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EVALUATION OF A SITE–SPECIFIC COMMERCIAL HOT DRY ROCK GEOTHERMAL POWER PROSPECT

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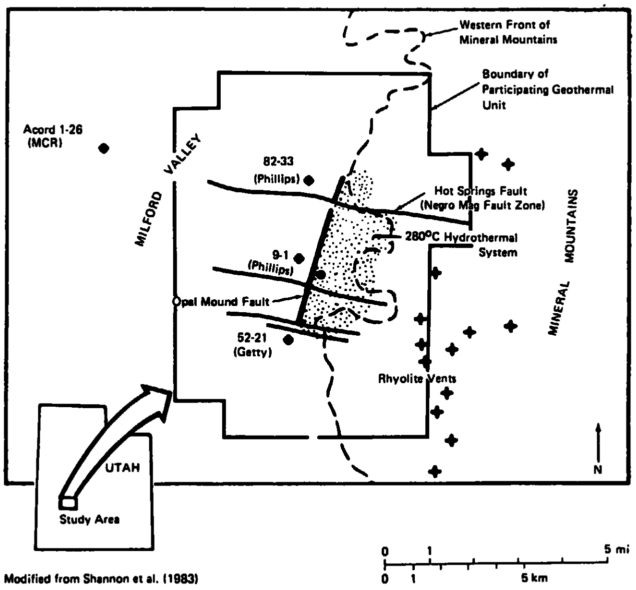
ABSTRACT

This study assesses a promising resource in central Utah as the potential site of a commercial hot dry rock (HDR) facility for generating electricity. The results indicate that, if the HDR reservoir productivity equals expectations based on preliminary results from research projects to date, a 50 MWe HDR power facility at Roosevelt Hot Springs could generate power at a cost competitive with new coal-fired plants. However, the information presently available leaves considerable uncertainty about the expected reservoir performance. Testing that develops solid data concerning productivity and depletion rate is needed to design and adequately evaluate a potential commercial HDR project.

INTRODUCTION

Hot dry rock (HDR) energy production is the process of mining thermal energy from the crust of the earth in situations where the temperature is high but the existing fluids or permeability are inadequate for transporting the energy to the surface. The largest HDR systems created to date, at Fenton Hill in New Mexico and at Rosemanowes, England, are research and development projects that have proved the technology concept by drilling into hot dry rocks, hydraulically fracturing the rock mass, and extracting thermal energy by circulating water through the man-made fractures. Although HDR systems have been created on a research scale, HDR has not yet been applied commercially. This study is the first site-specific evaluation to test the commercial readiness of HDR technology.

In mid-1986, the U. S. Department of Energy (DOE) issued a request for proposals to investigate a specific site for HDR commercial venture potential. In response to this request, Bechtel proposed to evaluate the Roosevelt Hot Springs, Utah resource as the location for a potential 50 MWe power generating facility, and DOE awarded a contract to Bechtel for this investigation. Access to the HDR site and data was granted by Intermountain Geothermal Company, a wholly owned subsidiary of Chevron Resources Company which is the operator of the Roosevelt Hot Springs Unit. Figure 1 shows the location and some of the prominent features of the Roosevelt Hot Springs resource area.



Modified from Shannon et al. (1983)

Figure 1 Location of Roosevelt Hot Springs

This investigation used currently available geotechnical data and current technology or reasonable extensions for well and reservoir design. These ground rules limited the technology base to the current state of the art so that commercial development could proceed if the project economics were favorable and the technical risks were acceptable.

This paper summarizes the results of the investigation and makes recommendations for the next step toward implementing a commercial HDR facility.

GEOTECHNICAL EVALUATION

The geotechnical evaluation of the HDR prospect at Roosevelt Hot Springs involved an assessment of the available site-specific information to estimate the HDR potential, to define the input parameters for the design of the subsurface reservoir, and to identify technical risks associated with development of a commercial HDR reservoir.

Regional Tectonic Setting. The Roosevelt Hot Springs known geothermal resource area is on the western flanks of the central Mineral Mountains. These Tertiary-age mountains are in the Basin and Range province near its eastern margin, which is transitional to the Colorado Plateau.

The most promising HDR prospect area at Roosevelt Hot Springs lies to the west of the Opal Mound Fault which is the structural boundary defining the western limit of the hydrothermal field where a 20 MWe power plant is in operation.

The geothermal heat source for the Roosevelt Hot Springs area is believed to be associated with Pleistocene emplacement of a pluton as a result of intrusive activity (Gertson and Smith 1979, Nielson, et al 1986). Youngest examples of nearby volcanic activity include a sequence of rhyolite flows and domes that range between 0.5 and 0.8 million years in age (Lipman, et al 1977).

Four major fault systems transect the central Mineral Mountains: Low-angle westward dipping faults, a system of high-angle northwest-striking faults, high-angle east-west trending faults which cut the low-angle faults, and north-south horst-graben extensional normal faults, which are the youngest structures in the area (Ross, et al 1982).

Fault-related issues of importance to commercial HDR development include resolving the existence, orientations, and spacings of fractures at anticipated HDR reservoir depths of 7,000 to 17,000 ft (2,100 to 5,200 m). These affect the wellfield design, the ability to control the growth of hydraulic fractures for the reservoir, the rate of water loss, and the probability of induced seismicity if long-term water loss rates are high. Published structural cross sections do not extrapolate faults deeper than 7,000 ft (2,100 m) (Nielson, et al 1986). Drilling of deep exploration and test wells would furnish data needed to resolve these issues.

Two distinct regimes of structure, lithology, and alteration are separated by a gently westward-dipping major fault zone located at a depth of 2,800 ft (850 m) near the Opal Mound Fault (Glenn, et al 1980). Above the fault zone, lithology is complex, alteration is moderate to intense, and evidence of structural disruption is abundant. Below the fault zone, the number of lithologies is few, the rock mass is relatively unbroken, and alteration is weak. An existing well shows that the rock to a depth of 6,885 ft (2,100 m) is granitic.

The magnitudes of the principal stresses at the average target bottomhole depth of 12,000 ft (3,660 m) are not presently known. Furthermore, the stress that must be overcome to initiate hydraulic fracture growth or to stimulate displacement on existing joints cannot be predicted with confidence from available site data.

Because information on deep subsurface jointing is not presently available, a conceptual well design and a drill-fracture-drill sequence for installation of the injection and production wells were developed that will accommodate a wide range of orientation and length of hydraulic fractures. Based on hydraulic fracture operations at Fenton Hill and Rosemanowes, relative shear displacement of existing joint faces may occur and thereby create self-propping fractures with apertures sufficiently large for water circulation (Albright and Pearson 1985; Dreesen, et al 1987; Murphy 1985; Murphy and Fehler 1986; Pine and Batchelor 1984).

During operation of an HDR reservoir, thermal stress cracking of the reservoir rock is expected to occur slowly and continuously at the rock/water interface; thus, the likelihood of building up an unrelieved stress that could generate a significant seismic shock is remote.

Subsurface Temperature and Thermal Energy. Temperature gradient data indicate that the depth to a nominal HDR reservoir temperature of 300°C (572°F) is shallowest near the Opal Mound Fault. Depths to similar temperature increase northward, westward, and southward from that location. Based on available data, the thermal gradient appears to be 56 °C/km, and the average depth to 300 °C (572 °F) would be about 12,000 ft (3,660 m).

The HDR resource within the existing unit for geothermal production appears to have potential for supplying several hundred MWe for a period of greater than 30 years.

Hydrogeology and Water Availability. It is estimated that a peak of 3,900 gpm (6,300 acre-ft/yr) of water may be needed to replenish the losses from a 50 MWe HDR facility. This water could be obtained from a shallow aquifer if rights to do so can be acquired. Due to the distance and low transmissivity between the Roosevelt Hot Springs area and the town of Milford (8 miles or 13 km south) (Mower 1978; Mower and Cordova 1974), pumping operations for a HDR facility at Roosevelt Hot Springs are not expected to affect the water supply near the town. Also, a potentiometric surface map indicates that the underground water flow from Roosevelt Hot Springs is toward the northwest (Mower and Cordova 1974). The proposed wellfield for make–up water lies within the most highly contaminated area of the aquifer (Vuataz and Goff 1987), directly down gradient from the hydrothermal field. However, no undue problems associated with the use of this water are anticipated for an HDR facility.

Overall Geotechnical Assessment. The Roosevelt Hot Springs area appears to be well suited for installation and operation of an HDR power facility with the most promising region lying to the west of the Opal Mound Fault and south of the Hot Springs Fault. The shallowest occurrence of possibly commercial HDR temperatures is in the eastern portion of this region.

SUBSURFACE SYSTEM DESIGN

Well Design and Completions Program. Results obtained early in the study emphasized the economic importance of creating large heat transfer area (fracture surface) per well pair and maximizing the target temperature consistent with technical constraints and cost considerations. This led to a concept for installing multiple, discretely created fractures using the following sequence:

- Drill an injection well to the depth corresponding to the target temperature (an average of 3,660 m or 12,000 ft for 300°C or 572°F at Roosevelt Hot Springs). Deviate the bore 20 to 25 degrees below 2,590 m (8,500 ft).
- Place and cement casing to the bottom of the injection well (7 in. liner in the deviated lower portion of the wellbore).
- Extend the depth of the injection well by 20 to 60 m (66 to 200 ft).
- Run 7 in. tubing from the surface to the top of the 7 in. liner. Hydraulically fracture the open-hole interval pumping through the 7 in. tubing and liner. The water used for hydraulic fracturing cools the wellbore for subsequent logging and perforating. During the hydraulic fracturing operation, use microseismic monitors to map the subsurface fractures.
- Allow the wellhead pressure to decay to 3,000 psi (20 MPa). Do not flow back the fracture fluid.
- Set a cast iron, casing cement retainer ring as a casing packer near the bottom of the 7 in. liner.
- Perforate 10 to 25 m (30 to 80 ft) of the wellbore for the second fracture interval.
- Hydraulically fracture the second interval while using microseismic monitors to map the fractures.
- Repeat the four steps above until 12 fracture intervals have been created in the injection well.
- Drill a production well approximately parallel to the injection well targeting the fracture zones with the deviated portion 250 to 500 m (820 to 1,640 ft) above the deviated section of the injection well.

Although this is an aggressive hydraulic fracturing program, present-day equipment and techniques are used throughout.

Conceptual Wellfield Design. The following characteristics were used as the average values for a base case injection/production well pair for the economic analysis:

- 300°C (572°F) target bottomhole temperature
- 12 fracture intervals
- 100,000 m^2 (1,080,000 ft^2) effective heat transfer area per fracture interval
- Doubling of the heat transfer area within the first year of well–pair production
- 10 l/s (160 gpm) per fracture interval
- 12 MWe initial salable power declining to 2 MWe after 30 years
- For 50 MWe of salable power
  - 4 injection/production well pairs initially
  - 8 additional well pairs over 30–year plant life to counteract expected loss in well-pair productivity with time

Table 1 summarizes the estimated costs for an HDR injection/production well pair drilled to 12,000 ft (3,660 m) at Roosevelt Hot Springs. These costs include site preparation, rig operations, casing/cementing, hydraulic fracturing, and wellhead fixtures.

For comparison, average costs for oil and gas wells drilled to 12,000 ft (3,660 m) in Utah are about $1 million and $2 million, respectively, in 1987 dollars (McClintock 1987).

Table 1
Average Cost per HDR Injection/Production Well Pair
($ million, 1987)

Item	Cost
Pumping services	2.2
Wireline services	0.2
Subtotal	2.4
15% Contingency	0.4
Subtotal	2.8
Drilling and casing (two wells)	6.7
Microseismic mapping	0.1
Subtotal	9.6
Management fee	0.5
Total	10.1

SURFACE FACILITIES

The surface facilities include all the systems and equipment needed to operate the HDR underground reservoir and to produce electric power as shown in Figure 2.

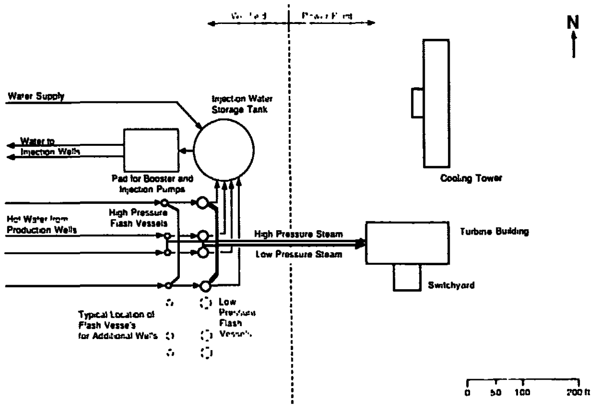


Figure 2 HDR Facility Plot Plan

Wellfield. The wellfield surface facilities include the injection, gathering, and flash systems plus the make–up water supply.

The injection system distributes water to the injection wellheads with enough pressure to produce the needed flow rate through the fractured reservoir. It consists of an injection water storage tank, a set of centrally located booster and injection pumps, and distribution piping to deliver the water to the injection wellheads.

The gathering system transports hot water from the production wellheads through carbon steel, aboveground piping to a centrally located flash system.

The flash system converts part of the hot water to steam in two stages (225 and 31 psia or 1,550 and 214 kPa) and transports it to the power plant.

The make–up water supply furnishes water needed for operating the facility. Up to 3,900 gpm (6,300 acre–ft/yr) of water from 13 wells is pumped about 2 miles (3.2 km) to the injection water storage tank where it is mixed with warm water from the low pressure flash vessels.

Power Plant. The two-stage flash process was selected for this HDR application because of its proven commercial service, its high energy conversion efficiency for the relatively high water temperatures expected, and its relatively low cost. In this process, steam is admitted to the turbine at two different pressures with the combined stream exhausting to a surface condenser.

Heat given up by the condensing steam is absorbed by the circulating water from the cooling tower. Condensate from the condenser is used as cooling tower make-up. Excess condensate not evaporated in the cooling tower is returned to the wellfield injection water storage tank for reservoir injection.

The electrical systems, turbine building, and auxiliary systems of the power plant are similar to those for an equal capacity power plant for other geothermal resources.

PROJECT COST ESTIMATE

Estimates of capital and O&M costs for the four initial well pairs, the wellfield surface facilities, and the power plant are summarized in Table 2. In addition, wellfield costs of $2.7 million for wellfield surface facilities and tangible well costs plus $8.9 million intangible drilling costs will be required at 3– or 4–year intervals as new well pairs are installed to make up for reservoir temperature decline.

ENVIRONMENTAL AND SOCIOECONOMIC ISSUES

There are no apparent environmental or permitting constraints to developing a 50 MWe power plant at Roosevelt Hot Springs.

The most important environmental consideration for development is obtaining the water needed to operate the facility. Although all available groundwater in the Milford Valley area is appropriated, the unused amounts are more than sufficient for a 50 MWe HDR power plant. If the water rights can be acquired, water wells drilled nearby could supply the operating requirements.

The major impact during construction, the socioeconomic effects of in-migration of the construction work force, will be temporary and generally stimulative to the local economy.

During operation, the environmental impacts will be relatively small since there will be low levels of air emissions, no point source water effluents, and little solid or hazardous waste.

DEVELOPMENT PLAN

Figure 3 shows the major activities and a schedule for developing a commercial HDR facility at Roosevelt Hot Springs.

Table 2
Summary of Estimated Project Costs

WELLFIELD--Four Initial Well Pairs	
Wellfield Capital Costs ($ million, 1987)	
Surface facilities	**9.3**
Tangible well costs	**4.3(a)**
Capitalized interest	**2.7**
Total Wellfield Initial Investment	**16.3**
Preproduction Costs	**1.1**
Total Initial Wellfield Capital Costs	**17.4**
Intangible Drilling Costs	**35.2(a)**
Total Initial Wellfield Costs	**52.6**
Wellfield O&M Costs	
Fixed O&M Costs ($ million per year, 1987)	**1.35**
Variable O&M Costs	
Make-up water (mills/kWh)	**0.35**
Geothermal royalties--10 % of wellfield gross	
Electric power --1.4 to 4.4 ($ million per year, 1987)	
POWER PLANT	
Power Plant Capital Costs ($ million, 1987)	
Power Plant and Transmission Line	**56.5**
Allowance for Funds Used During Construction (AFDC)	**10.5**
Preproduction Costs	**1.9**
Total Power Plant Capital Costs	**68.9**
Power Plant O&M Costs ($ million per year, 1987)	**2.3**

(a) The total of tangible and intangible drilling costs is $39.5 million. This is $600,000 less than four times the $10.1 million cost of a typical well pair given in Table 1. The difference results from adjustments to the mobilization costs and to repeated use of a single frac pond.

The first activity is an industrial HDR experiment to verify both the drilling/completion concept and the reservoir performance (e.g., heat transfer area per well pair, growth of heat transfer area, and thermal drawdown). Such a test would involve drilling and casing a full-depth full-bore injection well, fracturing four to six intervals, drilling a full-depth full-bore production well, and test flowing the well pair for about 2 years at a rate somewhat greater than commercial optimum to project long-term thermal performance.

The schedule in Figure 3 indicates that about 10 years would be required. This schedule is a deliberate one; it may be possible to accelerate the schedule 1 to 2 years, if necessary.

Year	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
Industrial HDR Experiment										
Drill and test a pair of test injection and production wells	x	~~xxxx~~	~~xxxx~~	~~xxxx~~	~~xxxx~~	~~xxx~~				
Secure water rights for 50 MWe HDR power facility		x	xxxx	xxx						
Drill and test two water wells				x	xxx					
Develop a numerical model to simulate, evaluate, and predict reservoir performance		x	xxxx	xxxx	xxxx	xxx				
Perform additional geology and geophysical evaluation		x	xxxx	x						
Drill exploration and observation wells		x	xxxx	xxxx	xxx					
Secure permits		xx								
Project Preliminary Design						~~xx~~				
Venture Formation						xx	~~xxx~~			
Negotiate power sales agreement						xx	xxx			
Prepare permitting plan and submit initial applications						xx	xxx			
Financing							xxx			
Final Design and Construction										
Wellfield										
Design and drill HDR injection and production wells								xx	xxxx	xx
Design and construct injection, gathering, and flash systems								xx	xxxx	xxx
Drill water wells and install pumps								xxxx	xxxx	
Construct make-up water pipeline								xx	xx	
Secure permits							xx	xx		
Power Plant										
Develop detail design for power plant							~~xx~~	xxxx	xxxx	xx
Construct power plant								~~xxxx~~	~~xxxx~~	~~xxx~~
Perform power plant startup										~~xx~~
Secure permits							xxxx			

——— Critical Path

Figure 3 HDR Project Schedule

ECONOMIC AND RISK ASSESSMENT

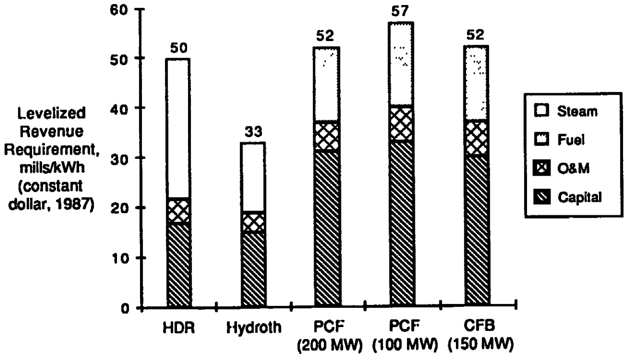
The economic and risk assessment concentrated on the comparative cost of electricity, commercial viability, and sensitivity to cost components and technical risks. The first full year of power production was assumed to be 1997 for purposes of economic projections.

Levelized revenue requirements were estimated assuming that the HDR resource is developed and operated by a non-utility resource developer and that the power plant is owned and operated by a privately-owned utility company.

Among the many economic parameters assumed for this evaluation, two of the prominent ones are the return on common stock for the resource developer (18 percent) and the power plant owner (15 percent). The constant dollar (1987) revenue requirements for the base case facility may be summarized as follows:

	Mills/kWh
Wellfield	28.2
Power plant	21.6
Total	49.8

Figure 4 illustrates how the cost of electricity production from an HDR power project compares with the cost for other options that are commercially available in Utah. This comparison shows that an HDR project could produce electricity at costs competitive with new coal-fired plants using Utah coal. This promising result is dependent to a large degree on the ability to create a sufficiently large fractured area per well pair to justify the cost of installing the wells.



HDR = Hot dry rock
PCF = Pulverized coal-fired
CFB = Circulating fluidized bed

Figure 4 Cost of Electricity Production

On the other hand, a hydrothermal plant at Roosevelt Hot Springs could produce electricity at a significantly lower cost; this difference is due primarily to lower drilling and completion costs for hydrothermal and to higher plant output needed to supply pumping power for HDR wellfield operation. With this economic advantage, the hydrothermal resource at Roosevelt Hot Springs is likely to be fully committed by the time HDR testing can be completed and a commercial HDR plant can be built.

Sensitivity analyses were performed to determine the impact of variations in cost and performance estimates. For these analyses, variations were selected arbitrarily to test sensitivity; they are not estimates of uncertainty. Figure 5 summarizes the results of these analyses. In general, the moderate sensitivity to a change in any one of these variables suggests that steam and electricity costs are not highly sensitive to variation in any single cost component.

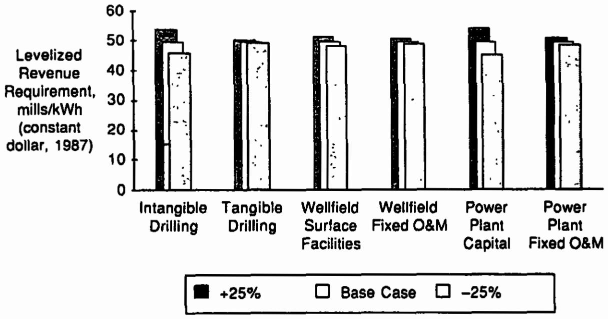
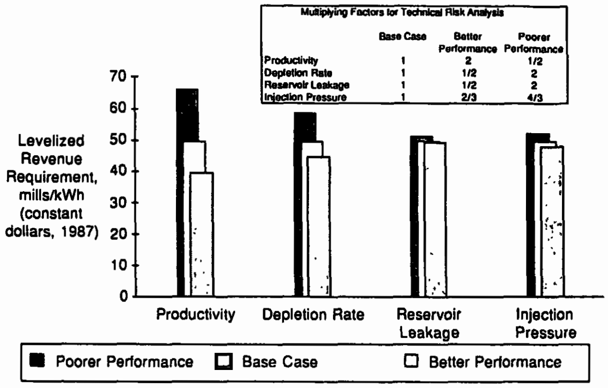


Figure 5 Sensitivity of Revenue Requirements to Cost Components

Potential cost impacts were investigated for the prominent performance characteristics that cannot be confidently predicted with the HDR data currently available. Figure 6 summarizes these results and shows that well-pair productivity and depletion rate are key performance variables that have pronounced effects on project economics. Testing that develops solid data for evaluating productivity and depletion rate is imperative before commitment for a commercial project.

RECOMMENDATIONS

The results of the economic analysis using reasonable and possibly conservative assumptions and present-day drilling and completion technology show HDR technology to be competitive with new coal-fired power generation. **<u>These results are so promising that a site-specific industrial HDR experiment at Roosevelt Hot Springs is highly recommended</u>**. The industrial HDR experiment would demonstrate the ability to create and access multiple intervals with large fractures, and it would evaluate the long-term thermal performance of a commercial-size reservoir created for heat mining.



Multiplying Factors for Technical Risk Analysis

	Base Case	Better Performance	Poorer Performance
Productivity	1	2	1/2
Depletion Rate	1	1/2	2
Reservoir Leakage	1	1/2	2
Injection Pressure	1	2/3	4/3

Figure 6 Sensitivity of Revenue Requirements to Technical Risks

The technical uncertainties of HDR technology and moderate earnings expectation currently prevent industry-funded HDR resource development even though installation of an HDR facility appears to require straight-forward but aggressive application of existing drilling, fracturing, and seismic monitoring technology. Furthermore, the electric energy market for the foreseeable future does not provide enough economic incentive for a private developer to invest in HDR energy technology development. Therefore, **<u>federal support for funding the industrial HDR experiment is recommended</u>**. Cost sharing by others, including industry participants and the state of Utah, is also recommended; however, these sources can be expected to provide only a small fraction of the funding required.

Further, **<u>a commercial-size first-of-a-kind HDR power plant project is recommended if the industrial HDR experiment verifies the technical and economic projections</u>**.

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