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Scientific Progress on the Fenton Hill HDR Project Since 1983

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ABSTRACT

The modern HDR concept originated at the Los Alamos National Laboratory and was first demonstrated at Fenton Hill, NM. Experience gained during the development of the deeper HDR reservoir at Fenton Hill clearly showed that HDR reservoirs are formed by opening pre-existing, but sealed, multiply-connected joint sets. Subsequent flow testing indicated that sustained operation of HDR systems under steady-state conditions is feasible. The most significant remaining HDR issues are related to economics and locational flexibility. Additional field test sites are needed to advance the understanding of HDR technology so that the vast potential of this resource can be economically realized around the world.

BACKGROUND

The HDR Concept and The First HDR Reservoir. The concept of extracting geothermal energy from hot dry rock (HDR) by circulating water through an engineered geothermal reservoir created by hydraulic fracturing originated in the United States more than 25 years ago. The original HDR patent (Potter, et al.) was issued to Los Alamos National Laboratory in 1974. That patent has now expired. Beginning in 1974, Los Alamos National Laboratory, working under the sponsorship of the United States Atomic Energy Commission, conducted numerous experiments and extensive field testing at the Fenton Hill HDR Test Facility located in the Jemez Mountains of northern New Mexico, USA. The world's first HDR reservoir was created at Fenton Hill between 1974 and 1978. Flow testing of that reservoir from 1978 to 1980 showed that it was possible to extract heat from HDR reservoirs at reasonable rates, and set the stage for worldwide interest in HDR technology (Dash, et al., 1981).

THE ROLE OF FENTON HILL IN THE EVOLVING UNDERSTANDING OF HDR

Development of the Deeper, Pilot-Scale HDR Reservoir

Initial Drilling. Development of the second, much larger, deeper, and hotter HDR reservoir at Fenton Hill began in 1980 under the direction of an international team comprised of scientists and engineers from Japan, Germany, and the United States. The initial concept for this reservoir was based on producing a very large heat transfer surface by creating a series of vertical, disk-shaped fractures connecting two inclined, vertically separated, wellbores. With this approach in mind, two wellbores were drilled sequentially, one above the other. The first wellbore (designated EE-2) was drilled to a vertical depth of about 4,400 m, with the bottom 1,000 m directionally drilled toward the east at an angle of 35° from the vertical. The temperature of the rock at its bottom was 327°C. The second wellbore (designated EE-3) was then drilled in a similar manner, starting from a point on the surface 46 m to the west of the first. The directionally drilled segment of wellbore EE-3 was positioned 380 m directly above the directionally drilled portion of EE-2.

Stimulation. Following the completion of drilling operations and some preliminary pressure testing, 8 hydraulic fracturing tests were carried out from May 1982 through October 1993, from two separate openhole intervals in the deeper wellbore, EE-2. After twice attempting to fracture below openhole inflatable packers set near the bottom of the hole, each resulting in a packer failure after a brief period of injection, an 89-m-long steel scab-liner/Polished-bore-receptacle assembly was landed off bottom and cemented in place,

leaving 136 m of open hole between the bottom of the scab liner at 4,480 m and the bottom of the hole at 4,616 m.

Three successful fracturing operations were conducted by injecting into the openhole interval below the scab liner, the largest involving 4,880 m³ of water injected at surface pumping pressures up to 49.6 MPa. However, no flow communication with the upper wellbore (EE-3) was obtained. At that time, this failure to connect was attributed to the growth of the stimulated region in an arcuate pattern, roughly normal to the inclination of the wellbore and dipping to the west at about 45°, and therefore ostensibly passing *below* the bottom of the upper wellbore. In retrospect, it now appears that our early seismic event location techniques, based on the single-tool hodogram method, were severely flawed, and the actual fractured region was very poorly delineated. In reality, the stimulated region was probably oriented symmetrically along the injection wellbore as was our experience at shallower depths.

Based on the faulty seismic evidence, a decision was made to abandon most of the lower part of EE-2 by sanding up the wellbore, and then to attempt to connect the wellbores by injecting into a restricted openhole interval below the casing shoe in EE-2. Three unsuccessful wellbore connection attempts were made from the upper part of EE-2 in the second half of 1982. Each of these fracturing operations utilized a casing packer set just above the casing shoe to protect the EE-2 casing from the high injection pressures.

In December 1983, in a continuing effort to achieve a flow connection between the two wellbores, a massive hydraulic fracturing(MHF) operation was performed in the upper part of the Phase II reservoir region. Water was injected into a further restricted openhole interval of the lower wellbore, extending from the bottom of the casing at 3,529 m to the top of the sand plug at 3,550 m. A pumping rate of 106 l/s at a surface pressure of 48 MPa was sustained for 61 hours with a total injection of 21,300 m³ of water, but no flow connection was observed.

The MHF test was terminated when one of the two side flanges on the wellhead injection manifold suffered a fatigue failure and the well started an uncontrolled vent. The flange failure at the surface resulted in rapid venting of fluid from the highly pressurized reservoir and the subsequent collapse of a portion of the casing above the casing packer due to the large pressure differential between the very high near-wellbore reservoir pressure and the sub-hydrostatic pressure of the venting steam and hot water inside the casing. Over the next two days, about 13,000 m³ of fluid was vented from the reservoir at an average rate of 80 l/s, providing a very graphic demonstration of the potential of HDR technology.

The cloud of microseismic events recorded during the MHF test (located using several deep geophones and the seismic travel-time method, not the much-less-accurate hodogram method) indicated that a volumetric region of fractured rock had been formed surrounding the EE-2 wellbore, which extended 300 to 400 m both above and below the very limited, 21-m-long, openhole injection interval in roughly the shape of an oblate spheroid. The orientation of this elongate reservoir region, dipping to the east at about the same inclination as the two directionally drilled wellbores, strongly suggested that one of the principal joint sets pressure-stimulated (i.e., opened) during the MHF test had almost the same inclination as the wellbores. In retrospect, employing directional drilling, at greatly increased cost relative to simple vertical holes, was not a wise decision. We couldn't have drilled these two deeper wellbores at Fenton Hill in a *worse* direction from an HDR reservoir development standpoint.

Although we were unsuccessful in establishing a flow connection to the upper wellbore, in its smallest dimension the seismically defined reservoir region appeared to span almost half

the distance separating EE-2 and EE-3 (the wellbores had a 310-m separation), with the stimulated region approaching almost a kilometer in both in the N-S direction and diagonal height. A final attempt to connect the wellbores by hydraulic fracturing was conducted in May 1984, by again injecting at high pressure, but this time into the upper wellbore (EE-3) at a point below a cemented-in scab liner set below the bottom of the casing. After pumping 7,570 m³ of water at a rate of 25 l/s without any hydraulic communication, the fracturing attempt was terminated. Again, the pressure-stimulated region developed along the general trace of the wellbore, but now preferentially downward from the injection interval and generally *above* the trace of the wellbore. This was definitely not the result we had anticipated or desired. It should be noted that if we had only been astute enough to have drilled EE-3 to the north or south of EE-2 with both wells drilled vertically (rather than inclined with one to the east of the other), we would easily have been able to connect these two wells by hydraulic fracturing from one or both wells.

Redrilling and Wellbore Connection. The hydraulic stimulation experience at Fenton Hill during 1982-1984 led to a complete change of thinking regarding the nature of HDR reservoirs. Extensive microseismic analyses and geologic evidence indicated that the original concept of large vertical flow passages created by forming new fractures in basement rock was incorrect. Instead, all evidence pointed to the opening of an interconnected array of existing joints that had been sealed by hydrothermal processes. As might be expected, the initial joint openings were found to occur in a direction approximately orthogonal to the least principle earth stress, with subsequent openings of other interconnecting joint sets occurring at higher pressures.

Based upon this revised concept of the reservoir, it was decided to sidetrack and redrill the upper wellbore with the goal of penetrating the reservoir volume created during the MHF as indicated by the microseismic data. Sidetracking was initiated at a depth of 2,829 m. Drilling continued to a final depth of 4,018 m, where a bottomhole rock temperature of 265°C was measured. The sidetracked well, designated as EE-3A, transected the seismic cloud and intersected a number of joints that had been opened during the MHF. Additional stimulation from EE-3A produced good flow connections between the two wellbores. This event marked the first time in the history of hydraulic stimulation that there was a direct verification of the assertion that induced seismicity indicates the flow of pressurized fluid.

Preparations for Extended Flow Testing

The ICFT. After some preliminary short flow testing, an initial closed loop flow test (ICFT) of the deeper HDR reservoir at Fenton Hill was conducted in the spring of 1986 (Dash, et al., 1989). During this and all subsequent flow tests at Fenton Hill, wellbore EE-3A was used as the injection well and EE-2 (designated EE-2A after its redrilling, as discussed below) was used as the production wellbore. The 30-day ICFT was run at two injection pressures, 27 MPa and 31 MPa. Pumping rates at these two pressures were typically 10.6 and 18.5 l/s, respectively. The production side of the loop was maintained at a backpressure of about 3.5 MPa to prevent boiling of the superheated water or release of the gases (principally carbon dioxide) entrained in the circulating fluid.

Only about 40 microseismic events were detected during the lower pressure part of the ICFT, but several hundred were observed when the pressure was raised to the higher level. The seismic activity was distributed in a highly asymmetric manner around the injection wellbore, with almost all the seismicity occurring on the side of the reservoir away from the production well. In other words, reservoir growth appeared to take place in that portion of the reservoir which was isolated from the pressure sink provided by the

production wellbore. If a second production wellbore had been drilled to penetrate that part of the reservoir, this would have alleviated the problem of reservoir growth at the higher injection pressure of 31 MPa and at the same time provided greatly increased energy production. This important observation highlights the importance of multiple-production wellbores to the development of efficient HDR systems.

The fluid temperature at the surface and the production flow rate continually increased over the course of the ICFT, eventually reaching 200°C and 14 l/s, respectively. By the end of the test, thermal energy was being produced at a rate of 10 MW. A total of 37,000 m^3 of water was injected over the course of the 30-day test. Sixty-six percent (66%) of this water was returned to the surface at the production well during the test itself, and another 20% was recovered during a subsequent venting operation. The results of this 30-day flow test demonstrated the suitability of the Phase II HDR reservoir for long-term flow testing.

<u>Sidetracking and Redrilling of the EE-2 Wellbore.</u> The EE-2 wellbore had been badly damaged by the catastrophic events that ended the MHF. Repairs to a depth of 3,268 m were completed prior to conducting the ICFT described above, but budgetary considerations and technical uncertainties led to a decision to make only temporary repairs below that depth. It was realized, however, that a competent wellbore would be very important in extended high-pressure testing. Therefore in 1987-1988, after the successful completion of the ICFT, the EE-2 wellbore was sidetracked beginning at a depth of 2,964 m to a new total depth of 3,767 m (Dreesen, 1989) After a number of preliminary pressurization, flow, and tracer tests, the well, now called EE-2A, was completed to give an open-hole production interval extending from 3,284 to 3,673 m.

<u>Design and Construction of a Permanent Surface Plant.</u> The flow tests of the Phase I HDR reservoir and initial flow testing of the Phase II system had been conducted with a combination of owned and rented equipment, and with temporary piping to connect the injection and production wells at the surface. In preparation for extended testing of the deeper HDR reservoir, a permanent surface facility, designed to power plant standards, was constructed at Fenton Hill between 1987 and 1992 (Ponden, 1991). The plant was designed for automated operation on a continuous basis with provisions for monitoring all the important parameters associated with the operation. It was run from a personal computer with numerous fail-safe measures incorporated into the system software. The sophisticated design of this plant permitted steady-state flow testing to be conducted with a minimum number of personnel. In fact, when operating under routine conditions, the plant often ran for long periods with no human intervention.

Reservoir Testing at Fenton Hill

<u>Static Pressurization Testing.</u> A number of pressurization tests were conducted during times when it was impractical to circulate fluid through the reservoir. One long static experiment entailed pressurization of the reservoir to different levels for extended periods. Several important results were obtained from this test. The most important finding was that the rate of water loss declined consistently with time at any given pressure, eventually reaching a very low level (Brown, 1991). This work showed that much of the apparent water lost in the Fenton Hill HDR operation was actually stored in the interstices of the rock just beyond the fractured boundary of the reservoir. Other static experiments entailed the determination of the flow-connected volume of the reservoir by measuring the change in reservoir fluid capacity as a function of applied pressure. The reservoir volume obtained by this hydraulic technique (about 16 million m^3) agreed substantially with that measured by tracer and geometric measurements and was consistent with seismic measurements.

The partitioning of injected fluid between joints and microcracks was also studied during periods of non-circulation, with the data showing that at or below 15 MPa, about 75% of the injected fluid was stored in microcracks but above that level most additional water went into storage in propped-open joints. Other work demonstrated that the reservoir had a very non-linear response to pressure, with each increment in pressure giving a greater reservoir inflation volume so that the effects of pressure increases grew substantially greater with pressure over the range of 5-12 MPa.

Simple monitoring measurements made after a rapid deflation of the reservoir showed that the reservoir pressure increased during periods of prolonged shut-in at a rate of 0.02 MPa per month (in spite of a leak of about 0.1-0.15 l/s to the surface) as fluid from the now-overpressured boundary region slowly seeped back into the deflated reservoir. In another straightforward observation, the response time at the production wellbore to pressure changes imposed at the injection wellbore was shown to be about 14 minutes for this reservoir, in which the two wellbores are separated by an average distance of about 110 m through production interval. Taken as a whole, these static reservoir studies, while simple and inexpensive to conduct, provided a great deal of fundamental knowledge about the deeper Fenton Hill HDR reservoir and formed the basis for some valuable insights into HDR technology in general.

Flow Testing. Water was circulated through the deeper HDR reservoir for a total of about 11 months in a series of flow operations carried out from April 1992 through July 1995. During three long steady-state test segments, flow rates of 5.5-6.5 l/s at temperatures in excess of 180°C were routinely maintained (Duchane, 1997). Although the reservoir management strategies during the interim periods between these steady-state segments varied significantly, they apparently had no effect on the reservoir productivity. Water losses under steady-state pressure conditions declined steadily regardless of whether or not circulation was maintained, thereby verifying that water consumption in HDR reservoirs, in the absence of reservoir growth, is largely the result of permeation from the pressurized joints into the micropores of the reservoir rock blocks and outward diffusion through the sealed joints and rock at the periphery of the reservoir.

Tracers tests conducted during all three steady-state flow periods revealed the dynamic nature of the flow paths within the reservoir, with some flow paths closing and others developing as circulation proceeded, and overall fluid access to the hot reservoir rock increasing with time. The geochemistry of the fluid being continuously recirculated through the reservoir was consistently benign. Dissolved solids rapidly reached equilibrium levels of 3,000-4,000 ppm (about one-tenth the salinity of sea water) and remained within that range during all three test periods. Almost no suspended solids were brought to the surface. Low levels of dissolved gases, principally carbon dioxide, were contained in the circulating water, but no gaseous emissions to the atmosphere occurred during normal, pressurized, closed-loop operations of the HDR system.

The potential for the operation of an HDR reservoir to meet time-varying energy demands was evaluated in two important short flow test segments (Brown, 1996). These brief tests showed that it was possible to increase the productivity of this HDR reservoir by as much as 60% within a period of about 2 minutes and to maintain that elevated level of production for at least 4 hours before rapidly reducing output back to the baseline level. This important result demonstrates the high level of operational control that can be imposed on an engineered geothermal reservoir to provide a load-following power output.

General Conclusions from the Fenton Hill HDR Program

Drilling and Reservoir Development. The entire concept of reservoir development has been revolutionized by the work at Fenton Hill since 1983 (Brown, 1990). The approach taken today would entail first drilling a single wellbore into the hot rock resource. Fracturing would then be conducted to create a reservoir. Seismic technology would be employed to rapidly assess the shape and orientation of the reservoir that nature was creating. The stimulation would be continued until seismic signals indicated that a reservoir of the desired fluid-accessible volume had been developed. Only then would the production wellbores be drilled. On the basis of all reservoirs developed to date, the need for 2 production wells, one on either side of the injection well, would be anticipated. These wells would be positioned to intersect the reservoir near the opposing boundaries so that access to the reservoir would be maximized and the pressure-relief aspects of the production wells could be capitalized upon. Consideration would be given to employing multiply-completed production wells to access as much of the reservoir as possible.

Based on our experience at Fenton Hill, we do not endorse the concept of multiple, vertically separated reservoirs accessed from one set of wellbores. In our view, experience has shown that there is no demonstrated way to control access to a single reservoir and there is certainly no way at present to deliberately apportion flow among multiple reservoirs. We do think that strategies to increase production, such as employing multiple collection points from a single reservoir or the use of downhole pumping, have a great deal of merit

Reservoir Operations The experience at Fenton Hill demonstrated beyond a doubt that it is possible to operate HDR reservoirs routinely and that a high degree of flexibility in reservoir operations is possible. The resiliency of HDR reservoirs was demonstrated by the ability to return to very similar levels of production after one period of intermittent operations characterized by an on/off operating schedule with the reservoir pressure maintained but intermittent circulation, and a second period of 2-years during which the reservoir pressure was allowed to decline from the operating pressure of 27 MPa to a low level of about 10 MPa. In all cases, steady-state operating conditions were quickly re-established after start-up. Finally, short cyclic flow tests showed the potential for load-following operational schedules.

Reservoir Characteristics. As the deepest, hottest, and tightest HDR reservoir developed to date, the deeper Fenton Hill reservoir is the best example of the "pure HDR" end of the geothermal resource spectrum. The reservoir properties identified at Fenton Hill must therefore be regarded as setting the standard of expectations for the characteristics of deep, hot, tight HDR systems.

The cumulative results of over ten years of study indicate that joint sets in the Fenton Hill reservoir open and close at different, but predictable, pressure levels. The reservoir flow paths have been found to be highly dynamic during circulation, with both gradual and sudden changes in the flow characteristics observed at various times. By contrast, the reservoir fluid showed an unusually stable geochemical profile. No matter what operating scenarios were imposed upon the reservoir the pH, total dissolved solids level, and other geochemical parameters remained essentially constant. Even when the recirculating fluid was replaced completely with fresh water, the geochemical parameters returned to the previous equilibrium conditions within a matter of a few weeks.

Experimental work at Fenton Hill also verified that the bulk of the impedance to flow in the reservoir was concentrated near the production wellbore. This is hard evidence for a conclusion that can be reached by simple logic (given the knowledge that the production wellbore is a center of pressure-depression during circulation). It should provide a strong impetus for directing future impedance-reduction efforts toward measures that have their

greatest effect near the production wellbore. It also suggests that, because the body impedance of the reservoir is only a small fraction of the total, impedance considerations should not be a barrier to the development of much larger reservoirs with greater wellbore separations.

Reservoir Thermal Lifetime. Because no significant thermal drawdown was observed, Fenton Hill provided little direct information on the expected useful thermal lifetime of HDR reservoirs. No tendency toward short circuiting was observed and, in fact, tracer studies indicated a dynamic flow redistribution to more, rather than fewer, flow paths over time. Using Fenton Hill flow test data as input, the GEOCRACK reservoir model, developed by Kansas State University, predicts that, when operated under controlled conditions, Fenton Hill type reservoirs can have long, highly-productive lifetimes.

The General Viability of HDR Technology. In spite of many technical and organizational difficulties, the sustained operation of the deeper HDR reservoir in a manner that faithfully simulated a commercial power-producing facility demonstrated that there are no fundamental technical obstacles to the development of commercial HDR systems. This reservoir, coupled to a power-industry-quality surface plant, routinely produced 2 to 3 times the amount of energy required to operate the facility. Extended automated operations lasting for weeks at a time showed the potential for routine power production with a minimum of manpower. Premature thermal drawdown, water loss, geochemistry, scaling, wellbore deterioration, and other factors that had been prophesied as possibly insurmountable HDR problems were shown to either be tractable or to be non-issues.

Economics and locational flexibility remain as the primary unanswered questions that hinder the development of commercial HDR facilities. The experiences at Fenton Hill and elsewhere have provided the technical base needed to develop lower-cost, more-productive HDR systems that will address these concerns and bring HDR technology to commercial fruition.

THE FUTURE OF HDR DEVELOPMENT IN THE UNITED STATES

The Current Prospects. The US Department of Energy (DOE), working through the Los Alamos National Laboratory (LANL) has to date been the primary sponsor of HDR work in the United States. Between 1974 and 1995, most work on HDR in the US was carried out at the Fenton Hill, NM field site, but that facility has now been totally decommissioned and most of its wellbores have been plugged. The DOE has declared its intent to pursue future HDR work through the commercial geothermal industry. In September 1997, the DOE issued a contract to a private firm to develop a plan for HDR development. According to DOE documents the plan should include a five year program to address the technology improvements needed to commercialize HDR, promote integration of HDR goals with the goals of the conventional geothermal industry, provide for field testing with industry partners, and foster continued interactions with international HDR efforts. If all these directions are actually pursued in a unified and concerted effort , there will be ample opportunities to bring HDR technology to commercial fruition in the US.

It is the view of the authors of this paper, however, that events of recent years indicate the most likely future direction of HDR research and development in the US will be to simply subsume it into the DOE hydrothermal program. Although such an approach may lead to increased productivity of marginal hydrothermal resources, it will not provide the inducement for the breakthrough demonstrations required to show the world that the vast geothermal resource found everywhere in the form of HDR can be economically extracted. Such a short-sighted direction will thus effectively condemn geothermal energy to a continuation of its current role as a minor and regional player in the world energy market.

<u>What Should Be Done.</u> What is needed in the US and elsewhere are operating HDR sites where field work can be conducted both to increase the understanding of HDR phenomena and to provide hard data regarding the economics of HDR energy production. To the extent possible, these should be new sites that can be developed based on our most recent understanding of the various HDR-related technologies and that do not carry the burden of existing underground operations that may now be obsolete. New, deep reservoirs are needed to confirm that Fenton Hill is not an anomaly. The current reservoirs in Japan and Europe are unique HDR-type systems, but they are somewhat more toward the hydrothermal end of the geothermal spectrum than was Fenton Hill. The Japanese reservoirs are much shallower and apparently much more open, while the system at Soultz-sous-Forets in Europe is actually a hot wet rock reservoir. Ultimately, we must learn to extract useful energy from the full spectrum of geothermal resources. To achieve that goal increased research and development to elucidate both the similarities and differences between HDR and conventional geothermal resources is imperative.

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