Chapter 2
The Enormous Potential for Hot Dry Rock Geothermal Energy

The concept of hot dry rock (HDR) geothermal energy originated at the Los Alamos National Laboratory. In 1970 it was proposed as a method for exploiting the heat contained in those vast regions of the earth's crust that contain no fluids in place—by far more widespread than natural geothermal resources (HDR represents over 99% of the total U. S. geothermal resource). Although often confused with the small, already mostly commercialized hydrothermal resource, HDR geothermal energy is completely different from hydrothermal energy. Whereas hydrothermal systems exploit hot fluids in place in the earth's crust, an HDR system[1] recovers the earth's heat via closed-loop circulation of fluid from the surface through a man-made, confined reservoir several kilometers deep. The technology bears little similarity to that of the hydrothermal industry, and unlike hydrothermal, it is applicable almost anywhere—hence the claim that HDR is ubiquitous.

The present-day concept of an HDR geothermal system has evolved considerably from the concept proposed by Bob Potter in 1970 and described in the original U. S. patent (see Chapter 1). As shown in Fig. 2-1, a first borehole is drilled and used for hydraulic pressurization of the naturally jointed basement rock—opening flow paths in the sealed rock mass. The reservoir of circulation-accessible hot rock thus created is then accessed by two production boreholes, drilled into the ends of the elongated reservoir region.

This current HDR concept also recognizes features of the earth's deep, hot crust that were not well understood during the early years of the HDR Project. It is now known that

- The deep crystalline basement is not homogeneous and isotropic, but is highly flawed—on a scale covering many orders of magnitude: from microcracks of a millimeter or so to an interconnected network of joints measuring a few centimeters to several meters, to faults extending tens of meters to several kilometers.
- Whereas open joints and faults are typical in the shallow, cooler layers of the earth's crust (to a depth of about 1 km), the joints and faults in the deep basement will typically have been resealed by the precipitation of secondary minerals dissolved in the hot, circulating fluids. Invariably then, the only open flaws in the basement are the microcracks[2]—except in regions that have undergone recent faulting or folding.

[1] The term "HDR geothermal system" typically refers to the *pressurized, closed-loop circulating system*, consisting of the HDR reservoir, the injection borehole, the production borehole(s), the surface piping, and the injection pumps.

[2] Evidence for these open microcracks in the earth's crust is given in Kowallis and Wang, 1983; Simmons and Richter, 1976; Swanson, 1985; and Wang and Simmons, 1978. The pervasive array of fluid-saturated microcracks gives rise to the finite, but very small (nanodarcy range), permeability of the crystalline basement.

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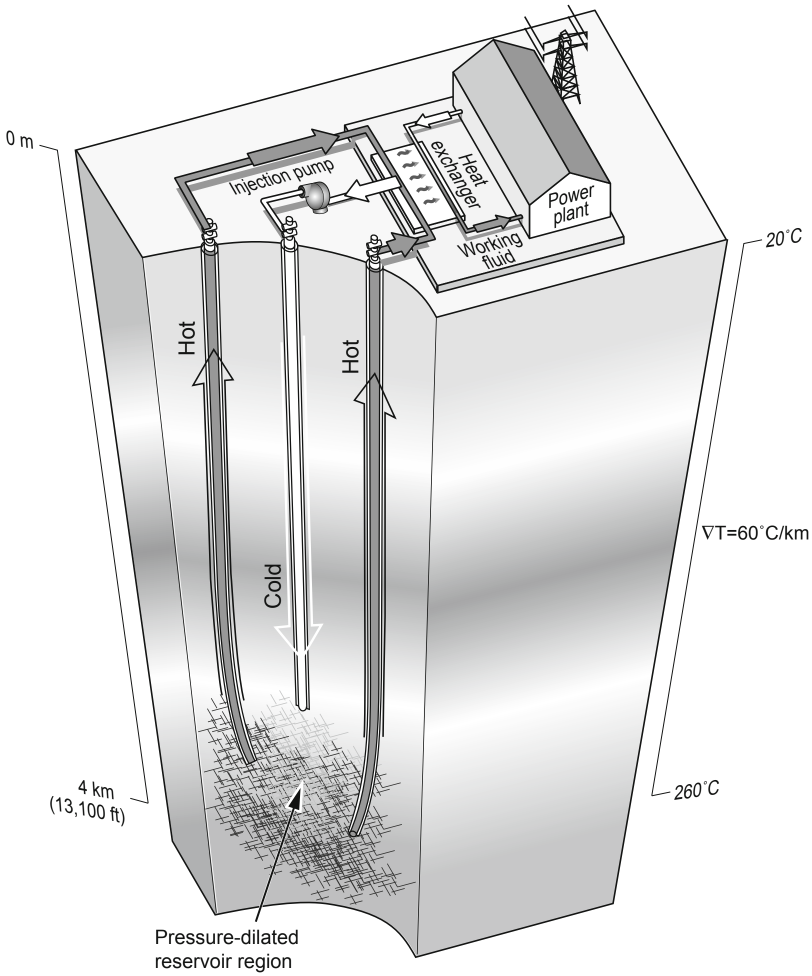

Fig. 2-1. Present-day conceptualization of a closed-loop HDR system.
Source: HDR Project files

- It is the network of pre-existing joints in the crystalline basement that ultimately controls the deformation of the rock mass during hydraulic stimulation. These joints, resealed by mineral deposits, are still more permeable than the adjacent rock and open at much lower stimulation pressures than those required to fracture the adjacent rock. As the network of pressure-dilated joints is extended and these joints intersect other joints, they appear to be terminated (truncated) by the intersected joints rather than to cross them. At the intersections, the high-pressure fluid in the extending joints will be diverted into the truncating joints, forming a dendritic pattern of interconnected joints.

Because the greatest portion by far of the earth's deep, hot crust is essentially sealed, it is available *only* for HDR development. Invariably, therefore, an HDR reservoir would be developed within a previously sealed rock mass and would remain totally surrounded by sealed rock.

Between 1974 and 1995, two separate HDR reservoirs were created in deep, hot crystalline rock, extensively studied, and then flow-tested for almost a year each. These experiments took place at the Fenton Hill HDR Test Site in the Jemez Mountains of north-central New Mexico, about 20 miles west of Los Alamos. The "Phase I" and "Phase II" reservoirs were created at depths of 2700 m and 3600 m, and temperatures of 180°C and 240°C, respectively. During the flow testing, thermal power production ranged from 4 MW for extended routine production intervals to as high as 10 MW for one 15-day period—proving beyond a doubt that it is technically feasible to recover useful amounts of thermal energy from HDR. To the authors' knowledge, these are still the only true HDR reservoirs created anywhere in the world. (As discussed below, the open reservoirs created in Japan, England, Europe, and Australia do not meet the criteria for HDR.)

Of the many insights gained during the creation and flow testing of the two HDR reservoirs at Fenton Hill, the most profound are these two:

1. **An HDR reservoir is confined**. This means that except for a small—and slowly decreasing—pressure-dependent diffusion of fluid from its boundaries, the reservoir of pressurized fluid is totally contained.
2. **An HDR geothermal system is fully engineered.** By "fully engineered," we mean that every aspect of the system—including the injection and production wells, the HDR reservoir, and the pressurized flow system—is engineered (as opposed to those partially engineered systems that are based on the pressure-stimulation of an existing, but unproductive or only marginally productive hydrothermal region). The central component of the HDR system is the man-made reservoir, which is created in an essentially impermeable region of hot crystalline rock through the use of hydraulic stimulation methods to open, pressure-dilate, and extend a network of pre-existing sealed joints.

These two key insights are discussed in more detail below.

The Magnitude of the HDR Resource

It has been pointed out in several recent publications (e.g., Tester et al., 1989a; MIT, 2006) that the HDR geothermal resource represented by the vast regions of hot rock at accessible depths in the earth's crust far exceeds that of the combined total of the world's fossil energy resources. Figure 2-2, in which various major energy resources are plotted on a logarithmic scale, shows that the potential energy supply from HDR is exceeded only by that from fusion energy (and it is still not known whether the latter will ever be developed for commercial power generation). In the case of HDR geothermal energy, the technology has already been proved via the two successful field demonstrations at Fenton Hill.

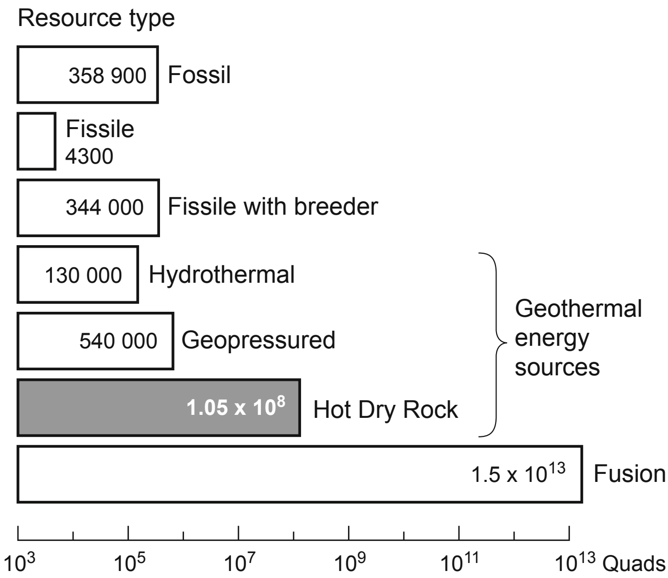

Fig. 2-2. Estimates of the worldwide resource base for geothermal and other energy sources.
Adapted from Armstead and Tester, 1987

Figure 2-3 presents a simplified geothermal gradient map for the U. S. Obviously, rock at temperatures suitable for a commercial-scale HDR power plant (generally recognized as above 150°C) is typically found at shallower depths in the western part of the country; but with the maturing of the HDR industry, most parts of the U. S. will become available for HDR development. In contrast to the very limited hydrothermal resource, therefore, the HDR resource can be considered essentially *ubiquitous*.

The size and distribution of the U. S. HDR resource are adequately discussed in two recent publications: *Assessment of Moderate- and High-Temperature Geothermal Resources of the United States* (USGS, 2008) and *The Future of Geothermal Energy* (MIT, 2006). Suffice it to say that the HDR resource is so large as to almost trivialize a discussion of its quantitative size. HDR researchers over the next 20 years will look back at the pioneering work done at Los Alamos National Laboratory and ask only why it took so long for the country to finally discover HDR.

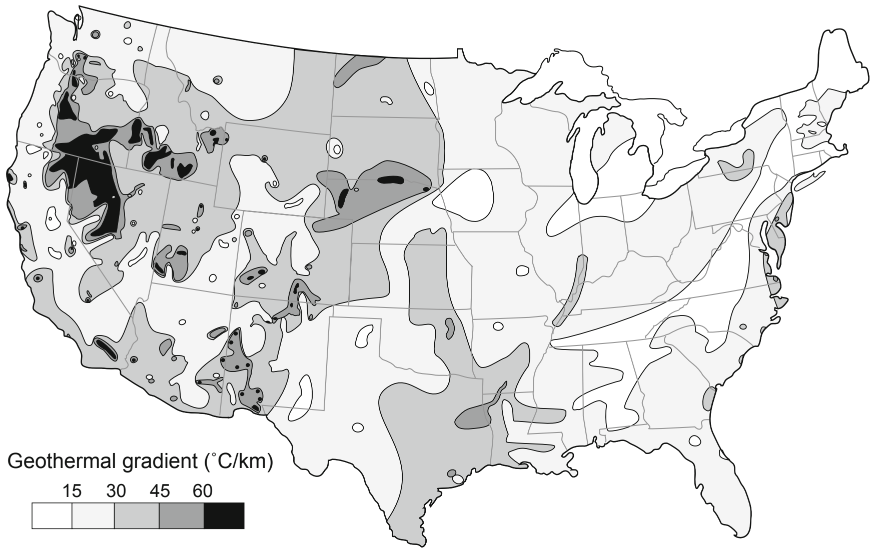

Fig. 2-3. Geothermal gradient map of the U. S.
Source: Kron et al., 1991

Properties of the Deep Crystalline Basement as They Relate to HDR Reservoirs

The Permeability of the Rock Mass

The essential feature of an HDR reservoir is that its permeability is man-made. How the reservoir will perform is only marginally related to the original permeability of the rock mass, and then only through the diffusion of pressurized fluid from the boundaries of the pressure-stimulated reservoir region (the so-called "water loss" from the reservoir). The deep, crystalline rock mass that forms the "basement" in almost all tectonically quiescent regions of the earth's crust will have a very low permeability, because the number of open faults and joints decreases rapidly with depth; it is thought that open joints, in particular, are virtually nonexistent at crustal depths below about 2 km. (Obviously, in developing an HDR reservoir, one would avoid regions of recent tectonism containing open faults or joint systems.)

Suitable crystalline rock masses would typically have permeabilities in the nanodarcy range at depths of 3–4 km (Brown and Fehler, 1989; SKB, 1989). On the basis of core studies, this very small, but finite, permeability is attributed to a sparse but interconnected network of microcracks within the matrix rock. (The resealed joints themselves probably have permeabilities one to two orders of magnitude greater than that of the matrix rock, but still very low.)

Most crystalline rocks in the depth range of 1–10 km have undergone natural modification, through two competing processes: (1) fracturing (due to deformation), which tends to open fluid conduits such as joints, faults, and breccia zones; and (2) sealing/healing of such permeable features. As hot fluids move through joints or faults in deep crystalline rocks, changes in the chemistry and temperature of the fluid can cause minerals to be precipitated. The accumulation of these minerals over time in joints or faults can reduce, and finally essentially stop, fluid flow. These sealing processes vary with depth (and therefore temperature and stress conditions), mineralogy, and fluid composition (Khilar and Folger, 1984; Carter, 1990). Heat-induced stresses can have similar effects, causing joints to close and thereby impede fluid flow. Other causes of reduced joint permeability include the formation of gouge material during shear displacement (Olsson, 1992) and lithostatic stresses—which, at elevated temperatures, cause dissolution at points of higher stress and re-precipitation at points of lower stress (Lehner and Bataille, 1984). Both the rate and degree of sealing appear to increase with depth and temperature. The very few areas of high permeability in the earth's crust, then, will be those rare hydrothermal regions in which jointing or faulting processes are currently active (for example, along portions of recently active faults within the Basin and Range Province of the western U. S.).

Sealed Joints in the Deep Basement: Potential HDR Reservoir Flow Paths

The principal geologic mechanisms that contribute to the jointing of crystalline rocks are tectonic activity (faulting, folding, and regional uplift) and lowering of the lithostatic stress by erosion. Folding is seen mainly in older rocks that were involved in ancient and deep-seated episodes of metamorphism, thrusting, or mountain-building. Regional uplift is always followed by erosion of the overburden, which gradually decreases the lithostatic stress on the underlying rocks, again resulting in jointing.

When a region of deep, hot basement rock is targeted for the development of an HDR reservoir, it is the network of interconnected joints in the rock mass—however formed and then resealed in the past—that controls how the reservoir develops. Knowledge of the orientations of the one or more joint sets in the rock mass would be desirable, but the nature of this network is not something that can be ascertained from the surface, or even by observation via a nearby drilled hole or an adjacent HDR reservoir. The orientations of the fluid-conductive joints within the HDR reservoir region will be determined after the reservoir is created, through analysis of microseismic data in concert with flow-testing results and post-stimulation borehole surveys.

The orientations of the several sealed joint sets relative to the contemporary stress field will determine which joints open first and at what pressures, how the pressure-dilating region will develop, and what the ultimate geometry of the HDR reservoir will be. The confined (pressure-tight) nature of a true HDR reservoir means that it can be operated, or circulated, at an elevated pressure relative to the least principal earth stress at the depth of the reservoir. Most important, the pressure of the circulating fluid would hold open—*against the joint-closure stresses*—one or more of the interconnected sets of the previously pressure-stimulated joints, thus giving rise to the man-made reservoir's porosity and permeability.

The Geological and Hydrological Setting of Fenton Hill: Influence of the Valles Caldera

As shown in Fig. 2-4, the Fenton Hill HDR Test Site is located 1.9 miles west of the 1.26-million-year-old, main ring-fracture of the Valles Caldera, and 4.3 miles southwest of San Antonio Mountain, a post-caldera rhyolitic dome that erupted along the ring-fracture as recently as 560 000 years ago. Although clearly outside the caldera, the test site is located on the ash-fall-tuff apron that extends several miles to the west of the caldera proper. Because of this proximity to recent volcanic activity, the deep basement rock at Fenton Hill has been affected by heat and pore fluid diffusing radially outward from the caldera over the last million years or more.

A major reason for the selection of this site was the expectation that proximity to the caldera would gain an additional increment over the regional heat flow. (In other respects, Fenton Hill is not very different from many other potential HDR sites in the western U. S.) However, the measured geothermal gradient (over 100°C/km) in the Paleozoic sedimentary rocks was misleading, being augmented by heat from the 100°C groundwater flowing west from the caldera on top of the Precambrian surface.

In addition, this site was centrally located within a large fault block whose principal faults—one mapped to the east, and one inferred (from hydrothermal activity) to the west—are roughly parallel. These two north-trending faults have essentially the same orientation as the deeper HDR reservoir later developed, which exhibited little tendency to grow in the direction of either of these deep faults. The basement rock is at a depth of about 2400 ft (730 m), and is a melange of Precambrian igneous and metamorphic rocks. Of more importance for HDR development, the rock mass is criss-crossed with an array of joints that, below a depth of about 3000 ft, have been resealed with secondary minerals. Except for the slightly permeable joints, the rock mass is extremely tight—in the range of nanodarcies. Because the joints are somewhat more permeable than the matrix rock, pressurized fluid can slowly diffuse into and then open them against the joint-closure stress.

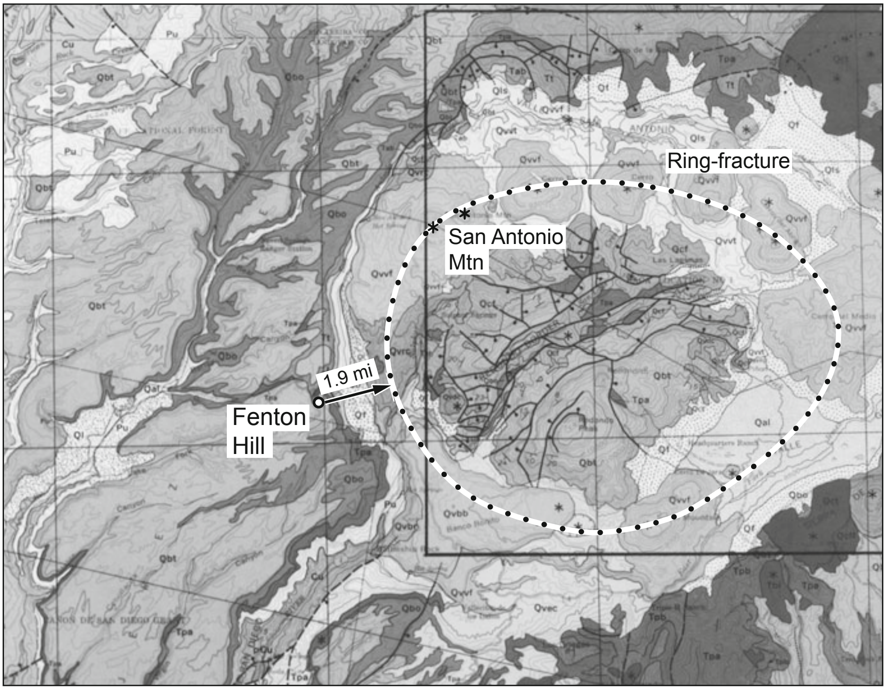

Fig. 2-4. The geological and structural setting of the Fenton Hill HDR Test Site, located to the west of the Valles Caldera in the Jemez Mountains of north-central New Mexico. (The large dots show the inferred position of the main ring-fracture of the Valles Caldera; the rectangular outline on the right delineates the Baca Location No. 1.)
Adapted from Smith et al., 1970

The Paleozoic sediments on top of the Precambrian surface were significantly altered by the hydrothermal outflow coursing westward from the caldera. Over time, this underground "river," at a temperature of just above 100°C, dissolved areas of the deepest limestone, producing an interconnected network of very large solution cavities. This cavernous zone was responsible for repeated losses of circulation, which severely hindered efforts to drill through the limestones and into the granitic rocks below. (Aggravating this situation was the fact that in this mountainous terrain, the water table was almost 1800 ft subhydrostatic!)

As it turned out, the enhanced temperature gradient (which enabled the desired reservoir temperature of about 200°C to be reached at shallower depths, reducing drilling costs) was offset by the damage caused by the high concentration of dissolved hydrogen sulfide (H_2S) in the pore fluid. Diffusing outward through the joint-filling materials, the H_2S caused hydrogen embrittlement of the high-strength steels used in the hydraulic fracturing and pressure-stimulation work. Pipe failures occurred repeatedly, most at pressures less than half those for which the steel was rated.

If we were to select an HDR site in the area today, on the basis of our current knowledge, it would be at least twice as far west of the ring-fracture as the existing site. The much lower amounts of CO_2 and H_2S in the pore fluid would more than compensate for the need to drill to greater depths to reach rock of temperatures equivalent to those at Fenton Hill.

A True Hot Dry Rock Reservoir is *Confined*

That a true HDR reservoir is confined is probably the most profound insight garnered from the 21 years of HDR research at Fenton Hill (Brown, 1999; Brown, 2009). What confines a true HDR reservoir region is the inherent tightness of the surrounding sealed rock mass, combined with the "stress cage" formed at its periphery by the earth's elastic response to the pressure-dilation of the reservoir (see Chapter 6 for a discussion of the "stress cage" concept). A confined HDR reservoir exhibits two characteristics not found in open, hydrothermal systems:

1. Water loss is extremely low, as has been verified experimentally. For example, Fig. 2-5 shows the water-loss profile from Expt. 2077, conducted in 1992 (see Chapter 7). For this experiment, the Phase II reservoir was maintained at a pressure level of 15 MPa (2200 psi) for a period of 17 months, by intermittent pressurization with a small, positive-displacement pump. As shown in the figure, the rate of water loss from this reservoir (a seismically determined volume of 0.13 km^3) decreased continuously over this time, to a final rate of about 2 gpm—less than the flow from a garden hose. If the Phase II reservoir had been *open*, the water loss, instead of decreasing, would have stayed relatively constant. (Note that the method of reporting HDR water loss as a percentage of production flow is nonsensical. Water loss is a function of the pressure at the periphery of the reservoir, which is not particularly related to the flow rate.)
2. At a constant injection rate and pressure (higher than the joint-opening pressure), the growth of the reservoir region is linear with time. This relationship is illustrated in Fig. 2-6: the growth in volume of the Phase II stimulated region corresponds linearly to the increase in the volume of injected water. If the stimulated region had been open instead of confined, the increase in seismic volume would have flattened out with increasing injection volumes (as often occurs with hydro-frac operations in the oil industry).

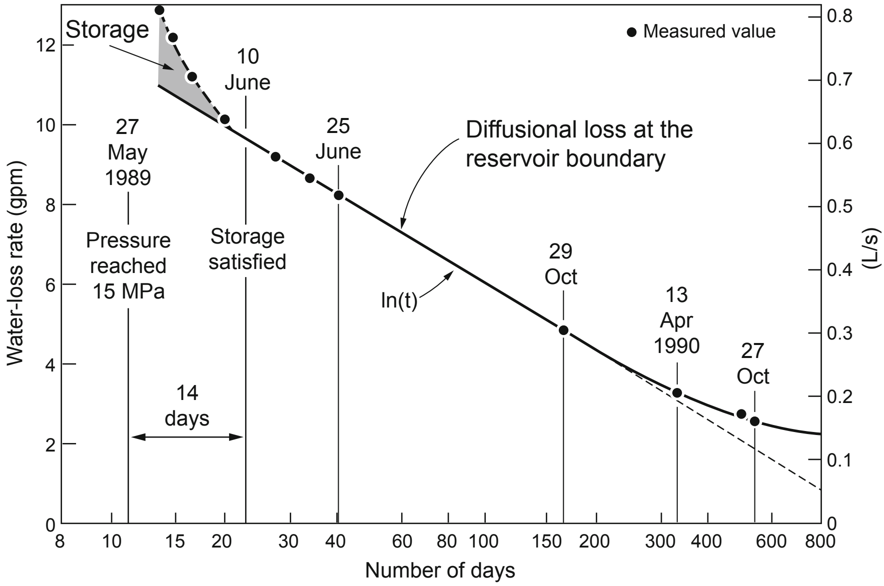

Fig. 2-5. Water-loss rate vs log (time) during the 15-MPa pressure plateaus of Expt. 2077 (diffusion of pressurized water to the far field).
Source: Brown, 1995b

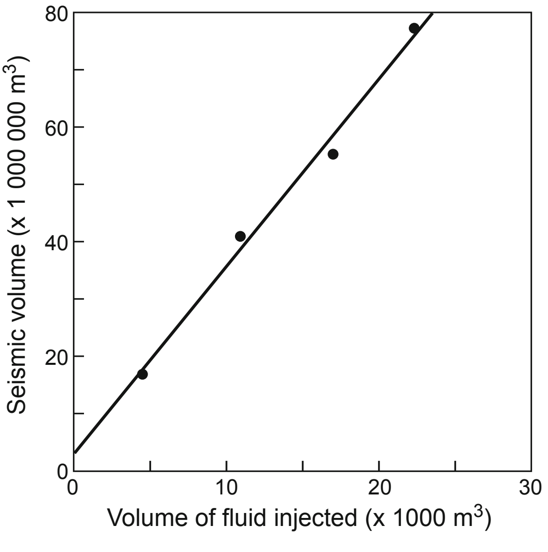

Fig. 2-6. Linear relationship between seismic volume and volume of injected fluid.
Source: Brown, 1995b

A True Hot Dry Rock Geothermal System is *Fully Engineered*

The creation of an HDR reservoir in a region of previously tight basement rock enables the system to be engineered in all its aspects. Those geothermal projects elsewhere in the world claiming to be HDR and/or "engineered" are only partially so. The reservoirs at Hijiori and Ogachi in Japan are both within volcanic calderas and associated with open, fluid-conductive fault and/or joint systems, making them *hot wet rock*, or HWR, geothermal systems.[3] In the late 1980s, hydraulic stimulation was successfully carried out at both these sites. But a few years later, recognizing the undeniably open (hydrothermal) nature of these regions, the Japanese researchers created a new project for HWR geothermal reservoir design (described in Takahashi and Hashida, 1993). Figure 2-7, taken from that publication, illustrates their view of the HWR concept vs that of HDR.

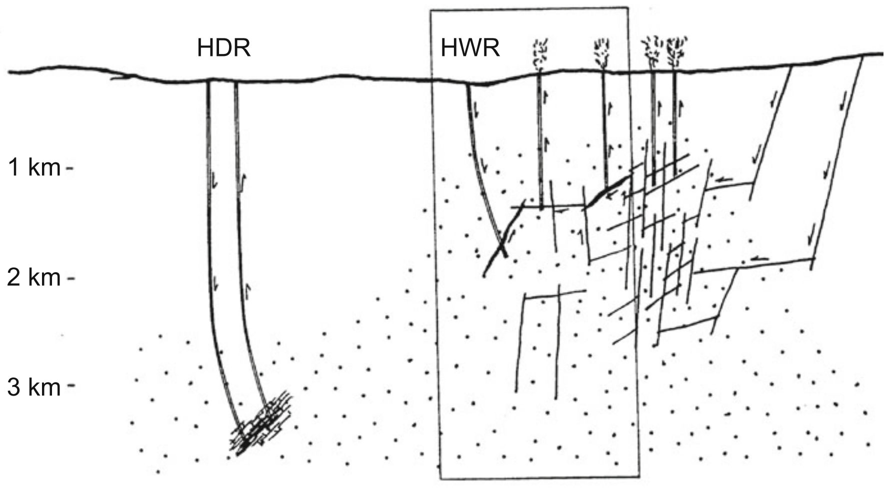

Fig. 2-7. The concept of a hot wet rock (HWR) geothermal reservoir. Source: Takahashi and Hashida, 1993

[3]so named by the Japanese in the early 1990s.

It appears that the "HDR" projects in the Cooper Basin of Australia are also open and unconfined. And the European "HDR" project at Soultz-sous-Forêts (Alsace) was renamed an enhanced geothermal system (EGS) project in 2001. In two extended flow tests, this system achieved only about a 30% recovery of injected fluid—highlighting the very open nature of the reservoir (Gérard et al., 2006).

All of these HWR systems are partially "engineered" (e.g., the natural joint/fault permeability has been enhanced by pressure stimulation, and in some cases also through zone isolation using casing strategies and/or down-hole pumping of the production well or wells); but because the reservoirs in question are not confined, none of these systems is *fully* engineered.

Only an HDR system with a reservoir enclosed and sealed at its boundaries can be fully engineered—that is, all key parameters can be controlled:

- Production temperature, by selecting the drilling depth
- Size of the HDR reservoir, by specifying the amount of fluid injected
- Reservoir injection pressure and flow rate
- Production well backpressure
- Placement of production wells for optimum productivity

Development of an HDR System

The system is developed through a series of distinct operations, as described in the following subsections.

Selection of a Site

Don Brown's direct involvement with the process of selecting Fenton Hill as the site of the world's only true HDR reservoirs affords him a unique understanding of the criteria to be used in choosing a site for the *next* HDR development—an electric power generating system. Such a site would be selected primarily to satisfy the requirements of the community it would serve, and only secondarily for the geological conditions (of which the most important is the absence of active faults at the proposed reservoir depth). The major criteria would be as follows:

- Proximity to a municipal load center, offering water and power availability as well as road access
- Tectonic quiescence of the targeted reservoir region
- An appropriate type of rock at the depth of the reservoir (almost any crystalline basement rock would be appropriate; it is the joint structure that primarily determines the characteristics of an HDR reservoir)
- Suitable geothermal gradient—at least 40ºC/km, as determined from an intermediate-depth exploratory borehole (drilled at least 500 ft into the basement rock to preclude any compromising of the gradient data from groundwater flows in the sediments above the basement)

Almost without exception, the terrain at depth would consist of igneous or metamorphic rock in which once-open joints have been hydrothermally resealed. The rock mass would exhibit very low initial porosity and permeability (i.e., it would be a region of hot, but essentially dry, rock). In such areas boreholes could be routinely drilled to depths of 11 000 to 16 000 ft (3400 to 4900 m). Only at such depths is it possible to (1) attain sufficiently hot temperatures for good commercial viability[4] and (2) ensure that the rock beyond the periphery of the HDR reservoir would remain tightly sealed, and therefore that the reservoir would be confined.

Drilling of an Injection Borehole

An injection borehole would be drilled to a depth at which the rock temperature is suitable for the generation of electricity. This first borehole would be drilled essentially vertical (no directional drilling would be involved because, before reservoir stimulation, very little would be known about the stimulation characteristics of the target reservoir region—e.g., the shape and orientation of the pressure-stimulated region, and the pressure required to open, and then extend, the contained array of joints). The injection borehole would be completed by cementing-in a short (about 1000-ft) scab liner 1000–2000 ft off bottom, to pressure-isolate the lower portion of the hole, and then installing a "frac string" (high-pressure pipe used in hydraulic fracturing operations) from the top of the scab liner to the surface.[5]

Initial Pressurization Testing

With the injection borehole complete, the deep rock mass is "interrogated" through pressurization. This testing gathers data essential for planning the creation of the HDR reservoir. A contract mini-frac truck (having a maximum flow rate of 5 BPM) and superlative instrumentation would be employed to determine

- the permeability of the exposed rock mass at a very low injection rate and a controlled pressure
- the initial "formation" breakdown pressure (the pressure level at which the most favorably oriented joints start accepting fluid)
- the asymptotic joint-extension pressure
- the presence of any open faults
- the orientation of the fluid-accepting joints (through pre- and post-test Schlumberger FMI logs)

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[4]At a mean depth of 14 000 ft and with a temperature gradient of 40°C/km, the reservoir temperature would be about 180°C.

[5]High-temperature/pressure inflatable packers, used to isolate the open-hole portion of the borehole during the Phase II experiments at Fenton Hill, proved to be unreliable (see in particular Chapters 4 and 6 for detailed accounts of packer problems). Even after a long period of collaborative development and testing by the Laboratory and an industrial partner, a 50% success rate was the best obtained.

Creation of the Reservoir

An HDR reservoir is created within a previously impermeable body of hot, crystalline basement rock, by means of high-pressure, hydraulic-stimulation ("hydro-frac") techniques commonly employed in the oil and gas industry. However, when used to create an HDR reservoir, these pressure-stimulation operations are generally much larger in scale and use higher pressures. The rock surrounding an isolated, open-hole interval at the bottom of the injection borehole is pressurized, in one or several stages of hydraulic stimulation, to create a very large (~1 km^3) region of pressure-dilated rock.

Via the injection well, fluid pressure is used to open a multiply interconnected array of pre-existing but resealed joints within the rock mass, such that a series of flow paths is formed that traverse the reservoir. These flow paths will later be accessed by the production wells. The flow impedance of each of these individual paths may be relatively high, but their aggregate impedance, as they carry fluid across the HDR reservoir, will be much lower.

During the initial development and subsequent growth of the HDR reservoir region, seismic activity will be monitored. As a result of the pioneering work done at Los Alamos, analysis of pressure-induced microseismicity has become the principal tool for determining the shape and orientation of this reservoir region (the observed "cloud" of microseismic event locations delineates the boundaries of the reservoir) as well as significant features of its internal structure (Albright and Hanold, 1976; Albright and Pearson, 1982; House et al., 1985; Fehler et al., 1987; House, 1987; Fehler, 1989; Roff et al., 1996; and Phillips et al., 1997). This information will be critical for determining the optimum locations for the production wells and the drilling trajectories that will best access the reservoir.

From the knowledge gained from the development of two separate HDR reservoirs at Fenton Hill, one can surmise that the typical HDR reservoir would be ellipsoidal in shape. This is because the stress field at depth in the earth's crust is invariably anisotropic. Within the Basin and Range Province of the western U. S. (which harbors most of the highest-grade HDR resources), the maximum earth stress is typically vertical, and the least principal earth stress is horizontal. Such a stress state would result in an elongate reservoir region whose smallest dimension is horizontal and whose larger dimensions are near vertical and approximately orthogonal to the direction of the least principal earth stress. The Phase II reservoir at Fenton Hill—which has been described as a steeply inclined, elliptical-shaped "pillow" sitting on edge, with its largest dimension in a north–south direction—appears to have followed this pattern of development.

The Initial Closed-Loop Flow Test (ICFT), performed in mid 1986 (see Chapter 7), in particular revealed that under high injection pressure (4570 psi [31.5 MPa]), the growth of the reservoir was predominantly toward the south—in the direction away from the production well (which was north of the injection well). The result was a "stagnant" high-pressure, southern reservoir region without any path to the production well. With this portion of the reservoir essentially isolated, the ICFT achieved a power production level of only 10 MW_{th}. But had a second production well been drilled into that southern portion of the reservoir, it is estimated that at least twice that—20 MW_{th}—would have been available from this HDR reservoir.

This elongated reservoir shape suggests that the best configuration for HDR reservoir production would be a centrally located injection well and *two* production wells, one near each end of the ellipsoidal reservoir region (Brown and DuTeaux, 1997). Because it is in these elongated boundary regions that the reservoir is preferentially extending during pressure stimulation, the two production wells would act as "pressure-relief valves": inhibiting reservoir growth in these critical regions and thereby enabling reservoir operation at even higher injection pressures than would be possible with a single production well.

The productivity of the reservoir is directly dependent on the flow impedance, or degree of resistance to flow through the reservoir (a concept unique to HDR geothermal energy). Flow impedance is usually expressed in units of psi/gpm or MPa per L/s. The overall flow impedance of the reservoir has three components: the *body impedance* (across the greatest extent of the dilated reservoir), the *near-wellbore outlet impedance* (near the production wellbores), and the *near-wellbore inlet impedance* (near the injection wellbore). These are discussed further in Chapter 4. With higher injection pressures, the principal flow paths across the reservoir would be further dilated, reducing the body impedance and increasing reservoir productivity.

Drilling of the Production Wells

The HDR circulation system would be completed by drilling *two* production wells to intersect the reservoir near the ends of the elongated reservoir region (the boundaries determined by seismic data).

Flow Testing

The completed HDR geothermal system would be flow-tested to determine the optimum production flow rate. Test parameters would include the available range of injection and production pressures. In the event that the cumulative flow rate from the production wells is too low, pressure/temperature cycling operations would be instituted to reduce the near-wellbore outlet impedances of these wells. In addition, laterals could be drilled from near the bottom of each production well to increase productivity.

Seismic Risks Associated with HDR Geothermal Energy

Because of the environmental consciousness of the HDR staff, seismic monitoring was a "given" for all the pressure-stimulation activities, starting with the experiments in Barley Canyon.

In the summer of 1972, Prof. Bert Slemmons, an expert on earthquakes from the University of Nevada, spent five weeks investigating the fault structure and earthquake history of the Fenton Hill area and assessing potential earthquake hazards associated with the planned hydraulic fracturing operations. (A very large body of data already existed on Fenton Hill. The Valles Caldera—one of the classic calderas in the U. S.—and its environs had been extensively studied by a number of geoscientists over the preceding years [e.g., Smith et al., 1970]).

Dr. Slemmons reported his findings in a Los Alamos National Laboratory publication (Slemmons, 1975). On the basis of low-sun-angle photography augmented by field studies, he confirmed the presence of the known faults in the area and discovered a previously unmapped minor fault in Virgin Canyon, 2.5 miles southeast of Fenton Hill. This fault had a very low average rate of movement, and trended away from Fenton Hill. There also appeared to be no earthquake hazard from other faults within a 15-mile radius of Fenton Hill. (Except for the Virgin Canyon fault, none was found that had displaced the geologically young surface volcanic rocks.)

Dr. Slemmons also collected and analyzed all available earthquake data for New Mexico. He concluded that the level of seismic activity in the region surrounding Fenton Hill was very low; that hydraulic-fracturing experiments in this area involved very little seismic risk from natural fault activity or local earthquakes; and that such experiments were not likely to activate any of the known faults in the area—including the closest and most recent one in Virgin Canyon.

During the ensuing 22 years, the magnitude of the largest induced seismic event was only about 1.0 on the Richter Scale (Leigh House, Los Alamos National Laboratory, personal communication, May 2009). It is notable that for the 844 microearthquakes reliably located during the MHF Test in 1983 (on the basis of arrival times recorded by five downhole geophone stations), the range of magnitudes was –3 to 0 (House et al., 1985). It is the confined nature of the reservoir in an HDR system that explains the greatly reduced seismic risk vis à vis "enhanced" hydrothermal reservoirs. Only *within the pressurized envelope* of the stimulated HDR region is seismic activity generated—and then typically at magnitudes below zero on the expanded Richter scale. Any nearby faults would be shielded from activation (pressure stimulation) by the pressure-sealed boundary of the HDR reservoir.

In contrast, the pressure-stimulation of regions within or adjacent to known hydrothermal systems (e.g., the HWR systems at Hijiori and Ogachi in Japan, and the "HDR" systems now being developed deep below the Cooper Basin in Australia) carries a significantly higher risk because of the *open* (unconfined) nature of these systems. As an example, such a pressure-stimulation was recently attempted at Basel, Switzerland, within the southeastern margin of the Upper Rhine Graben—an area of "elevated seismic activity."[6] To enhance hydrothermal flow in the deep granitic basement, 11 600 m^3 of water was injected over six days into a deep injection well ("Basel 1," drilled *within* the city). The bottom-hole temperature of this well, at a depth of 5000 m, was about 195°C. With injection pressures finally reaching as high as 29.6 MPa (4300 psi), on December 8, 2006, a magnitude 2.7 earthquake occurred. As pre-planned, injection was terminated. Four hours later (at a shut-in "reservoir" pressure of about 19 MPa), a magnitude 3.4 earthquake shook the city and brought the entire effort to a halt (Dyer et al., 2008). Even so, because of the large volume of water injected at high pressure into the fault system, tremors continued for a year or more. Although such a high level of induced seismicity has rarely if ever been seen in other HWR stimulations around the world, it stands as a warning of what *could* occur if an open hydrothermal system is subjected to high-pressure stimulation.

Note: The injection pressures used at Basel (29.6 MPa) were only slightly higher than those routinely used during flow testing of the Phase II reservoir at Fenton Hill, which averaged about 27.3 MPa.

The Economics of HDR Geothermal Energy

The researchers most involved with the development of HDR geothermal energy believe that the preferred route for HDR commercialization is the generation of electricity. This belief has been shared by the U. S. Department of Energy (DOE) throughout its long association with the HDR Geothermal Energy Program at Los Alamos, simply on the basis of economics. At the same time, it is possible that some concentrated, direct-heat applications (such as those described in Tester et al., 1989a) could be brought on board competitively. For instance, HDR geothermal heat could be used directly to supply feed-water heating for a co-located, fossil-fuel electric power plant; in this case—in light of the current tax credit for renewable energy and anticipated cost incentives for reductions in carbon dioxide emissions (e.g., a carbon tax)—the economics of HDR direct heat could be favorable. Although it may not be intuitively obvious, if an HDR system cannot

[6]In 1356, an earthquake with an estimated magnitude of 6.2 destroyed parts of the medieval city of Basel.

economically generate electric power under the given conditions, it probably cannot economically be used for direct heating either. With a direct heating system, the cost of transporting the pressurized hot water to its final destination would be significantly higher than for natural gas. This assertion is based on present-day natural gas prices. As a corollary assertion, HDR-derived geothermal heat of only moderate temperature is not economical compared with natural-gas heating.

At the time of this writing (spring 2012), it is difficult to accurately forecast the economics of constructing an HDR power plant, particularly when no such plant has ever been built. The primary capital costs are those of drilling the deep injection well, developing the pressure-stimulated HDR reservoir, and then drilling the two production wells. These costs are estimated to represent about two-thirds of the total capital investment for a complete HDR power generating system (depending principally on the depth of the wells).

In the summer of 2010, oil prices were considerably lower than they are at present. In past months a number of factors—not least the widespread upheavals in the Middle East—have intervened to return prices to their 2008 levels. Given the impossibility of predicting such fluctuations, an estimate provided in 2008, of about $24 million for drilling and completing three boreholes to 13 500 ft (Louis Capuano Jr., ThermaSource, Inc., personal communication, September 2008), remains the best currently available. But a further consideration is that a new drill-bit technology on the horizon (David Hall, Novatek International, Inc., personal communication, June 2011) could cut that cost in half!

In estimating the power output of an HDR plant, the principal unknown is the productivity of the reservoir. On the basis of the flow testing of the deeper (Phase II) reservoir at Fenton Hill, the output of a three-well system is projected to be at least 20 MW_{th}. Further, if an HDR plant were to be established at the decommissioned Fenton Hill site, this productivity could be increased through various strategies—the most viable being the drilling of a lateral from the bottom of each of the production wells, which could conceivably increase power output to near 40 MW_{th}. Other strategies include pressure- and/or temperature-cycling (to reduce the near-wellbore outlet impedance), both of which appear to be attractive approaches but must be verified through field demonstrations.

In reality, then, until the first true HDR power-generating system is up and running, the actual costs for such a revolutionary new power source can only be guessed at. (Note: such a system was very close to being constructed when the DOE withdrew funding in 1995—see Duchane, 1995d).

Armstead and Tester (1987), in discussing the generation of electric power from HDR geothermal resources, considered both open (flashed-steam) and closed (binary-cycle) systems. It has been the Los Alamos HDR Project's contention since the early 1980s that a closed-cycle earth loop is the preferred approach, from both environmental and water-use standpoints. With this type of system, the heat contained in the produced geofluid (the fluid being maintained at a pressure sufficient to ensure that it remains liquid) is transferred via a heat exchanger to vaporize a secondary working fluid, which is then expanded through a turbine, producing mechanical power. The secondary working fluid is next condensed in a cooling tower or an air-cooled heat exchanger, repressurized, and returned to the primary heat exchanger to be reused.

Milora and Tester (1976) considered seven possible working fluids for a binary-cycle system. The variation in thermodynamic availability of each of these as a function of temperature, over the range of probable geofluid production temperatures from 100°C to 300°C, is shown in their Figure 3-3. A commercial HDR development at typical production temperatures would be on the high side of this range; therefore, according to this analysis, ammonia appears to be the best working fluid.

The true picture of the economics of HDR power generation must await commissioning and then operation of a prototype power plant—not yet even in the planning stage. Further, the principal economic issue of reservoir productivity must await pre-operational flow testing of the reservoir, which would be carried out before a binary-cycle power plant is constructed. During this flow testing, several proposed methods of production enhancement would be evaluated.

Using an HDR Reservoir for Load-Following

A very significant experiment was conducted in July of 1995, near the end of the long-term flow testing of the Phase II reservoir (see Chapter 9). This experiment demonstrated a concept referred to as "load-following," whereby an HDR reservoir can be operated for several hours each day with greatly increased thermal power production (Brown, 1996a, 1997b).[7]

For six days, while the injection pressure was held steady at 3960 psi (27.3 MPa), a 20-hour period of high-backpressure (2200 psi [15.2 MPa]) operation was alternated with a 4-hour period of greatly increased production flow (maintained through a controlled decrease in the backpressure—to a final value of 500 psi). The last two of the six 24-hour cycles are shown in Fig. 2-8.

[7]Only a few weeks after this experiment all flow testing was halted, and at the end of the fiscal year the DOE terminated the HDR Project.

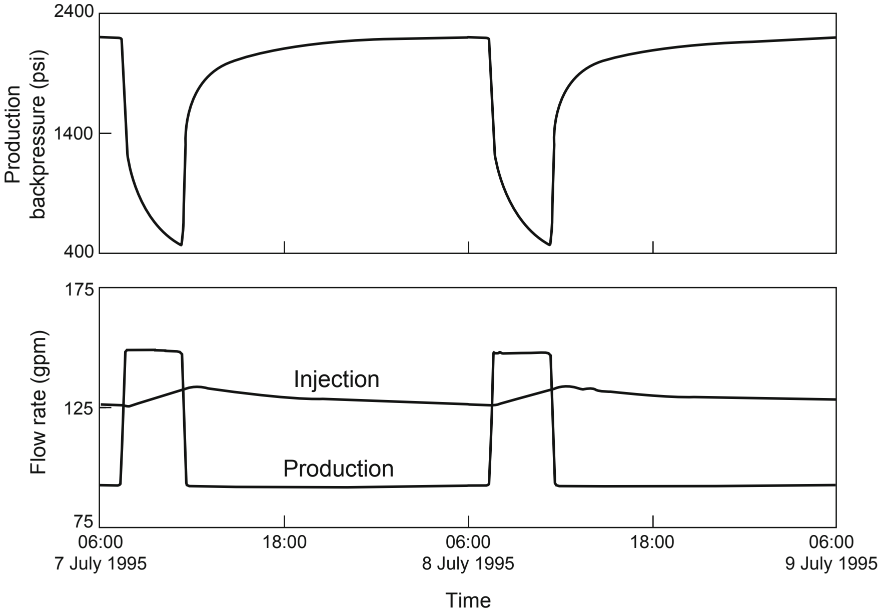

Fig. 2-8. Injection and production flow profiles vs the controlled variation in the production well backpressure during the last two daily cycles of the Load-Following Experiment (1995).
Source: Brown, 1996a

During the 4-hour portion of the daily cycle, the production flow rate was increased by a constant 60%. With the associated 10°C increase in the production fluid temperature, the overall power level achieved was 65% higher than that of the preceding 20-hour period of steady-state operation.

As shown in the figure, for each cycle the production well backpressure began at 2200 psi and ended at 500 psi. However, to maximize reservoir power production during the 4-hour portion of the cycle, the backpressure for the 20-hour portion could have been increased somewhat (e.g., to 2400 psi) and the final pressure could have been dropped to near 182 psi (the saturation pressure for water at 190°C). These operational changes would have increased the power multiplier for the 4-hour period of enhanced production from 1.65 to closer to 2.0—a considerable improvement.

When an HDR reservoir is used in this advanced operational mode, one can also take advantage of the principle of "pumped storage"—the storage of additional pressurized fluid within the reservoir. In essence, during the Load-Following Experiment at Fenton Hill, a portion of the high-pressure reservoir fluid stored near the production well was being vented down (temporarily produced) during the 4 hours; then, during the next 20-hour period of steady-state operation at a backpressure of 2200 psi, the reservoir was reinflated by injection at a somewhat higher rate (the rate gradually returning to its previous steady-state level during the subsequent 20-hour period).

Note: During flow testing of the Phase II reservoir, it took only about two minutes to nearly double the reservoir's power production, by simply opening the motor-driven throttling valve on the production well. Making use of this HDR load-following capability would reduce the local electric utility's need to draw on its natural-gas-fired "spinning reserve" during times of peak demand (a very costly—but also very common—method of load-following, particularly during the summer air-conditioning season).

The demonstrated ability of HDR geothermal systems, operating in a base-load mode, to provide peaking power upon demand confers on HDR power plants an additional cost advantage that has not been considered in *any* of the HDR economic studies done so far. The premium for peaking power is typically more than twice the base-load price. For example, for a base-load busbar price of 9 cents/kWh and a peaking price of 21 cents/kWh for 4 hours, the overall effective price would be 11 cents/kWh—a premium of 2 cents/kWh, which could markedly change the profitability of an HDR power plant.

The pumped storage aspect of this experiment was not particularly emphasized at the time. The experiments at Fenton Hill suggest that upon reinflation, the region surrounding the production well behaves like an elastic spring, storing pressurized fluid for delivery the following day. The recent growth of wind power (often generated at night) presents an appealing opportunity for exploiting this aspect: excess wind power could be used to power an additional injection pump during all or a portion of the 20-hour reinflation phase—the supplemental store of pressurized fluid thus created turning the HDR reservoir into a kind of "earth battery." Most of this excess pressurized fluid could be recovered the next day in the form of increased power generation for peak demand periods. In other words, the reservoir could be hyper-inflated to a mean pressure level *above* that used for steady-state operation, enabling a greater quantity of pressurized fluid to be stored during the off-peak hours. The quantity would be limited only by the requirement to keep the pressure below a level that would cause renewed—or excessive—reservoir growth.

The Challenges of HDR Technology

In the early days of the HDR Project, a number of concerns—or challenges to implementation of the technology—were expressed by the earth sciences community. Ongoing research of the HDR geothermal energy concept at Los Alamos National Laboratory and the field experiments at Fenton Hill led to successful resolution of most of these. In addition to the two most important ones (water loss and induced seismicity, discussed above), these challenges included the following:

- *Controlling growth of the reservoir region.* During Phase II, when the reservoir was tested for over two years at a very high pressure (3960 psi), there were no indications of reservoir growth.
- *Preventing chemical scaling*. After years of flow with hot, mineral-laden water through the mild-steel, air-cooled heat exchanger, only a very thin—and actually protective—coating of iron carbonate was found (possibly owing to the injection of fine-grained calcium carbonate during the Massive Hydraulic Fracturing [MHF] Test in December of 1983—see Chapter 6). Further, no detrimental build-up of mineral deposits was found in any of the surface plumbing or downhole piping. Therefore, chemical scaling proved to be a non-issue.
- *Creating sufficient reservoir volume for a commercial-scale operation*. The Phase II reservoir at Fenton Hill had a circulation-accessible volume of at least 20 million m^3—sufficient for the continuous production of at least 20 MW of thermal energy for at least 10 years with very little thermal drawdown. In addition, if sufficient heat-transfer volume is a concern, before power production begins the circulation-accessible reservoir volume can easily be increased through additional pressure stimulation, at a very modest cost.
- *Achieving higher productivity.* Increasing the rate at which energy can be extracted from the man-made reservoir is the primary remaining challenge to the commercialization of HDR geothermal energy. This rate is dependent on the flow impedance ("I" in the following equation), which determines the amount of water that can be circulated through the pressure-dilated reservoir region for a given set of reservoir inlet and outlet pressures (as measured at the surface):

$$I = \frac{\text{(injection pressure – production pressure)}}{\text{production flow rate}}$$

Reservoir productivity is particularly closely linked to the near-wellbore outlet impedance (see also the discussion of flow impedance in Chapter 4). This impedance can be significantly reduced by operating the production wells at an elevated backpressure, which keeps the reservoir flow outlets partially dilated. These outlets would otherwise be held almost closed by the combination of the wellbore stress concentration and the decreasing differential pressure[8] as the flow converges to the production wellbores.

- *"Short-circuiting" of flow within the reservoir.* This concern was allayed by very favorable data from the Long-Term Flow Test of the deeper reservoir (1992–1995). Tracer testing showed that the flow patterns became *more* diffuse with time, suggesting that more of the reservoir was being accessed as flow continued—with no tendency toward short-circuiting.

A Major Observation and a Practical Lesson

A major observation from our Fenton Hill HDR reservoir testing and development is that the characteristics of the jointed rock mass are variable, and unpredictable. For example, the joint-extension pressure in the Phase I reservoir was only about 2000 psi, whereas the corresponding joint-extension pressure for the Phase II reservoir—only 2300 ft (700 m) deeper—was 5500 psi, a remarkable difference. This pressure is controlled not by the earth stresses per se, but by the orientations of the principal flowing joints relative to the earth stresses—something that cannot (as yet) be discerned from borehole observations nor, assuredly, from the surface! Although microseismic observations are essential to understanding HDR reservoir development, there is much more to do in this field—particularly in understanding/discerning that portion of the induced seismicity that is specifically related to the opening of the joints that constitute the principal flow paths.

[8]This *differential pressure*—the difference between the pressure of the circulating fluid acting to open the joints and the normal stress acting to close them—rapidly declines from its positive value in the body of the reservoir to a neutral and finally a negative value as the flow converges to the reservoir's outlets into the production boreholes. This phenomenon, unique to HDR reservoirs, explains why an increase in the production-well backpressure decreases the near-wellbore outlet impedance. It follows that the larger (i.e., the more negative) this differential pressure, the more tightly closed are the joints in the vicinity of the production well.

The most practical lesson from the Laboratory's HDR work is that the engineering of an HDR geothermal system begins with the creation of the reservoir from the initial borehole. The reservoir is then accessed by two production wellbores drilled to near the boundaries of its (seismically determined) ellipsoidal volume. To first drill two boreholes, and then try to connect them by hydraulic pressurization, is almost impossible. (The reason for drilling *two* production wellbores is twofold: First, to markedly increase productivity by much more fully accessing the reservoir; and second, to permit even higher reservoir operating pressures to further dilate the flowing joints and further reduce the body impedance, while constraining additional reservoir growth.)

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Brown, D.W.; Duchane, D.V.; Heiken, G.; Hriscu, V.Th.

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