silica is always present in granitic formations.[12] When the brine reaches the surface or at the flashing point below the surface, the sudden release of pressure often causes deposition of hard scale on pipes, valves, and fittings. This can be extremely awkward since in time openings become clogged and useless. Furthermore many waters are extremely aggressive (i.e., corrosive) and mercilessly attack common metallic surfaces. However, with proper care as to where and when the pressure is released, and with due regard to choice of materials, the problems due to scaling and corrosion can be managed; this has been satisfactorily demonstrated in a number of installations in Iceland, Hungary, France, and elsewhere.

The "noncondensible" gases that come out of solution, notably hydrogen sulfide, can be objectionable even if concentrations are so low as not to present a hazard to health or to the integrity of the geothermal installations. Commercial methods of sulfide scrubbing, if necessary, are available; consequently these noncondensible gases need not present insoluble problems.

Environmental Problems

In addition to the problems enumerated in the disposal of brine and the control of noxious gases, two other environmental issues must be dealt with. One is the noise that often is associated with the well discharge, particularly when and if it flashes to steam. This is handled in a straightforward (albeit somewhat expensive) way by properly designed noise mufflers.

The other is the question of subsidence.[13] If fluid that supports in part the lithologic overburden is removed, will the rest of the column consolidate and thus result in surface subsidence? This question commands considerable attention in the form of basic and applied research, particularly at the University of California and at the University of Texas, and it is still not totally resolved. In most formations, the best current opinion is that the magnitude of subsidence will be slight, particularly if the effluent is reinjected into the same formation. That is, in time the pressure will redistribute itself with only little effect on the surface.

Electric Usage

The principal use of geothermal energy in the United States and elsewhere up to now has been the production of electricity. The Larderello field has been producing electricity since 1904. The Geysers has been supplying the Pacific Gas and Electric Company experimentally since 1925 and commercially since 1960. Technically these dry steam fields produce moderately superheated steam (at a pressure of 110 psi) and drive turbogenerators of conventional type.

At a number of other locations — Cerro Prieto, for example — a mixture of low-pressure steam and water introduces the added complexity of separating the steam from the water, which is about 70% by weight. Generally the separation is effected by a centrifugal device that drives the water to the periphery and ejects the dried steam from the center. From there on, the technology is quite conventional except that the low superheat requires the resurrection of bulky turbogenerator designs reminiscent of the earlier part of this century.

Next in order of desirability for electricity generation are hot-water systems, generally between 200 and 300°C. The geothermal fluid remains in the liquid phase until the pressure is relieved at some point below the surface, whereupon it suddenly flashes into steam. This presents some minor engineering complications in the generation of electricity. Single flashes or several flashes at progressively lower temperatures and pressures may be used. Alternatively, the geothermal fluid may be used in a heat exchanger, while kept under pressure so as not to flash, thus avoiding all the problems of scaling associated with pressure release. The geothermal heat energy is imparted to an auxiliary fluid of low boiling point. A typical auxiliary fluid is one of the many halogenated hydrocarbons (Freons) whose boiling points are well below that of water. Consequently considerable superheat can be achieved at the temperature of the geothermal fluid. It would take us too far afield to discuss the temperature-entropy diagram and operating points of such "binary-cycle" systems.[14] Suffice it to say that experimental cycles are being tested in the Imperial Valley of California and at Raft River, Idaho.

Many new technical problems emerge as a consequence of using a high molecular weight substance as the working fluid: for example, the efficiency of heat exchangers poses difficult technical questions, to the point where a large program to investigate direct-contact heat exchangers (fluid-to-fluid) has shown promise.[15] There is much yet to be learned, however, about the practicality of both flashed and binary electrical systems.

Direct Use of Geothermal Energy

As one descends the scale of quality, the nonelectric, or direct, use of geothermal energy becomes dominant. What these lower enthalpy fluids lose in "quality," they must make up in quantity. By far the greatest potential use of accessible geothermal energy is at a temperature well below that necessary for efficient conversion to electricity. In common with other mineral resources, it is conjectured that geothermal resources are distributed worldwide in a more-or-less log-normal fashion. That is, the abundance of any resource as a function of its quality (temperature, concentration, etc.) takes the form $\log A \cong \exp(-cQ^2)$, where we denote abundance by A, quality by Q, and c is a constant. The larger Q, the less the abundance, and the drop-off is precipitous. Thus major attention should be paid to the exploitation of these relatively easy-to-find, but relatively low-temperature, geothermal resources, leaving the few high quality resources for production of a high quality end-product, namely, electricity. Figure 7 conveys an idea of the distribution of usage of resources of various quality. It is remarkable how the low temperature usages dominate.

Heating and Cooling

More than 25% of all energy consumed (or transformed) in the United States is used for heating and cooling residential, commercial, and industrial space. It is obvious that relatively low quality heat is involved. Seldom are buildings heated with air above 120°F or water above 160°F. Air-conditioning by the absorption process (ammonia is used commercially, lithium bromide occasionally) can be accomplished at temperatures from 150 to 200°F. It is extravagant of Nature's bounty to use such superior, high quality fuels as oil, gas, or coal, each of which is perfectly capable of melting iron or steel, for such lowly tasks as heating or cooling.

It is in space conditioning, therefore, that geothermal energy can well find eventually its greatest practical application. The Icelanders heat the entire city of Reykjavik by geothermal energy; the Hungarians provide heat for hospitals, apartments, greenhouses, and thermal baths; in France, upwards of 20,000 apartment units are already heated by water from the hydrothermal aquifer of the Paris Basin. In years gone by, Klamath Falls in Oregon heated several hundred houses by geothermal energy, since displaced by artificially cheap natural gas. Recent price escalation has prompted a resurgence of interest and of activity in once again heating by geothermal means.

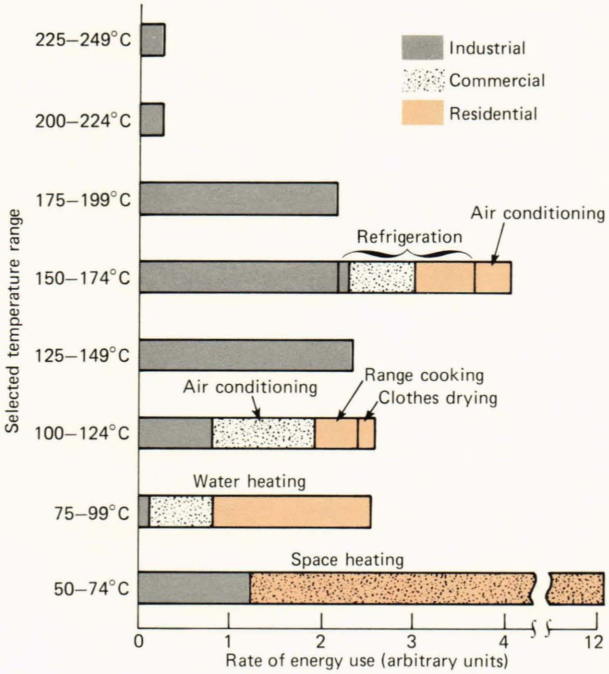

Fig. 7—Most heating fuel usage below 125°C provides heat at comparatively low temperatures. Over one-half of all heating fuel used in the United States generates temperatures below 75°C. Above 125°C, the bulk of the fuel is used in industrial processes. (*Proc. Second United Nations Symp. on the Development and Use of Geothermal Resources*, May 20-29, 1975, p. 2163.)

In principle, the technology is simple. The geothermal water may be used directly in the radiator system of the building, as is done in Hungary, or a heat exchanger can serve to distribute properly treated and controlled water, while the aggressive geothermal water is returned to the ground. Figure 8 is a schematic illustration of the latter system. Cooling by the ammonia absorption cycle, for example, can be accomplished by introducing a water solution of ammonia into the circuit (Fig. 9). The geothermal energy is used to distill pure ammonia from solution; the enriched ammonia solution, under pressure, is piped to the air conditioner heat exchanger where its temperature is lowered by Joule-Thomson expansion. The ammonia gas, after absorbing heat from the heat exchanger, is returned to the still, mixed again with water, and the heat dissipated by a wet or dry cooling tower; and the process is repeated. To date, however, we know of no such geothermal cooling installations, but the process is clearly commercially viable (as practiced in the once-popular gas refrigerator). Sooner or later, as the economics warrant, this or a similar process will find its role.

Introduction of heating and cooling by geothermal energy depends entirely on the economics of the total system, as will be discussed in the accompanying article. To anticipate here, however, it appears that the geothermal heating of individual residences is unlikely to happen unless they are connected as part of a district heating system, much as is done in Sweden to dispose of the waste heat from electricity-generating plants. In such a case, the large expense of the well(s), of the reinjection well(s), and, above all, of the piping system for distribution is spread over a substantial number of users, as well as over typical periods of twenty or more years. In such cases, the costs may well be affordable. For high density complexes, such as industrial plants, condominium units, and the like, direct use of a geothermal well appears promising, even today.

SUMMARY

It is becoming increasingly clear that geothermal augmentation of United States energy resources could be a reliable, non-polluting, domestic asset of great value. While it is unlikely that these resources will become a major contributor to United States energy self-sufficiency before the end of this century, there are regions, conspicuously California, where both steam and hydrothermal energy from the ground can make substantial inroads well before that time.

In the East, however, the going will be slower and will depend on commercializing hot water in the 60 to 120°C range. To the extent that enough is found in juxtaposition to population or industry load centers, it is very likely that these resources will eventually penetrate space heating/cooling and industrial process markets as they become economically viable. However, Federal demonstration projects will undoubtedly be required to establish that

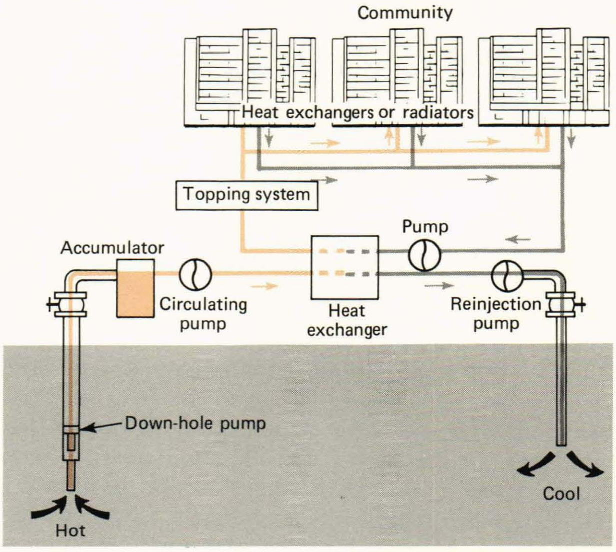

Fig. 8—Community heating by a hydrothermal resource. Two water loops are employed because geothermal water is generally too aggressive to circulate in the community. Geothermal water from a well is passed through a heat exchanger to heat the secondary loop and is reinjected into the same or a different aquifer. Ordinary treated water in the secondary loop circulates the heat through the community. Another heat exchanger or conventional hot-water radiator provides heat to each residence.

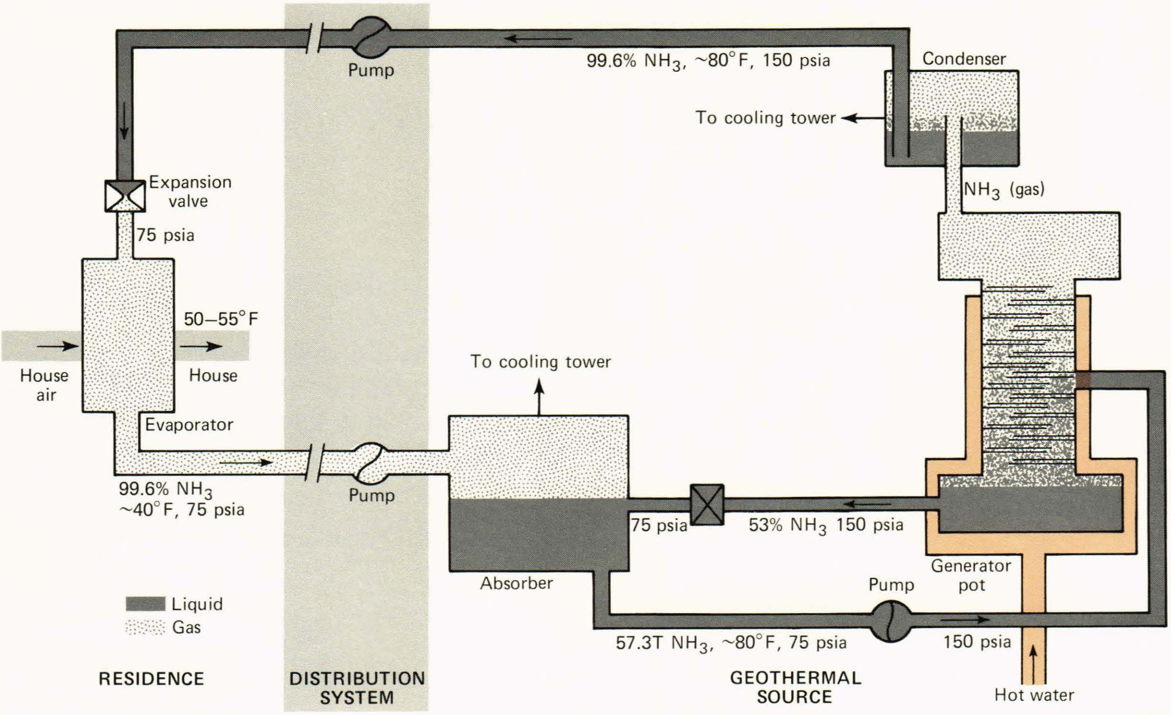

Fig. 9—Concept of a geothermal-driven cooling system. Ammonia liquid, expanding through a nozzle, cools rapidly and is used commercially in ice-making machines. As the text describes, this property can be combined with the distillation of gaseous ammonia from an ammonia-water solution by geothermal heat to form the building cooling system here illustrated.

the technology is relatively risk-free, to develop a commercial, technical, and financial infrastructure, and to promulgate reliable cost figures. Once these three areas of uncertainty are dealt with, and adequate state laws and regulations are enacted, the twenty-first century should dawn on a sound geothermal industry which will help to keep us warm in winter, cool in summer, and wash our pots and pans.

REFERENCES and NOTES

[1] We adopt in this paper the mixed units that are conventional in geothermal literature, e.g., "lb" for weight, "Btu" for thermal energy, etc. To use SI (or other) units consistently would impede the ability to compare or dispute any statements made here with other publications in the field.

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