Hot Dry Rock: *A Realistic Energy Option*

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Introduction

The world runs on energy. Today that energy is supplied primarily by fossil fuels such as coal, oil, and gas. These resources are, of course, finite and, in fact, are expected to be in short supply in the readily foreseeable future. In addition, we are beginning to realize that they bring with them some serious environmental problems. When coal is burned, significant amounts of sulfur and nitrogen oxides are released to the atmosphere. These gases combine with water in the air to produce acids, which are brought to earth in rainfall downwind of the emissions source. The so-called "acid rain" thus produced has been demonstrated to have a serious effect on aquatic and plant life in regions where it has been observed.

On a more global and long-range scale, the world appears to be warming steadily because of the so-called "greenhouse effect" resulting from the large quantities of carbon dioxide being released to the atmosphere due to the burning of fossil fuels. The long-term consequences of the greenhouse effect are unknown but could include melting of the polar ice caps with resultant raising of sea levels and flooding of coastal cities, increased desertification of the planet, and other undesirable events. Evidence pointing toward greenhouse warming includes documented increases in the carbon dioxide content of the atmosphere over the past century and weather records that seem to indicate that the world is warming. For example, in the United States the decade of the 80s saw 6 of the 10 warmest years encountered since records began to be kept in the nineteenth century. While not conclusive, these facts certainly point out the need to consider mitigating action now, before we are overtaken by our own emissions.

Hydropower, the world's primary nonfossil energy source, is both cheap and clean. It has been widely developed in many parts of the world but will never fill more than a small part of the world's total energy needs. Among other alternative energy sources potentially available for exploitation are nuclear fission, solar, wind, fusion, and geothermal, including both hydrothermal and hot dry rock (HDR).

Nuclear fission is already widely used, but is currently suffering from a lack of public confidence, particularly in the United States, as the result of incidents such as Three Mile Island and Chernobyl. Solar has been demonstrated on a small scale, as has wind power. Although both of these technologies represent renewable energy sources, they can be relied upon to deliver power only intermittently and are subject to the whims of local weather conditions. Nuclear fusion is potentially an almost unlimited source of energy, relying for fuel upon isotopes of hydrogen, which are found in abundant amounts in seawater. Fusion has been unambiguously demonstrated, however, only in the highly intractable form of a thermonuclear explosion. It is estimated that it will be well into the second or third decade of the twenty-first century before ignition and containment of the fusion reaction by more controllable, nonnuclear ignition sources, such as lasers, can be developed to the point where this technology may find practical application as a power source.

Geothermal resources, in the form of naturally occurring hydrothermal fluids, are being exploited today to provide useful energy as electrical power or heat in many parts of the world including the United States, Italy, Japan, Mexico, Iceland, and the Philippines. At present, hydrothermal sources provide only a minute fraction (5000 MWe) of the world's energy needs, but the potential resource base available for exploitation is of the same order of magnitude as fossil fuel resources. Hydrothermal sources are much cleaner than fossil fuels with regard to greenhouse gas emissions, generally releasing only about 10 percent or less of the amount of carbon dioxide emitted by an energy-equivalent amount of fossil fuel. On the other hand, hydrothermal resources are of limited geographical extent, occurring primarily in areas of tectonic or volcanic activity. Thus, many densely inhabited parts of the world are poorly located for the exploitation of hydrothermal sources.

Hot dry rock underlies much of the globe. Unlike hydrothermal, HDR is widely distributed and is a common occurrence in the earth's crust. It is a resource of vast magnitude. Like fusion, it provides an almost unlimited source of energy for the planet. It is much further along the road to development and practical application than fusion, however. Hydrothermal plants now in operation demonstrate conclusively that the heat of the earth can be used as a practical source of both thermal and electrical energy if natural hot water or steam can be accessed. HDR is a logical extension of hydrothermal technology to tap into a vastly larger, universally distributed energy resource.

Magnitude of the Resource

The total quantity of heat present in the interior of the earth is extremely large, but only a small fraction of it is readily accessible by current, technically sound methods. Estimates of the recoverable energy present in HDR can be made by examining the thermal gradient with depth of rocks around the world and relating these numbers to depths attainable with present drilling technologies. Extensive information on thermal gradients is available for the United States. As the accompanying map (Figure 1) illustrates, thermal gradients of 30-50°C/km or greater are common in the western U.S. In the east, gradients are typically less than 20°C/km, but widely dispersed areas of higher-gradient rock are found, particularly along the heavily populated eastern seaboard. Estimates of the extent of exploitable HDR energy have been developed by taking into account the heat capacity of rocks, thermal gradients, reservoir sizes that can be realistically developed, drilling capabilities, and required utilization temperatures. Based on all these factors, the HDR resource base in the United States has been calculated to be between 10 and 13 million quads. As a point of comparison, world energy consumption in 1982 was slightly less than 250 quads (Armstead and Tester, 1987), and estimated worldwide fossil fuel reserves in all forms combined are only about 360,000 quads. Even if one considers just those HDR areas in which the thermal gradient is greater than 45°C/km, the U.S. HDR resource base alone, at 650,000 quads, is far greater than the combined worldwide fossil fuel resources. HDR thus represents an untapped resource which could contribute to energy security for literally thousands of years, and it could do so in an environmentally benign manner.

The existence of a pervasive heat resource residing in the earth itself has been postulated since ancient times. Thermal springs have long been used for heating. The production of electricity from hydrothermal sources began in the 1920s and is now a small, but locally significant, factor in power production at numerous locations around the world. The concept of literally "mining" the energy omnipresent in HDR is relatively new, however and has become possible only because of advances in oil and gas technology in the 1950s and 1960s.

The process of extracting energy from HDR entails the creation of a closed fluid circulation system by drilling a well into the hot dry rock and applying hydraulic fracturing techniques to induce permeability by stimulating existing natural fractures or creating new fractures. An HDR reservoir is thus created, the extent of which is governed by the pressure and volume of the hydraulic fracturing fluid as well as by the nature of the rock structure and *in situ* stresses. Water can then be pumped down the injection well, circulated through the HDR reservoir, and recovered as hot fluid at a second well drilled into the reservoir at some distance from the injection well. Heat exchangers at the surface are used to recover the mined heat from the circulating water for use in electrical power generation or for direct thermal applications such as space heating. In this manner, heat can be mined continuously from otherwise inaccessible geothermal sources without a significant net consumption of water. As an added benefit, essentially no venting of gaseous or saline fluids to the environment occurs. The result is a process for producing power that does not emit any carbon dioxide or acid rain precursors such as sulfur dioxide. HDR is thus in the same class as solar, wind, or hydropower in being an environmentally benign source of energy.

HDR History at Los Alamos

The United States Department of Energy has sponsored more than 15 years of active work by the Los Alamos National Laboratory to test the HDR concept. An extensive field test program has been under way at Fenton Hill in the Jemez Mountains of northern New Mexico, where the world's first HDR reservoir was created in 1977.

Phase I Reservoir Testing, 1974-1980

After drilling an injection well deep into granitic basement rock, water was injected at a depth of about 2.75 km (9000 ft) at an ultimate surface pressure of 14 MPa (2000 psi) in order to hydraulically fracture the rock. The reservoir thus created, the Phase I Reservoir, was accessed by an extraction well, which intersected it approximately 100 m from the injection wellbore. This system was operated for a total of about 108 days over a 2-year period, with the longest continuous run lasting 75 days. It produced pressurized hot water at temperatures in excess of 130°C at the surface with flow rates in the range of 100-200 gpm.

The Phase I Reservoir was enlarged in 1979 by further hydraulic stimulation. It was then operated for another

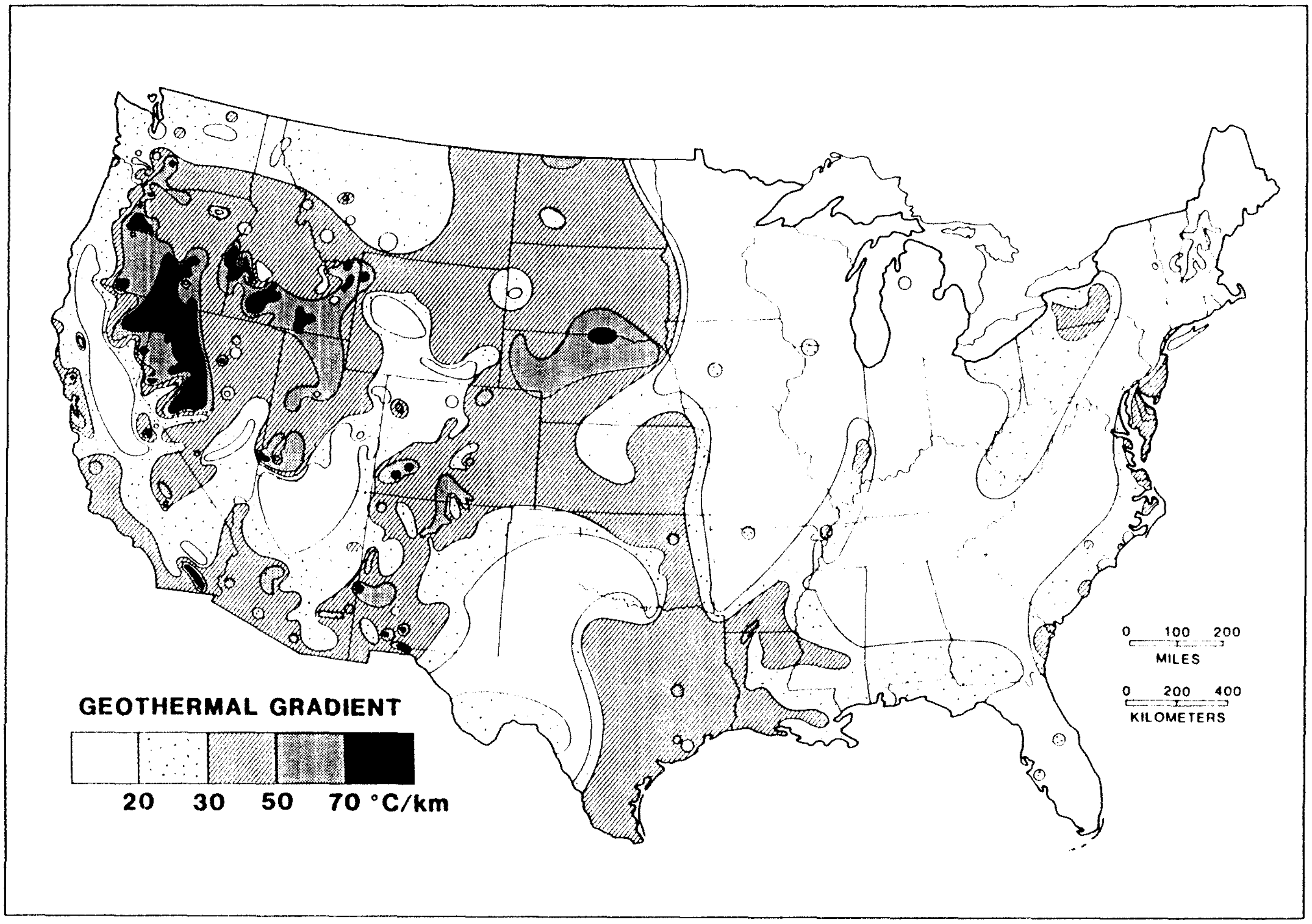

Figure 1
This geothermal gradient map shows that high thermal gradients with depth are found in much of the western United States and at a number of locations in the east.

286 days to measure its thermal and hydraulic performance characteristics over time and to determine the feasibility of the construction of a larger system for sustained energy production. It proved to be an excellent pilot scale facility for verifying models of reservoir behavior and for developing techniques and equipment to measure reservoir size and characteristics.

The understanding of the properties of reservoir rock, which is essential to the development of HDR systems, increased rapidly during the construction and operation of the Phase I system. Temperature measurements in the production well indicated that hydraulic stimulation produced multiple fractures rather than large, discrete, monolithic fractures. Prolific microseismic events were recorded during hydraulic stimulation of the rock, but the energy of these individual earthquakes was small, less than -1 on a local magnitude scale, and they were not even detectable at seismic stations located on the surface. Highly conductive fractures were produced and sustained without the use of proppants.

Slow variations were observed in the fluid flow from individual fractures during long runs. The onset, duration, and direction of these changes were unpredictable, but fortunately, they did not have a significant effect on the overall flow in the system. In fact, at constant wellhead pressures, recoverable water storage and heat extraction area increased while the impedance to flow decreased. The total dissolved solids in the fluids produced during prolonged circulation trials was low (,700 mg/l) relative to levels commonly encountered in hydrothermal brines, and there were no problems with scaling or fouling of surface equipment.

Numerous advances in technology were made during the testing of the Phase I Reservoir. It was demonstrated that hot crystalline rock could be drilled at rates comparable to those achieved in deep sedimentary formations. Deep, hot, crystalline rock was massively fractured for the first time. Methods for operating and thermally protecting sophisticated borehole instruments were devised and implemented. In cooperation with industry, mechanical seals, transducers, and electronic components were upgraded for high-temperature use. An accompanying article provides a more detailed look at the borehole logging instrumentation developed as part of the HDR program.

Significant advances were made in techniques for reservoir characterization. Microseismicity associated with the creation of hydraulic fractures was used to determine the extent and orientation of the zone of fractured rock. Interwell seismic surveying was used to detect the presence of fractured rock between wells. Methods for producing, handling, and detecting tracers in HDR reservoirs were developed and applied. Radioactive bromine with a short half-life was found to be an ideal tracer for following fluid flow in HDR.

Technological deficiencies were also highlighted by the work done on this project. In many cases these mirrored problems in the larger hydrothermal community. Estimates of reservoir size obtained by different methods varied by as much as two orders of magnitude. No way was found to reduce the pressure drop in the reservoir between the injection and production wells to very low levels without short-circuiting the flow between the wells. Commercial wirelines, logging tools, cements, and packers were all unreliable at the high temperatures encountered in HDR. Computational capabilities to model and predict performance and to estimate economic development costs were in their infancy. All these problems presented fertile ground for innovative research and development. The promising results achieved in this Phase-I work in the face of these myriad obstacles set the stage for the development of a larger scale HDR system, the so-called Phase II system.

Phase II Reservoir Testing, 1979-Present

Phase II drilling was begun in 1979. In order to connect the wells most efficiently, this system was designed to have the last 1000 m of each of the two wellbores inclined at an angle of 35 degrees from the vertical and in a direction parallel to the least principal stress in the rock formation as illustrated in Figure 2. Extensive fracturing operations were carried out in the lower well at a depth of 3500 m (11,700 ft) with the goal of connecting the two wellbores by a number of thermally isolated vertical fractures. The final attempt at fracture connection involved surface pressures as high as 48 MPa (7000 psi) at pumping rates averaging about 1700 gpm. Microseismic analysis of this fracturing trial indicated that a large reservoir, the Phase II Reservoir, had been created. Estimated dimensions were on the order of 900 m in the north-south direction, 200 m in the east-west direction, and 900 m high. Unfortunately, the Phase II Reservoir was inclined approximately 25 degrees from the vertical in a direction almost parallel with the injection well, with the major portion of the Phase II Reservoir being located below the injection well. Indications were that further stimulation would still not lead to a reservoir connection between the two wells. In order to overcome this problem, the lower portion of the other well was redrilled to penetrate into a fracture zone within the Phase II Reservoir that had been located on the basis of seismic measurements. Further fracturing was then carried out in the redrilled well, and a highly connected HDR system was created. This HDR system, which was located at a depth of about 3.6 km (12,000 ft), accessed only a portion of the Phase II Reservoir. It had an average temperature of 240°C. The separation between the wells over the reservoir interval was 110 m.

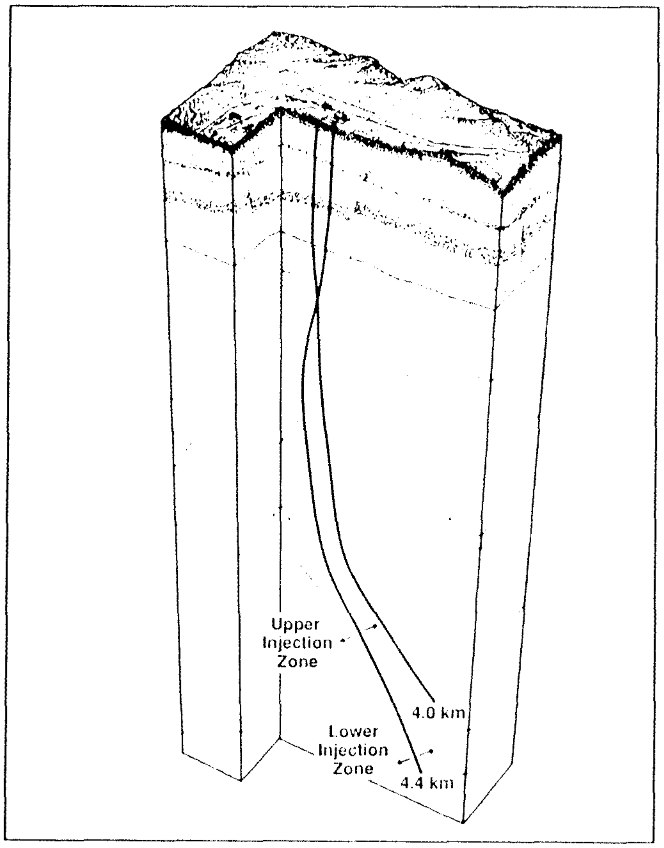

Figure 2

Phase 2 HDR wellbores were drilled at an angle of 35 degrees from the vertical for the last 1000 meters.

A 30-day trial run was conducted in the spring of 1986. This short experiment resulted in a number of important findings. Impedance to flow through the fracture system decreased by a factor of two during the test. Wellhead production temperatures steadily increased, reaching a level of 190°C by the end of the trial. Measurements indicated that there was no thermal drawdown even though only part of the Phase II Reservoir had been accessed during the test. The volume of water stored in the fractures of the reservoir increased somewhat from an initial level of 250 m^3 to a final value of 350 m^3. Water loss rates from the periphery of the reservoir during the test were strongly correlated to changes in pumping pressure, as might be expected, but declined markedly over time at a fixed pumping rate. More recent testing of this reservoir has indicated that the steady-state water loss rate at operating pressures will be very small. In late 1987, the original injection well was sidetracked to bypass damaged casing, and surface equipment was installed in preparation for extensive testing of the larger system.

Studies of the Phase II Reservoir have continued to challenge our understanding of deep basement rock. The microseismicity that occurred during hydraulic stimulation of fractures in the Phase II Reservoir was more energetic than that found in the Phase I work, having a maximum local magnitude of 2. Analysis of microseismic data indicated that variations in temperature and penetration rate encountered during Phase II drilling, could be closely correlated with flow paths in the reservoir. In addition, flow impedance has been shown to be related to both reservoir structure and the orientation of *in situ* stresses in the reservoir zone. The significance of these findings and other aspects of reservoir engineering are discussed in detail in a companion article on reservoir engineering in this issue of the Geothermal Resources Council *BULLETIN*.

Enabling Technologies

Progress in the development of enabling HDR technologies has also been substantial. It has been demonstrated that sidetracking and deepening of wells in deep, hot, crystalline rock can be accomplished at costs comparable to those for similar operations in deep wells in sedimentary basins. Large diameter, open-hole packers have been engineered to give reliable performance at temperatures as high as 300°C. As discussed in an accompanying article, a wide variety of drilling and logging tools that are suitable for use in high temperature environments other than HDR reservoirs have become available both in industry and the national laboratories. Modifications in drill bit design and drilling muds have improved drilling performance, and cement compositions have been refined to obtain optimal performance at high temperatures.

A tracer with a thermally dependent decomposition rate is under development. It will be used to measure the growth of cooled rock volume during circulation in order to predict reservoir drawdown rates and remaining lifetimes. It is detectable in reservoir fluids at levels of less than 1 ppb, even in the presence of contaminants such as diesel oil or drilling fluids. Computer code capabilities have advanced to the point that reservoir test results can now be used to run simulations that are accurate enough to provide realistic predictions of long-term performance. These codes are so sophisticated that they can be applied to exploratory studies of methods for increasing energy extraction from Fenton Hill and future HDR reservoirs.

The results of all the work carried out in this phase of the HDR program are extremely encouraging. The technology base developed will be extremely valuable in the creation and operation of additional HDR facilities.

International HDR Interest

The first work on the HDR concept outside the United States began in the United Kingdom in 1977. This program was recently described in detail in the Geothermal Resources Council *BULLETIN* (Parker, 1989). The U.K. project began with the drilling of two shallow (300 m) wells in a granite quarry in Rosemanowes, Cornwall. Hydraulic stimulation was used to connect the wells and water was circulated through them. This was followed in the 1980s by deeper drilling and considerable work on the development of instrumentation. Wells were sunk to 2000 m into a region with temperatures in the range of 80°C. In a scheme similar to that employed at Fenton Hill, directional drilling was used in an attempt to connect the injection and production wells by stimulation of vertical joints. Like the Fenton Hill project, connecting the two wellbores proved to be a difficult technical challenge. The growth of the stimulated reservoir was not as expected, and water losses were significant. Finally, a third well was drilled and connected to the original reservoir by further hydraulic stimulation. The system thus created was run for an extended period.

Experiments have recently been carried out to evaluate the use of proppants to improve HDR reservoir performance, and specialized stimulation work is being planned with the goal of accessing selected portions of the reservoir. A conceptual design study has recently been commissioned to design a commercial HDR installation. This study will include design of a prototype system that can be used to demonstrate the feasibility and costs of HDR development in Cornwall, United Kingdom.

International participation in the HDR project at Los Alamos began in 1980 in the form of strong financial and technical support for the second phase of the Fenton Hill HDR Project from both West Germany and Japan. Over a span of 5 years, Germany contributed \$12.5 million and had three engineers on-site full time. The Japanese contributed \$15 million to the project over 6 years. They sent 27 different people to work at the site for varying lengths of time, typically averaging a few months in duration.

The Japanese have since mounted an extensive HDR program of their own. Major activity is centered in Hijiori in the northern part of the island of Honshu. They have used an abandoned hydrothermal well for initial stimulation work and as their injection well. Two production wells have been drilled. The first well was only weakly connected to the stimulated reservoir, but the second well produced energy in the range of 4.5 MWt. There have been significant water loss problems with this system in spite of relatively low injection pressures.

The Japanese propose to drill a third well at Hijiori this year to access that portion of the reservoir on the opposite side of the injection well from the current two production wells. Eventually, the hydrothermal well will be abandoned and a deeper reservoir created by additional drilling and fracturing in the wells specifically drilled for this program. A three-well system will thus be created with the injection well approximately in the middle and production wells near opposite ends of the reservoir. This should result in more efficient utilization of the total reservoir thermal potential, reduced water loss, and inhibition of unwanted reservoir growth (see the companion article on reservoir engineering). Long-term testing of the three-well system is scheduled for 1993-1994. Energy production in the range of 10MWt is anticipated.

At present, the Japanese program, with a budget of more than $6 million, is larger than that in the United States. Many of the personnel sent to the United States by Japan in the 1980s are currently working in the Japanese HDR effort.

West Germany and France are currently involved in a joint HDR program. Geophysics and stimulation studies are being carried out at a depth of 2000 m at a site in Soultz, near the German border in the northeastern corner of France. There is also an effort in the USSR under the direction of the Leningrad Technical Institute involving field testing at two sites.

Future Plans at Los Alamos

The major objective of the U.S. HDR program being carried out at Fenton Hill is to demonstrate the temporal viability of the resource with a long-term flow test (LTFT) of the Phase II system. This experiment is scheduled to begin in 1992. Preparations for it include a complete rebuild of the surface fluid-handling and pumping system to match it to the characteristics of the Phase II Reservoir. These involve injection and production pressures as high as 3500 psi and 1000 psi, respectively, temperatures in the range of 200°C at the surface, and an increase in thermal power production to a level of 10 MWt from the 3 MWt of the Phase I system. In addition, the surface plant will be able to accommodate changes in the chemistry of the production fluid and the continual reduction in flow impedance that are expected in light of observations in the Phase I work.

Thermally activated tracers, being developed at Los Alamos, will be applied to the measurement of reservoir heat exchange areas and changes in reservoir temperature profiles. Computer codes for predicting long-term reservoir performance will be revised on the basis of data obtained during the LTFT to provide more accurate reservoir lifetime information and improved cost estimates for the operation of HDR systems – all with the aim of acquiring more of the data required for the construction of a commercially viable HDR facility.

In this regard, the development of a so-called second-site HDR system in the United States is of paramount importance. The Los Alamos operation at Fenton Hill serves as a test-bed to demonstrate that HDR can provide a source of usable energy in practical quantities over a reasonable length of time. A second U.S. site, at another location and in a different geological environment, is essential to verify the general utility of the hot dry rock technology developed at Fenton Hill.

Summary

In 1970, the concept of utilizing HDR as a practical energy source was little more than science fiction. Today, after more than 15 years of intensive field work at Fenton Hill, the viability of this concept has been demonstrated in experimental systems. Worldwide interest in the development of this resource has led to active programs in a number of countries. The goal for the future is to overcome existing impediments so that this abundant, widespread, and environmentally sound technology can be brought to the market by industry at an economically competitive price.

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