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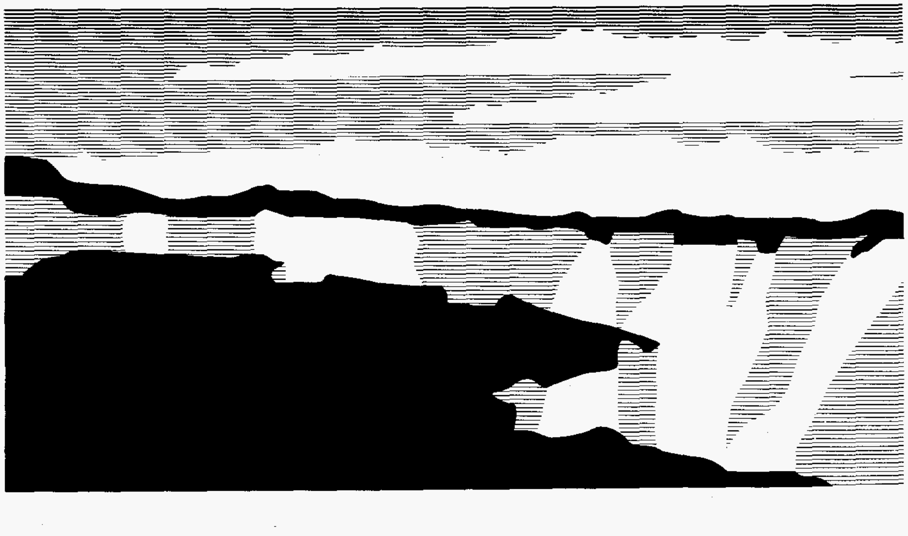

Los Alamos
NATIONAL LABORATORY

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THE HISTORY OF HDR RESEARCH AND DEVELOPMENT

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Abstract

An energy source rivaling the sun exists in the form of the heat emanating from the interior of the earth. Although limited quantities of this geothermal energy are produced today by bringing natural hot fluids to the surface, most of the earth's heat is trapped in hot dry rock (HDR). The application of hydraulic fracturing technology to tap this vast HDR resource was pioneered by Los Alamos National Laboratory beginning in 1970. Since that time, engineered geothermal reservoirs have been constructed and operated at numerous locations around the world. Major work at the US HDR facility at Fenton Hill, NM, and at the British HDR site in Cornwall, UK, has been completed, but advanced HDR field work continues at two sites on the island of Honshu in Japan and at Soultz in northeastern France. In addition, plans are currently being completed for the construction of an HDR system on the continent of Australia

Over the past three decades the worldwide research and development effort has taken HDR from its early conceptual stage to its present state as a demonstrated technology that is on the verge of becoming commercially feasible. Extended flow tests in the United States, Japan, and Europe have proven that sustained operation of HDR reservoirs is possible. In support of these field tests, an international body of scientists and engineers have pursued a variety of innovative approaches for assessing HDR resources, constructing and characterizing engineered geothermal reservoirs, and operating HDR systems. Taken together, these developments form a strong base upon which to build the practical HDR systems that will provide clean energy for the world in the 21st century.

Introduction

With one exception, all energy resources are ultimately derived from solar radiation. Fossil energy consists of solar energy placed in long-term chemical storage, hydropower and wind energy are the products of much shorter-term solar energy storage, and photovoltaic and direct-thermal processes immediately convert solar energy to electricity or heat for use by mankind. Only geothermal energy, arising from the primeval heat of the interior of the earth and from natural radioactive decay, is derived from a source that is entirely independent of the solar flux. Geothermal waters from hot springs have been used since the dawn of civilization and, during the twentieth century, natural reservoirs of geothermal fluids have been tapped to produce ever-increasing amounts of electric power.

Today, the commercial geothermal industry is established in many parts of the world but, unfortunately, the technologies presently employed permit extraction of only the small fluid fraction of the very large available geothermal resource. To date, geothermal energy has been commercially produced only at those relatively isolated locations where natural reservoirs of hot water or steam exist. The technology to retrieve and use the vast hot dry rock (HDR) resource found at reachable depths, but locked in rock that is hot but not in contact with mobile fluid, is only now beginning to reach fruition.

Development of this advanced geothermal technology began in about 1970 when a method of extracting geothermal energy from HDR was conceived at Los Alamos National Laboratory. Beginning with that pioneering work in the USA, progress toward utilizing HDR energy has been moving forward at an ever-increasing rate. More nations are becoming involved in HDR development, and a store of knowledge is being accumulated that is continually broadening the base of HDR technology. In the past three decades, major HDR research, development, and demonstration projects have been mounted in the US, Great Britain, continental Europe, and Japan. More recently work to develop HDR resources has begun on the Australian continent. This paper is an attempt to review the history of HDR, and thereby to demonstrate the progress that has been made, as well as inspire the additional work needed to bring this revolutionary technology to commercial fruition.

Scientists from Many Nations Working Together

International cooperation has been a hallmark of HDR research and development from almost its earliest days. International participation in the original HDR project in the US included extended visits by scientists from Europe and Japan, ultimately leading to a 6-year, large-scale collaboration from 1980-1986, conducted under an agreement put together by the International Energy Agency. Virtually all other HDR field projects have also benefited from participation by multi-national groups of scientists and engineers, including most recently the extensive flow-testing program conducted in 1997 at Soultz in northeastern France.

Regular international conferences such as the HDR Forum series have served to foster the exchange of ideas and information among researchers from around the world. These have been supplemented by special meetings such as the HDR Academic Review held at Sendai, Japan in 1997 and several earlier similar conferences, and by special sessions on HDR at meetings of the International Geothermal Association and similar organizations. In addition to these broad avenues of international cooperation, topical collaborations on HDR support technologies, such as the Japanese-sponsored MTC project on seismic technology development, have promoted even greater international cooperation on specialized aspects of HDR science and technology.

HDR Concept Development Around the World

Field testing to demonstrate the validity of the HDR concept began at Los Alamos in 1973. By the late 1970s, HDR field work was underway at a number of locations around the world. These early efforts involved drilling, fracturing, and circulation experiments that provided a wealth of basic scientific information, served as testing grounds for scientific tools and techniques, and created an international community of HDR experts. All of the major HDR programs discussed later in this report had their origins in the preliminary work summarized below.

The hot dry rock patent application filed by Los Alamos National Laboratory in March 1972, and subsequently granted on January 22, 1974 (Potter, et al.), describes two wellbores connected to opposite ends of a vertically oriented crack produced by hydraulic fracturing in crystalline basement rock. The concepts described in this patent provided the framework for early HDR experiments. Preliminary work at Los Alamos began in 1971 with the drilling of shallow wells and heat flow measurements at a number of locations in the nearby Jemez Mountains. In the spring of 1973, the first hydraulic fracturing test in crystalline rock was conducted at a site known as Barley Canyon about 35 miles west of Los Alamos (Smith 1995). This test proved successful, but the location was not suitable for the construction of a permanent HDR test site. Further HDR work in the US was therefore conducted at Fenton Hill, a more convenient location a few miles away.

In Britain, a granite quarry at Rosemanowes, near Penryn in Cornwall, was selected as the site for initial HDR work by the Camborne School of Mines (Parker 1989). This provided immediate access to the type of hard crystalline rock that was considered most suitable for HDR development. Beginning in 1977, researchers drilled 2 boreholes to a depth of 300 m, stimulated the granite to create a connection between the boreholes, and circulated water through the rock. Rock temperatures were not an issue in these early studies because the British HDR project was not directed toward producing energy, but rather at understanding the hydraulic fracturing process and its application to the generation of connected fluid pathways in jointed rock.

Early HDR studies on the European continent included work at Falkenberg from 1978 to 1986 and at Urach from 1977 to 1983 (Rummel et al. 1992). In the Falkenberg project, an artificial fracture was stimulated from a well at a depth of 450 m. Seven additional wells were subsequently drilled in a pattern above the fracture. Several of these wells intercepted the fracture to the extent that small amounts of water could be circulated through the fracture, and extensive hydraulic and rock mechanical experiments could be conducted. Among other findings, the Falkenberg experiments proved that hydraulic pressure alone could keep joints open. At Urach, a borehole was drilled to 3,500 m where temperatures reached 150°C. Deep hydraulic stimulations and related experiments were performed there over a period of many years and, for a time, Urach was one of the sites considered for the establishment of the joint European Community HDR facility.

After preliminary investigations beginning in 1978, fundamental fracturing and circulation work was carried out in the Massif Central (Le Mayet de Montagne) in France between 1984 and 1989. Two 800-m boreholes were drilled and borehole packers were used to isolate a number of zones over a span of several hundred meters for multiple stimulation experiments. Several small circulation experiments were completed at this site. Perhaps most notable is the fact that electrical borehole imaging was first put into practice at Le Mayet de Montagne.

Field work in Sweden was conducted at Fjallbacka, where two 450-m deep boreholes were drilled and a small circulation loop was constructed in the late 1980s. Rock mechanics and related studies at Fjallbacka continued into the mid-1990s. In 1986, the Germans and French began to work at Soultz, located in the Rhine Graben north of Strabourg. The area around Soultz has some of the highest geothermal gradients in northern Europe.

The Japanese began preliminary HDR field work at Yakadake near Nagano in 1978. Their initial efforts included fracturing, acoustic emissions, and other fundamental studies under the sponsorship of the New Energy Development Organization (NEDO). These experiments set the stage for the development of a complete HDR system within the Hijiori Caldera in northern Honshu (Tomita, et al. 1988). In the late 1980s, a second Japanese HDR project, sponsored by the Japanese Central Research Institute for the Electric Power Industry (CREIPI) got underway at Akinomiya, also on Honshu, using a unique approach to create vertically-separated reservoirs from a single wellbore (Kaieda 1990).

HDR work has also been carried out in the former Soviet Union and in Eastern Germany (before unification). In total, the past 25 years have seen HDR drilling and fracturing conducted at about a dozen sites around the world. These diverse experiments created a cadre of HDR experts, many of whom remain deeply involved in HDR research and development today.

Comparison of Some Major HDR Systems: Similarities and Differences

The history of HDR research and development can perhaps best be understood by a review of some of the major field projects conducted in the various countries. Without exception, HDR field development activities have been evolutionary in nature. In all cases, the original plans were modified to adapt to unanticipated conditions and events. Unique contributions to the present day picture of HDR were made during the course of each project, but no single project has totally defined the HDR situation as it is understood today or as it is likely to be encountered in the construction of future reservoirs.

As HDR technology has matured, it has become apparent that each new HDR system will have unique characteristics. In fact, the only thing the world's HDR projects have entirely in common is that the reservoirs involved were created by hydraulic fracturing in hard, crystalline rock. There are, however, a number of underlying reservoir development and characterization concepts that have been found to be generally applicable to all HDR situations. Tables 1 and 2 summarize some salient features of selected HDR systems developed over the past 25 years, and more details about each of the projects associated with these systems are provided in the discussions that follow.

The Phase I Fenton Hill Reservoir: Pioneering Work at Los Alamos (1974-1980). The world's first functional HDR reservoir was developed at Fenton Hill, New Mexico, USA, beginning in 1974. Fenton Hill lies on the western flank of the large Valles Caldera within an area of elevated geothermal gradient (65°C/km). The granitic rock at Fenton Hill is overlain by about 730 m of volcanics and sediments. The first well was drilled to a depth of 2.9 km where the temperature of the granite was 197°C. After a number of preliminary scientific measurements at several depths, a series of hydraulic fracturing experiments was carried out. A second wellbore was then drilled toward the apparently induced fracture.

Table 1: Physical Characteristics of HDR Reservoirs

Location	Natural Rock Permeability	Depth to Reservoir, km	Nominal Reservoir Temperature	Estimated Reservoir Volume, $m^3 X10^6$
Fenton Hill Phase 1	Low	2.9	170 - 190	0.6
Rosemanowes	Low	2.6	80 - 100	3.5
Fenton Hill Phase 2	Very low	3.5	240	6.5
Hijiori	High	1.8	240	0.7
Ogachi	High	0.7 - 1.0	200	1.3
Soultz	Natural flow	3.5	170	240

Table 2: Representative Flow Parameters of Selected HDR Systems

Location	Typical Injection Pressure, MPa	Typical Injection Flow Rate, l/s	Best Sustained Water Recovery (% of Injected Flow)	Notable Features
Fenton Hill Phase 1	8	6	90	First thoroughly flow-tested system
Rosemanowes	10	20-25	80	Longest sustained flow testing: thermal drawdown observed
Fenton Hill Phase 2	27	6	93	Tightest reservoir; best true HDR example; no thermal drawdown; sustained, automated production
Hijiori	3-5	13	79	Best example of multiple-wellbore production
Ogachi	7	7-8	25	Two reservoirs from single wellbore via casing reamer/sand plug method
Soultz	2-4.5	20-25	100	Balanced injection/ production by design; beneficial use of downhole pumping; best HWR example

(The data presented in Tables 1 and 2 were drawn either from a comparative study of heat extraction from HDR reservoirs authored by Kruger (1995) or from references cited in the discussions of the individual projects, below.)

The performance of the Phase I system was evaluated in a series of flow experiments (Dash 1981). Rapid thermal drawdown (from 175°C to 85°C) was observed initially, indicating that only a small heat transfer area existed. Therefore, the reservoir was enlarged by further hydraulic fracturing and redrilling. Sidetracking of the production wellbore was necessary to establish a better reservoir connection via a combination of one apparently-induced major fracture manifolded to a number of pressure-opened joints. Altogether, the hydraulic fracturing operations employed to create and enlarge the Phase I HDR reservoir involved the injection of somewhat less than 2,000 m^3 of water. After enlargement of the reservoir, additional experiments were conducted, including a 286-day heat extraction flow test during which the fluid production temperature declined from an initial value of 156°C to a final level of 149°C.

The cooldown of the Fenton Hill reservoir made it clear that a much larger and hotter HDR reservoir would be needed to produce energy at the high rates and temperatures required for commercial power production. For this reason, plans were developed for a Phase II HDR reservoir which would be larger, deeper, and hotter. The results of Phase I led to the assumption that hydraulic fracturing typically resulted in the formation of thin, vertical fractures, and that the size and heat production capability of an HDR system could be manipulated by employing a number of fracturing operations to produce multiple, independent vertical fractures of this type. Until these preconceived notions were cast aside, extreme difficulties were encountered in the creation of a Phase II HDR system at Fenton Hill.

The British Deep Reservoir at Rosmanowes: Opening Joints and Studying Rock Mechanics (1980-1989). Having demonstrated the viability of fracturing in the local Carmelis granite, the British proceeded to develop a second system at the same site, but at a greater depth where stress conditions were thought to be more similar to those of the hot rock from which commercial quantities of HDR would eventually be extracted (Parker 1989). In 1980, they drilled two wellbores into the granite to a depth of 2.1 km. The lower portions of these wells were deviated from the vertical at an angle of 30° in order to properly align them with the anticipated stress and jointing characteristics of the granite. The boreholes were separated by 300 m at the target depth, and the bottom hole temperature was 79°C. A large simulated region was created by first using explosives to provide improved access to the granite and then employing hydraulic fracturing to open pre-existing joints. A poor connection was achieved initially, with most of the injected fluid acting to extend the system in a downward direction away from the primary flow access between the two wellbores.

To rectify this situation, a third wellbore was drilled to a depth of 2.6 km where the bottom hole temperature was about 100°C. It was directed to intercept the open-joint system that had already been developed. Stimulation was conducted in this third well using a viscous gel to increase joint opening as opposed to dilation by shear slippage. The volume of the reservoir at this stage was estimated from the location of seismic events detected during its formation, to be about 1-million m^3, but this estimate was later raised to 5- to 10-million m^3 on the basis of flow experience.

At present, Rosemanowes holds the record as the site of the world's longest HDR circulation experiment. Flow was maintained over a period of almost three years between 1985 and 1988. This long flow experiment consisted of three segments. In the first stage, the injection flow rate was increased stepwise and a number of steady state production levels from about 5 l/s to 35 l/s were maintained for short periods. Water losses were of the order of 20% at first but at the highest production rate, where the injection pressure was 11.5 MPa, water losses increased and seismicity indicated downward growth of the reservoir. The optimum circulation rate was found to be 24 l/s at 10 MPa injection pressure. In the second stage of flow testing, a downhole pump was used to lower the pressure in the production well to 4.5 MPa. Unfortunately, this procedure led to stress-closure of the flowing joints at the production well. Thermal drawdown at a rate of about 1°C/mo had been observed over the course of the above testing, and modeling indicated the possible presence of a short circuit. Therefore, a third stage of the flow test was conducted to investigate the flow paths through the reservoir by using tracers added to the circulating fluid. The tracer data indicated that a short-circuit flow path had indeed developed.

At this point in time, a feasibility study was undertaken to evaluate the practicality of constructing a commercial HDR facility at Rosemanowes in much hotter rock at an even greater depth of about 6 km. During this period, the British team was working to address the joint pinch-off problem associated with downhole pumping by using a proppant to hold the joints open near the production well. The proppant appeared to work but it made the short-circuit problem even worse. An attempt to eliminate the short-circuit pathway by sealing off the parts of the production wellbore believed responsible, subsequently led to much lower production rates. All these issues became moot when the British suspended field activities at Rosemanowes and, in 1991, redirected their HDR program towards participation in a European HDR partnership (MacDonald, et al. 1992). Over the course of the project, many innovations had been implemented at Rosemanowes and several of these were to find subsequent application at other sites as the British became involved in HDR efforts around the world.

The Second Reservoir at Fenton Hill: Deep, Hot, and Impermeable (1980-1995). In 1980, under the auspices of the International Energy Agency, Japan and the Federal Republic of Germany formally joined the Fenton Hill HDR effort. Both countries contributed funding and personnel to the project for the next five years and the Japanese continued to be a part of the program for one additional year. Development of the Phase II system by this international group took place at the Fenton Hill Site within about 100 m of the Phase I wellbores. Work proceeded under the assumption that hydraulic fracturing would lead to vertical fractures as discussed above. Therefore, two wells were drilled before any fracturing was attempted. The deeper well was drilled to a vertical depth of 4.39 km with the bottom 1.0 km directionally drilled at an angle of 35° to the vertical. The temperature of the rock at the final depth was 327°C. The second well was drilled in a similar manner to the first, but with the inclined section located 380 m vertically above the lower wellbore. The intent was to position the wellbores so that a sequence of individual vertical fractures, far enough apart to be thermally isolated from one another, could be created to connect the two wellbores.

A number of fracturing operations were conducted during 1982-1984. During the largest of these in December 1983, over 20,000 m^3 of water (more than 10 times that injected during all the experimental work with the Phase I system) was injected into an isolated zone of the lower wellbore. Neither this operation, nor any of the other hydraulic fracturing experiments conducted during this period, resulted in a connection between the two wellbores. Furthermore, microseismic data indicated that a flow connection between the two wellbores would never be established by hydraulic fracturing. In order to connect the two wells, the Los Alamos group thus decided to sidetrack and redrill the upper wellbore to penetrate the cloud of microseismic events observed during hydraulic fracturing. The sidetracked wellbore intersected a number of stimulated joints and, with some additional stimulation in that well, good flow connections between the two wellbores were obtained.

The experience of five years of drilling, fracturing, and redrilling at Fenton Hill led to a complete change of thinking in regard to the nature of the fractures produced in HDR reservoirs formed in deep crystalline basement rock. Extensive microseismic analyses and geologic evidence indicated that the original concept of vertical flow passages created by actually forming new fractures in the basement rock was incorrect. Instead, all the evidence pointed to the opening of previously existing, but sealed, joints.

A surface plant suitable for automated operation was installed and connected to the Phase II wellbores between 1987 and 1992. From 1992 to 1995, flow testing was conducted that included three steady-state production segments of 112, 56, and 65 days respectively (Duchane, 1995). Water was injected at pressures in the range of 27 MPa and produced in quantities of 5.6-6.6 l/s at temperatures consistently in the range of 180-185°C. Water losses reached as low as 7% of the injected volume. All indications were that it would have been possible to reduce water losses even further by longer steady-state operation. By the close of the Fenton Hill Phase II experiment, no reduction in the temperature of the produced fluid had been observed and much new understanding of the dynamic behavior of an HDR system had been gained. This work pointed up Fenton Hill as the best example of a truly confined HDR system, at one end of the geothermal spectrum, created in a region of deep, jointed crystalline rock with extremely low permeability and essentially no communication with open fractures or faults.

Hijiori: Multiple Wellbores into a Single Reservoir (1985-Present) Under the sponsorship of NEDO, HDR development at this locations began in 1985 when an abandoned hydrothermal well (SKG-2) within the Hijiori Caldera was refurbished for HDR work. In 1986, fracturing was conducted to create a reservoir originating from SKG-2 at a depth of about 1.80 km where temperatures were in excess of 250°C. A new well (HDR-1) was drilled to a depth of 1.8 km in 1987 to complete the first HDR circulation system in Japan. In a short circulation test, hot water and steam at 180°C were recovered. Wellbore HDR-1 was subsequently deepened to 2.2 km, another well (HDR-2) was drilled nearby to 1.9 km, and a 1-month circulation test was conducted. In both these initial tests, water recovery was less than 50%. Finally, a third well (HDR-3) was drilled to about 1.9 km and a 3-month circulation test conducted (Yamaguchi, et al. 1992). Recovery during the 3-month test ultimately reached almost 77%. At one point in this 3-production-well test, HDR-1 produced about 18% of the fluid, while HDR-2 and HDR-3 produced 39% and 43%, respectively. The Hijiori system was relatively small with the wellbores separated by only 40-70 m, but this system clearly illustrated the advantages of producing fluid simultaneously from several wellbores. The open nature of the Hijiori system is apparent from the relatively high injection rate of 15.1 l/s that was obtained at injection pressures of less than 4 MPa.

After this first series of flow tests, the Japanese abandoned Wellbore SKG-2 and, in 1992, stimulated a new, deeper reservoir from HDR-1. Well HDR-3 was deepened and well HDR-2 was both sidetracked and deepened to penetrate the new reservoir. Periodic flow and pressurization testing established that connections existed between the deepened wellbores, via the new reservoir located at a depth of about 2.2 km, but also that the upper and lower reservoirs communicated, as indicated by the production of fluid from both reservoirs even when all injection was into the lower reservoir. Evidence showed that the inter-reservoir connection existed within the body of the reservoir rock rather than as a leakage pathway near any of the wellbores (Matsunaga 1997).

Additional flow testing in 1995 and 1996 demonstrated that the connection from HDR-1 to HDR-2 is better than that from HDR-1 to HDR-3. The testing also indicated that much of the fluid is produced out of the upper reservoir. This composite reservoir system is complex, and the details of its characteristics are still being investigated. Flow modeling studies are underway to predict the behavior of the system under a variety of scenarios in order to determine the best procedures to follow during long-term flow testing scheduled to begin at Hijiori in the early years of the 21st century (Nagai & Tenma 1997).

Akinomiya/Ogachi: Vertically-Separated Reservoirs from a Single Borehole (1986-Present). The second Japanese project, sponsored by CREIPI, was begun in 1986 at Akinomiya in the Akita prefecture in far northern Honshu. Two shallow wellbores were drilled and preliminary fracturing work was conducted at several points down to 400 m. This initial work resulted in a very weak connection (about 0.1% water return). The Akinomiya site was the first demonstration of the "Casing Reamer and Sand Plug (CRSP) method, a technique for isolating zones prior to fracturing operations that eliminated the use of open-hole packers which had often been unreliable in other HDR projects (Kaieda & Hibino 1990).

The CREIPI work was moved to Ogachi in 1989. There, between 1990 and 1992, two HDR reservoirs, at depths of 700 and 1000 m, respectively, were created from a single wellbore using the CRSP technique. Seismic data appeared to indicated that the two reservoirs were oriented approximately perpendicular to one another with the deeper one directed NNE and the upper one (created after the deeper one) oriented ESE. A production well was drilled about 80 m from the injection well in 1993. The Ogachi reservoir system has been tested extensively since 1994, but it still is experiencing high water losses. With injection at 13 MPa, the production fluid temperature reached 160°C by the end of the first long flow test period, but only about 10% of the injected fluid was recovered. Additional drilling to add 27 m to the open-hole length of the injection well, and additional fracturing coupled with supplementary stimulation in the production wellbore, increased water recovery to 25% at a reduced injection pressure of 7 MPa in 1994. To date, the maximum water recovery at Ogachi has been less than 35% (Kitano 1997). Current plans are to first conduct a detailed geological survey of the immediate area, and then to drill another production well to recover a greater fraction of the injected fluid.

Soultz: Hot Wet Rock with Downhole Pumping for Enhanced Energy Extraction (1986-Present). The early European HDR projects culminated in the development of the HDR system at Soultz-sous-Forets in northeastern France. The Soultz project originated as a joint French and German venture. The British formally joined the project in 1991, and scientists from other European nations such as Sweden and Switzerland, as well as the US and Japan, have also worked at the Soultz site or on data generated at Soultz. In common with most of the HDR work conducted on the European continent, the Soultz project from its beginning has involved researchers from a wide range of universities, government scientific organizations, and, to a lesser extent, private industry, with funding provided by several national and pan-European sources.

At Soultz, two deep wells were drilled 2.0 and 2.2 km, respectively, into the Rhine Graben. These wells were separated by a distance of 0.5 km, the greatest well separation for any HDR system developed to date. Artesian flow was observed at 1.82 km in the first well (GPK-1) and at 2.17 km in the second well (EPS-1). Although previous HDR systems (e.g. Hijiori) have intercepted open faults, up to now hot wet rock (HWR) has been developed using HDR stimulation techniques only at Soultz. GPK-1 was subsequently deepened to 3.5 km, but EPS-1 was abandoned because of structural problems with the wellbore itself. During the ensuing years numerous fracturing and pressurization tests were conducted in the GPK-1 wellbore. The productivity of the borehole was increased by a factor of 15-20 by these operations, indicating a considerable reduction in flow impedance and/or the opening of new fracture pathways (Baria, et al. 1995).

In 1995, another well (GPK-2) was drilled to 3.9 km where the temperature reached 168°C. Stimulations using a heavy brine (density =1.18) and natural brine (density=1.06) were carried out in GPK-2 in an attempt to establish communication with the deepest part of GPK-1. In addition to improving the injectivity (and thus openness) of wellbore GPK-2, these test showed an immediate pressure response in GPK-1. Well GPK-2 was located 450 m from GPK 1, making the Soultz engineered reservoir system by far the largest in the world, at least in terms of wellbore separation.

During circulation tests in 1995, the utility of downhole pumping for maximizing fluid return was established. Water was brought to the surface at temperatures as high as 136°C and at rates of more than 21 l/s. Only modest injection pressures were required in this open, HWR system (Baria, et al. 1996). No tracer return was observed during 6 weeks of circulation during this test. Although total chemical degradation or adsorption on the rock surfaces could have accounted for the loss of the tracer, it was considered more likely that the lack of tracer recovery was simply indicative of a very large reservoir volume.

In 1997, the Soultz team conducted a 4-month circulation test using a downhole pump to draw water into the production well. The system was run very successfully. Water at a temperature eventually reaching in excess of 140°C was produced at a rate of 20 l/s. The injection and production rates were kept in balance by design, resulting in a steady circulation rate with effectively zero water loss. The injection pressure required to maintain the fluid balance declined with time, from about 4 MPa initially to somewhat more than 2 MPa by the last month of the test. The power balance in this experiment, with more than 10 MW of thermal energy being produced and only 200-250 kw of electricity being consumed during normal circulation, indicated that practical amounts of net power could be generated from Soultz-type systems (Baumgartner et al. 1998). Extensive tracer testing was implemented during this 4-month circulation experiment. This time, the tracers were recovered and the tracer studies provided valuable information about the nature of the Soultz reservoir (Aquilina, et al. 1998).

The recent circulation test at Soultz was conducted under conditions closer to design specifications than any previous experiment in the history of HDR research and development. The results hold great promise that engineered reservoirs with the operating characteristics needed for commercial production are within the reach of HDR technology. Indeed, plans are now underway at Soultz to drill to 5.5 km, into rock that is sufficiently hot to supply the thermal power for an industrial pilot plant capable of producing several net megawatts of electric power. If the promise of this advanced project is realized, HDR will have taken a major step toward the commercialization threshold.

Supporting Technologies

Advances, or lack thereof, in the supporting technologies needed to develop, operate, and understand HDR reservoirs have been key factors in moving HDR technology toward commercialization. Drilling and completion techniques employed by HDR projects have generally been derived from the petroleum and geothermal industries, where improvements in these very cost-intensive activities have been evolutionary rather than revolutionary over the past 30 years. Drilling and completion remain the most expensive components of HDR field projects.

Although, hydraulic stimulation is a fundamental part of HDR reservoir development, novel stimulation procedures have for the most part been implemented on an ad-hoc basis. Except for the fact that some HDR stimulations have been far larger in scale than those typically employed in the petroleum industry, perhaps the most notable non-standard stimulation procedures have been those involving the use of modifiers to increase the viscosity or density of the stimulation fluid or reduce friction, and the application of the CRSP method to avoid the use of downhole packers when isolating sections of the wellbore for stimulation operations.

Downhole logging has also played an essential role in advancing HDR technology. Many of the logging tools applied in HDR projects have been derived from those used in the petroleum and geothermal industries, sometimes without modification, but often with adaptations to permit operations in higher temperature environments. Important logging devices developed specifically for HDR projects include temperature and caliper tools as wells as a variety of borehole televiewers which rely on acoustic or visual signals to provide a picture of the wellbore rock surfaces and fractures at depth.

HDR projects around the world have dedicated a significant portion of their funds and manpower to the improvement of reservoir characterization techniques. Microseimic signals generated during the creation of HDR reservoirs are the primary indicators that joint opening has taken place, and the points of origin of such signals provide the best information available about the location, shape, and extent of an HDR reservoir. Because of the fundamental importance of microseismic data, virtually all the nations involved in HDR have devoted a significant part of their financial resources to advancing microseismic technology. The multi-year, Japanese-sponsored MTC (More Than Cloud) project, just completed, significantly advanced the state-of-the-art of microseismic technology by fostering cooperative field, analytical, and information exchange efforts to improve the quality and validity of microseismic data.

Tracer studies have always been important to HDR reservoir evaluation because tracers are the only means available at present to obtain essential information about flow through the body of the reservoir. Tracer development and application have continuously been a part of all major HDR field projects, but there remains a high potential for advanced tracer studies that could significantly improve our understanding of reservoir characteristics. The simultaneous injection of several tracers, including temperature sensitive and adsorbent compounds used in conjunction with an internal standard, for example, holds the promise of providing verifiable data regarding temperature profiles and surface areas in the body of the reservoir. Geochemical data has typically been collected during HDR flow tests and the fluid geochemistry can, in many respects, be considered a type of natural tracer for evaluating reservoir parameters. The fluid geochemistry can also provide important information about the nature of the reservoir rock, indicate natural flow sources originating in the reservoir, and warn of the potential for scaling, corrosion, or other systemic chemical problems.

Since the early days of HDR, research groups around the world have been constructing and modifying reservoir models with the goal of understanding and predicting the behavior of HDR systems. Models have been developed using a number approaches based on a variety of experimental and theoretical inputs. These range from highly mathematical simulations of joint structure based on fractal geometry, through the application of continuum theory and micromechanics to predict reservoir shape and size, to codes that utilize acoustic emissions data to define reservoir hydraulic properties, and discrete element models incorporating fluid flow and mass transfer. A wide array of models appear to be desirable and even necessary, since different models may serve complementary purposes in creating an overall picture of HDR reservoir characteristics. Because of the high "up-front" capital investment required in geothermal projects, believable models of reservoir performance will be essential to the widespread commercialization of HDR. Modeling will therefore continue to be an important part of all HDR research projects.

Summary

The diverse nature of the HDR projects discussed above together with the range of the data presented in Tables 1 and 2, testify to the fact that HDR technology has not yet advanced to the point that a system can be simply drilled and operated according to a standard, preconceived plan. The wide variety of flow test conditions, with injection at high pressures and low pressures into large reservoirs and small reservoirs at shallow and great depths, as well as production at high temperatures and moderate temperatures with high, low, and essentially zero water loss, all tend to illustrate the wide variety of HDR situations that may be either naturally encountered or established by engineering design.

The scientific conception of HDR has progressed from an early view of HDR systems as a collection of surface areas to a picture that envisions volumetric engineered reservoirs that are in many ways similar to natural hydrothermal reservoirs. Although the surface area for heat exchange is still considered important, its magnitude can only be conjectured at present. The volume of the reservoir is somewhat easier to calculate from seismic, tracer, hydraulic, and geometric considerations, but the true value of even this important parameter is highly uncertain for all the reservoirs created to date. A wide range of HDR conditions have been investigated in field experiments worldwide, and the HDR scientific and technical community has learned from all of them. If we are to gain the additional understanding required to make HDR a widely-accepted energy resource, we must continue to build and run additional experimental facilities.

The worldwide experience of almost three decades highlights both the potential and the problems of HDR. We have made HDR technology work in a variety of situations. We have shown the value of multiple production wellbores and we have extended the engineered reservoir concept to situations of low natural flow (HWR). What we have not yet done is effectively apply this experience to create an HDR system that can be completely pre-engineered. We need to do much more to integrate the vast body of HDR knowledge that has now been developed, and to bring the supporting technologies to bear on reservoir design as well as real-time reservoir analysis. As we look over the past three decades of HDR research and development, we see advances in the understanding of important HDR phenomena and increases in scale of individual HDR field projects. Much has been accomplished to bring HDR to the brink of commercial viability. With diligent effort on the part of all HDR practitioners, the next few years should see the firm establishment of an HDR industry that can provide abundant, clean energy to the world for many generations.

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