LA-UR -92-978

C

LA-UR--92-978

DE92 011234

TITLE: HDR OPPORTUNITIES AND CHALLENGES BEYOND THE LONG-TERM FLOW TEST

AUTHOR(S): DAVE V. DUCHANE

SUBMITTED TO: USDOE GEOTHERMAL PROGRAM REVIEW

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO. 836 R4
ST. NO. 2629 5/81

DISCLAIMER

HDR Opportunities and Challenges Beyond the Long-Term Flow Test

by

David Duchane
Earth and Environmental Sciences Division
Los Alamos National Laboratory

Abstract

The long term flow test (LTFT) of the world's largest, deepest, and hottest hot dry rock (HDR) reservoir currently underway at Fenton Hill, NM, is expected to demonstrate that thermal energy can be mined from hot rock within the earth on a sustainable basis with minimal water consumption. This test will simulate the operations of a commercial facility in some ways, but it will not show that energy from HDR can be produced at a variety of locations with different geological settings. Since the Fenton Hill system was designed as a research facility rather than strictly for production purposes, it will also not demonstrate economic viability, although it may well give indications of system modifications needed for economic HDR operations.

A second production site must be constructed, ideally under the direction of the private geothermal community, to begin the process of proving that the vast HDR resources can be accessed on a worldwide scale. This facility should be designed and engineered to produce and market energy at competitive prices. At the same time, a wide variety of techniques to advance the state-of-the-art of HDR technology must be pursued to develop this infant technology rapidly to its maximum potential. A number of design and operational techniques have been conceived which may lead to improved economics in HDR systems. After careful technical and economic scrutiny, those showing merit should be vigorously pursued. Finally, research and development work in areas such as reservoir interrogation, and system modeling must be accelerated to increase the competitiveness and geographical applications of HDR and the geothermal industry in general.

This paper addresses the above issues in detail and outlines possible paths to future prosperity for the commercial geothermal industry.

Introduction

The development of the technology to extract the geothermal energy found almost everywhere beneath the earth in the form of hot dry rock (HDR) has been underway for almost two decades. A technique for mining the heat from HDR was scientifically demonstrated at the Los Alamos National Laboratory in the late 1970's (Dash, Murphy and Cremer 1981). Subsequent work, both in the United States and in a number of other countries around the world, has focused on expanding the scientific understanding of the heat mining process, while at the same time engineering HDR systems to demonstrate that the technology can produce energy at economically attractive costs.

The HDR heat mining process, as developed at Los Alamos, entails first drilling a well to reach rock which is sufficiently hot to be useful. Water is then pumped down the well under pressures high enough to open up natural joints in the rock and create a man-made reservoir consisting of a relatively small amount of water dispersed in a large volume of rock. One or more additional wells are subsequently drilled to intercept the reservoir at some distance from the first.

The system is operated by circulating pressurized water down one well (the injection well), then forcing it across the reservoir and up the other wells (the production wells). As the water flows across the hot reservoir, it becomes heated by contact with the hot rock. At the surface, this thermal energy is extracted by a heat exchanger and the water is recirculated to repeat the process. The same water thus flows repeatedly around the system in a closed-loop to mine the heat from the depths of the earth.

The world's largest, deepest, and hottest HDR reservoir was created at Fenton Hill, NM, over a period of 6 years between 1980 and 1986 (Tester, Brown, and Potter 1989). In the process of doing this, numerous technical challenges related to drilling, logging, and reservoir stimulation were encountered and overcome. A 30-day flow test was conducted in 1986 using rented pumping equipment and a temporary installation at the surface. Results of that test were extremely promising (Dash 1989), as shown in Table 1.

Table 1. 30 Day Flow Test: Final Operating Data	
Injection	
Pressure	31 MPa (4500 psi)
Temperature	18°C (64°F)
Flow	285 gpm
Production	
Pressure	6.9 MPa (1000 psi)
Temperature	200°C (390°F)
Flow	220 gpm
Thermal Power Production	10 MW
Water Loss (based on injection flow)	23%

During 1987-1988, modifications were made to the underground system to improve its structural integrity. Figure 1 shows a view of this system as it exists today.

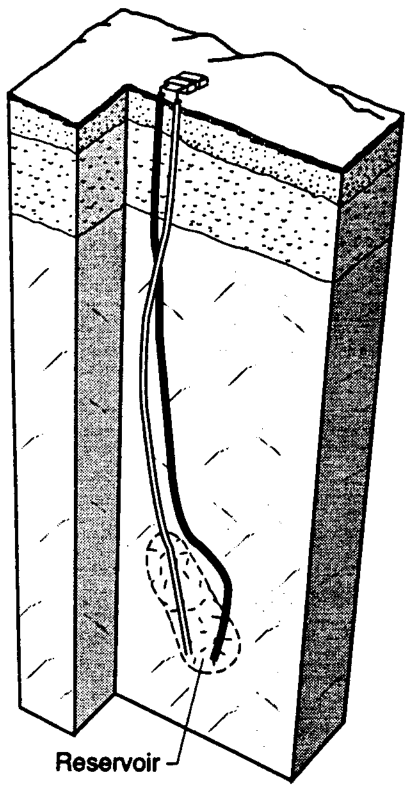

Figure 1. The Phase II HDR reservoir. The reservoir is ellipsoidal in shape with gross dimensions of approximately 200x1000x1000 meters. It is centered about 3.6 kilometers below the surface.

In the past, the course of reservoir test programs was often determined more by difficulties in pumping or in fluid handling at the surface than by reservoir performance or the best-laid reservoir assessment program. In order to overcome this problem, a permanent surface plant was designed and constructed at the Fenton Hill HDR site between 1988 and 1991 (Ponden 1991). This facility has been built to power plant standards and is highly automated. With construction of the surface plant now complete, the entire system is ready for extended testing.

A long-term flow test (LTFT) of the Fenton Hill reservoir is now underway. The duration of the LTFT is still not clear as this paper is being written. Depending upon imminent funding decisions, the test could run for as little as 90 days during Fiscal Year 1992, or could extend for a continuous period of 1 or more years. The LTFT has been designed to answer important questions regarding the ability of the Fenton Hill reservoir to deliver energy in useful quantities over an extended time period. Conduct of the LTFT over a time period long enough to produce credible thermal lifetime estimates anc thorough documentation of the test results are the nex essential steps in the development of HDR in the United States.

This paper begins with a presumption that a satisfactory LTFT will be completed and that the results will show that the effor to wrest geothermal energy from HDR is still worth pursuing From that starting point, a number of potential future technology advancements which could make HDR the geotherma energy source of the future are suggested.

HDR: The Geothermal Energy of Tomorrow

The fact that a vast amount of energy is stored underground in the form of HDR is unquestioned. Calculations based or reasonable assumptions have indicated that millions of quads o geothermal energy exist in HDR under the surface of the Unitec States at depths reachable with today's technology - enough tc supply all the energy needs of the world for thousands of years (Armstead and Tester 1987). While HDR is ubiquitous, the depth as which usefully hot rock can be reached is highly variable and is related to both local and regional geologica conditions. Figure 2, a geothermal gradient map of the Unitec States, shows that in the west HDR lies relatively near the surface in many places but in the east the resource is almost uniformly found at much greater depths.

HDR can also be an extremely clean energy source. When an HDR facility is operated in a closed-loop mode as described above, only heat is permanently removed from the earth in the course of normal operations. Since the fluid, including all dissolved species, is continuously recirculated there is no pollution of the atmosphere, terrestrial waters, or the earth, and no long term residues accumulate to present disposal problems for future generations.

Can the vast store of energy in HDR be extracted economically? A number of economic studies have indicated that it can. The most recent comprehensive analysis of the costs of producing energy from HDR appeared in a report by the Energy Laboratory of the Massachusetts Institute of Technology issued in 1990 (Tester and Herzog). This work brought together a number of previous studies on HDR economics and put them on a common footing. In addition, a great deal of new information was generated. Some important results of the MIT study are summarized in Table 2.

Table 2. Busbar Costs of Electricity From High-Gradient HDR Resources*	
Base Case	5.8¢/kWh
Optimized Drilling	4.2¢/kWh
Two Producers per Injection	3.8¢/kWh

*There are thousands of square miles of land with high-grade HDR potential in the Western US.

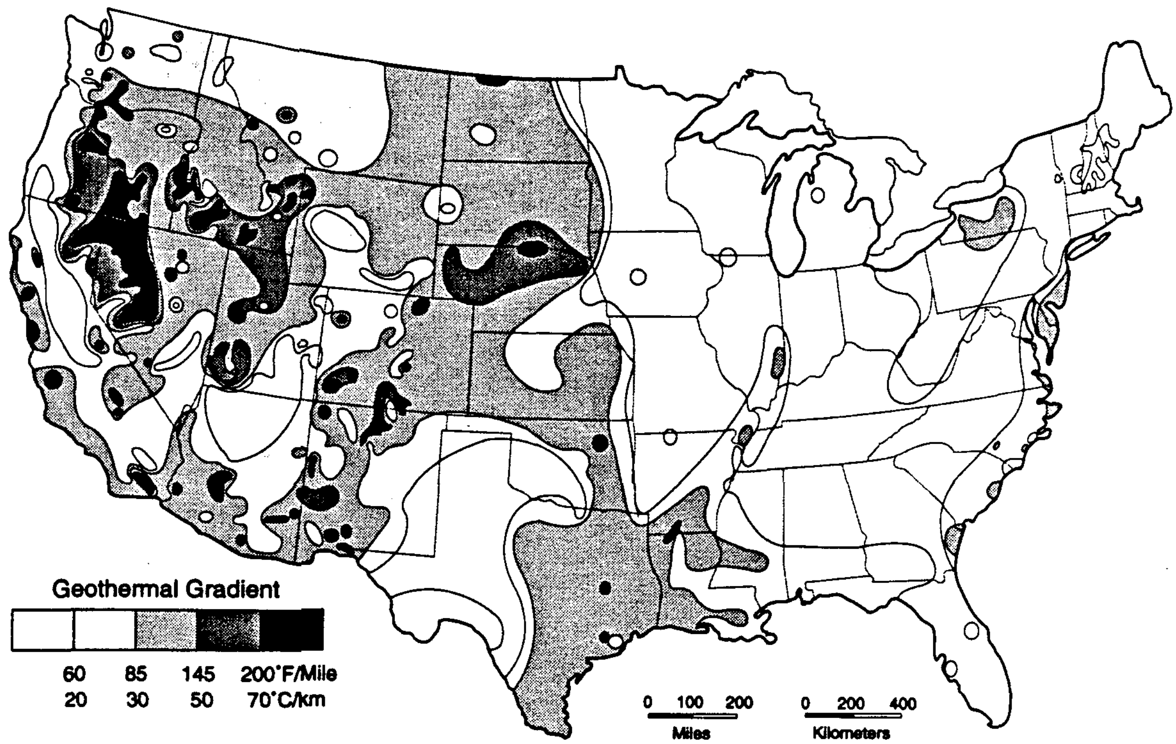

Figure 2. A geothermal gradient map of the United States. High grade HDR resources are concentrated in the west.

The data in Table 2 show that, even at the current state of technological development, electricity from high-grade HDR resources appears to be competitive with coal and nuclear energy, and while these technologies are mature, HDR is still in its infancy, with very significant cost reductions still highly probable. To date, all HDR experimental work in the United States has been conducted with two-well systems. However, as shown in Table 2, the MIT study indicates that additional operational economies could be achieved by building three-well HDR systems consisting of two producing wells and one injector. In Japan, a multiple-production-well HDR system has been developed and has shown promising technical results (Matsunaga, 1991).

Long-Term Flow Test Objectives

The LTFT will address the following issues of primary interest in future commercialization of HDR:

HDR Reservoir Thermal Lifetime: This test should demonstrate that practical amounts of energy can be extracted from the Phase II HDR reservoir over an extended time period. Studies have indicated that the Phase II reservoir has a flow-connected volume of 5-20 million cubic meters, and contains enough heat to provide high temperature fluid for many years (Robinson 1991). The LTFT will show conclusively whether or not that heat can be continuously extracted in practical amounts.

Previous extended tests of HDR reservoirs have yielded mixed results. In 1978-1980, the Phase I reservoir was flow tested in 5 segments for a total operating period of over a year (Dash, Murphy, and Cremer 1981). During the last part of that test, the fluid production temperature dropped from 158°C to 149°C over a period of about nine months while the reservoir grew in size and the impedance to flow declined. This first reservoir was undoubtedly much smaller than the current Phase II system and may have been considerably different in structure so it provides only broad guidance as to what may be expected in the current test.

The British conducted extensive flow testing of their reservoir at Rosemanowes in Cornwall, U.K., during 1985-1989 (Parker 1989). This reservoir is located at a depth of about 2 km, and has an estimated volume of 1-5 million cubic meters. The temperature of the rock is less than 100°C. Thermal drawdown on the order of 1°C per month was observed during much of the flow testing period, but this was attributed in part to the development of a short circuit causing rapid transport of water from the injection to production well with consequent inefficient heat capture. While the British test provided interesting and scientifically significant information, there is no indication that it can serve as a benchmark for expectations in flow testing of the deeper, hotter reservoir at Fenton Hill.

Reservoir Water Consumption: Water consumption has always been an issue in the operation of HDR systems. In the past, the Japanese have experienced extremely high water losses on the order of 60% or more, but in a recent test of a 4-well system, they recovered 80% of the injected water (Matsunaga 1991). The British also experienced high water losses early on but were able to keep water losses to about 20% during some phases of their circulation testing (Parker 1989).

Water losses in the range of 25% were observed at the close of the 30-day flow test of the Phase II HDR reservoir in 1986 under operating conditions leading to reservoir growth, but water consumption dropped from more than 10 gpm to less than 3 gpm over the course of a long static pressurization test of the Phase II reservoir during 1989-1991 (Brown 1991). If these results hold up in the LTFT, water consumption could be under 5% of the injected volume. Such a result would go a long way toward demonstrating that HDR plants can be built to operate with minimal amounts of makeup water.

Maintenance and Operations Issues: The surface facility at Fenton Hill was designed and constructed during 1988-1991. It has been built to industrial standards, and is highly automated. Until now, little regard has been paid to the above-ground portion of HDR plants, since development and characterization of the HDR reservoir has always been the overriding objective of previous HDR flow tests. During the LTFT, it will be practical to monitor all aspects of the performance of the surface plant. Thus it will be possible for the first time to obtain experimental data regarding parasitic power requirements, maintenance factors, scaling, and corrosion in a simulated HDR energy production facility

After the Long Term Flow Test

A Second HDR Site: The LTFT should set the stage for direct involvement in the development of HDR by the private sector. Perhaps the most important step in moving HDR toward commercialization after the completion of the LTFT will be the establishment of a second domestic HDR facility. Ideally, this installation will make full use of the technological lessons learned at Fenton Hill but will be built and operated primarily by private industry. It should be located in an area where there is a market for power and be designed to make and sell electricity at a competitive price.

Creative approaches may be required to assure that the second HDR site is economically viable. Multiple-well concepts designed to extract the maximum amount of energy at the lowest cost must be considered in designing the underground system. These are discussed in more detail below. In addition, it may be advantageous to minimize the economic risk by making HDR one component of a hybrid facility in which natural gas or another well-established fuel provides a fully-secure energy source for the substantial above-ground capital investment in powe generation.

It is unlikely that private industry will bear the entire risl inherent in constructing a second domestic HDR site. The fac that it would be the world's first HDR power producer implies a higher risk level than the power industry normally assumes Government participation may thus be required to make the development of a second site a reality. If properly conceivec and executed, however, the second HDR site could set the stage for the rapid development of fully-privatized HDF installations.

HDR Research Center: A dedicated facility to further develor and advance HDR technology is needed to assure that nev techniques to improve efficiency and address potentia operating problems are continuously made available to HDF production plants. Reduction in the impedance to fluid flow ir the reservoir body, for example, could significantly lowe pumping costs and increase production rates. During the LTFT, this is being attempted through control of the backpressure on the production well.

As illustrated in Figure 3, modeling has indicated that a low pressure zone forms around the production well during flow of the system. As a result the joints in this region tend to close up but, in theory, can be propped open by maintaining an elevated backpressure at the production wellhead (Robinson 1991). By this technique, the net pressure drop across the system may be reduced without a collateral reduction in the flow rate. Preliminary results from the LTFT seem to support this contention.

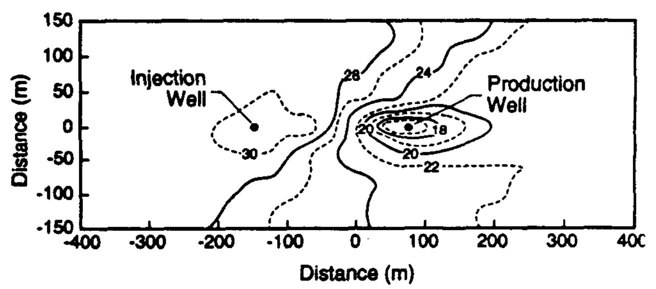

Figure 3. Simulated pressure distribution in an HDR reservoir for two-well circulation. A low pressure zone exists around the production well.

Previous attempts to reduce flow impedance have entailed jolting the reservoir with a high pressure surge in a "stress unlocking experiment" at Los Alamos (Murphy 1981) and the use of proppant materials by the British (Parker, 1989). Results were promising, but not unambiguous. Much more work needs to be done in the area of impedance reduction.

Short circuits, in which extremely rapid pathways from the injection to the production well are opened, can bring about rapid declines in HDR fluid production temperatures. Uneven cooling of the reservoir rock mass can lead to the same result. The development of sealing techniques to selectively close off unwanted flow paths would significantly advance HDR technology and improve the prospects for long-term reservoir performance.

Abrasive or chemical action by materials present in the circulating fluid may over time greatly change the nature of the flow paths within the reservoir but little is known about these effects at present. Finally, while important and novel tools for interrogating HDR reservoir have been developed, many more improvements are possible with a concerted research and development program.

All of the above efforts are important to the understanding, management, and most efficient operation of HDR reservoirs. Progress on them requires that an HDR research center dedicated to advanced research and development be maintained. It should be a joint undertaking of industry and government, and have the laboratory and plant facilities needed to carry worthwhile concepts from the initial design and testing stages all the way through field testing.

Multiple Production Wells: The LTFT is being conducted at an HDR facility consisting of one injection and one production well. Since an HDR reservoir generally forms symmetrically around the injection well, it is obvious that in any two-well arrangement, about half of the reservoir volume (that on the side opposite the production well) is wasted. In fact, calculations have indicated that the productivity of the Fenton Hill system could be increased by approximately a factor of 3, simply by addition of another production well to the system (Robinson 1991). By simultaneously applying other advanced operating strategies, the gain in productivity could be significantly greater. The Japanese have significantly improved the performance of their facility at Hijiori by the installation of multiple production wells (Matsunaga 1991).

In addition to the obvious added production possible from another outlet at a different location in the reservoir, a second production well also permits the entire system to be operated at a higher pressure. This is because production wells act as pressure relief devices in the reservoir. Experience has shown that expansion of the Fenton Hill reservoir during flow testing at high injection pressures takes place exclusively on the side of the injection well without an outlet (Duchane 1990).

Modeling, as illustrated in Figure 3, has clearly shown that production wells act as pressure sinks (Robinson 1991). The higher injection pressures made possible by two or more strategically located production wells mean that water can be pumped into the system at a greater rate and the production capacity of the system substantially increased.

Economic and technical studies have both indicated significant advantages for multiple well HDR systems. As mentioned above, it may thus be desirable to design the second HDR site as a multiple well facility in order to achieve the maximum operating efficiencies while at the same time moving HDR technology significantly forward.

Cyclic Operations: Operation of an HDR facility in the cyclic mode may offer both technical and economic advantages (Robinson 1991). In one variation of this operational strategy, water is injected under high pressure with the system shut in, the system is held at an elevated pressure for a period of time, and then a production well is opened to return the water to the surface. This water brings with it both the thermal energy absorbed during storage and much of the mechanical energy stored in the rock structure by the injection process.

In a cyclic operation, water is pumped to the far reaches of the reservoir during injection and then pushed toward the surface even from dead-end fractures by the compressive force of the reservoir rock as it relaxes during the production phase. Access to the reservoir is thus maximized. Cyclic operations also eliminate short-circuit problems by providing a fixed minimum storage period for the injected water. Thermal energy transfer is thus made independent of the pathway the water traverses between the injection and production wells.

A cyclic HDR operation could provide valuable peaking power to electric utilities. Viewed as a pumped storage facility, it might be possible to attain more than 100% efficiency, in sharp contrast to the relatively inefficient pumped storage schemes in common use today. When used as part of a hybrid system with solar or wind electric generators, cyclically operated HDR reservoirs could turn these environmentally benign but intermittent energy facilities into round-the-clock power suppliers. Alternatively, an HDR reservoir with a number of production wells could be operated in a staged mode with each individual production well cycled but overall system output maintained at a constant level.

To date, almost no experimental work has been done on cyclic operation of HDR systems. The fact that water forced into an HDR reservoir can return with incredible force was amply demonstrated, however, when a wellhead failure forced the emptying of the Phase II HDR reservoir in 1984 (Franke, et al 1986). Steam returned to the surface at an estimated power level of greater than 60 megawatts thermal during a two-day period of rapid venting and for several hours this release exceeded 100 megawatts of thermal energy. This unintended and crude experiment brought approximately 54% of the fluid stored in the reservoir rapidly back to the surface and vividly illustrated the potential of cyclic HDR production to deliver large amounts of power over a relatively short time frame. To clearly demonstrate the advantages of cyclic HDR operations, however, well designed and carefully controlled studies will be required.

Water Purification: In all the HDR facilities constructed to date, the conservation of water by continuous recirculation in a closed-loop mode has been of paramount concern. However, in some circumstances where abundant supplies of low quality water are available, it may be possible to utilize an HDR facility for both electricity generation and water purification. The need for high quality water is continually increasing around the world. At the same time vast quantities of gray water are being generated in the form of treated sewage.

An HDR facility could be designed to operate on such treated sewerage, for example. The plant could be operated in either an open-loop or partial recirculation mode to adapt to the quantities of water available. Temperatures reached underground would certainly be sufficient to destroy harmful microorganisms thus eliminating the need for chlorination. At the surface, the usual binary system could be employed to produce electricity. Excess water could then be released for other uses. Alternatively, if the hot water were free enough from minerals, it could be flashed to steam to drive a turbine directly and the steam could be recondensed for beneficial use.

Obviously the same technical approach could be used in a desalination facility to produce pure water from the sea or any of the widespread brackish groundwater sources found around the world. Because of the high mineral content typically present in such waters, techniques for removing and processing the waste salts would have to be developed or adapted from current desalination technologies.

Direct Thermal Applications: The direct use of the thermal energy from HDR for space and industrial process heating may seem like an obvious application of the technology, but significant commercial interest in this area will be aroused only when the construction of HDR systems is recognized to be highly reliable. Thermal energy is not usually marketed externally like electricity but is generally consumed by the generator. Thus it is a means to an end rather than a primary product for sale.

If HDR technology can be shown to be reliable in bringing thermal energy to the surface at almost any location, direct thermal applications will rapidly appear. Those in the geothermal power industry who have perfected HDR technology for electricity production will then be in an ideal position to exploit the opportunities for direct thermal applications. Indeed, process and space heat production from HDR may be the route to making the geothermal energy a national rather than a regional industry.

Novel Operating Fluids: Today costs and environmental considerations limit the choice of circulation fluids in HDR systems to water. In the future, however, as the technology matures, reservoir management techniques are perfected, and tighter systems are developed, other fluids may offer operational advantages. Two novel fluids seem worthy of mention even at this early stage of HDR development. Carbon dioxide is relatively cheap and is already in use in enhanced oil recovery. It is certainly practical to operate an HDR system under pressures higher than the supercritical point of carbon dioxide. Under these conditions, carbon dioxide has a density high enough so that it may act as an efficient heat transfer fluid. With carbon dioxide as the circulating fluid, it might be practical to employ a flash process to generate electric power, thereby eliminating the inefficiencies of the binary power plant. In the same manner, it may be possible to use ammonia/water mixtures directly as circulating fluids and run the facility using a version of the Kalina cycle (Kalina and Tribus 1989).

In both of these cases, a large amount of work would be necessary to demonstrate that the materials are environmentally and chemically compatible with the hot reservoir rock as well as the structural materials of the system, that systems can be built to run without excessive fluid losses, and that net efficiencies in electric power production are achievable. Even the beginning of substantial work in this area is probably 5-10 years off. The topic is addressed in this paper merely as another illustration of the many potential techniques available for increasing the efficiency of HDR operations.

Summary

It has already been unambiguously demonstrated that energy can be extracted in useful amounts from the HDR resource. The long-term flow test currently underway at Los Alamos will show that this energy can be obtained reliably over a long time period without excessive water consumption.

The next steps in making HDR technology commercial are to show that it can be applied in a variety of geographical settings and that it can be economically exploited. While studies have indicated that power plants based on conventional HDR concepts may be able to produce electricity at competitive costs, a number of as yet uninvestigated approaches may lead to further significant improvements in the efficiency of energy extraction from HDR and give the technology an economic edge.

HDR technology today is in its infancy. It might be compared to the electronics industry in the days of crystal radio sets. As that technology progressed through vacuum tubes and transistors to the highly sophisticated integrated circuits of today, so HDR can move from its current embryonic stage toward multiple well installations and cyclic operational schemes and thus fulfill its role as an ever more efficient energy source.

There is no doubt the energy is there or that it can be extracted. There is also no dearth of ideas on ways to move the technology forward toward ever greater efficiency. What is needed are strong individual and institutional commitments to see this technology through its difficult early stages to the fruits of its maturity. Those organizations with the foresight to do so will surely reap the benefits that this vast energy source can provide.

References

Armstead, H. C. H. and J. W. Tester, 1987. Heat Mining. London: E. F. Spon.

Brown, D. W., 1991. Recent Progress in HDR Reservoir Engineering, Proceedings of U. S. Department of Energy Geothermal Program Review IX, pp 153-157.

Dash, Z. V., ed., 1989. ICFT: An Initial Closed-Loop Flow Test of the Fenton Hill Phase II HDR Reservoir, Los Alamos National Laboratory Report, LA-11498-HDR.

Dash, Z. V., H. D. Murphy, and G. M. Cremer, eds., 1981. Hot Dry Rock Geothermal Reservoir Testing: 1978-1980, Los Alamos National Laboratory Report, LA-9080-SR.

Duchane, D. V., 1991. Moving HDR Technology Toward Commercialization, Department of Energy Geothermal Program Review IX, pp 143-148.

Franke, P. R., D. W. Brown, M. C. Smith, and K. L. Mathews, 1986. Hot Dry Rock Geothermal Energy Development Program Annual Report Fiscal Year 1984, Los Alamos National Laboratory Report LA-10661-HDR.

Kalina, A. and M. Tribus, 1989. The Kalina Power Cycles A Progress Report, Proceedings of the American Power Conference.

Matsunaga, I., National Institute for Resources anc Environment, Agency of Industrial Science and Technology Ministry of International Trade and Industry, Tsukuba, Japan Personal Communication.

Murphy, H., ed., 1981 Relaxation of Geothermal Reservoi Stresses Induced by Heat Production, Los Alamos Nationa Laboratory Report, LA-8954-MS.

Parker, R., 1989. Hot Dry Rock Geothermal Energy Researcł at the Camborne School of Mines, Geothermal Resources Counci Bulletin, vol. 18, no. 9 (Oct.), pp 3-7.

Ponden, R. F., 1991. The Design and Construction of a Hot Dr Rock Pilot Plant, Proceedings of U. S. Department of Energy Geothermal Program Review IX, pp 1149-151.

Rannels, J. W. and D. V. Duchane, 1990. Geothermal Development in the USA: A Vast Potential Resource, Power Generation Technology, London: Sterling Pub., pp 177-180.

Robinson, B. A., 1991. Alternate Operating Strategies for Hot Dry Rock Geothermal Reservoirs, Transaction of Geothermal Resources Council Annual Meeting, Vol 15, pp 339-345.

Tester, J. W., D. W. Brown and R. M. Potter, 1989. Hot Dry Rock-A New Energy Agenda for the 21st Century, Los Alamos national Laboratory Report, LA-115114-MS.

Tester, J. W. and H. J. Herzog, 1990. Economic Predictions for Heat Mining: A Review and Analysis of Hot Dry Rock (HDR) Geothermal Energy Technology, Massachusetts Institute of Technology Energy Laboratory Report, MIT-EL 90-001.