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Case Studies of Low-to-Moderate Temperature Hydrothermal Energy Development

**A Joint-Project Report of
Lawrence Berkeley Laboratory and
The Idaho National Engineering Laboratory**

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CASE STUDIES OF LOW-TO-MODERATE TEMPERATURE HYDROTHERMAL ENERGY DEVELOPMENT

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Published October 1981

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Berkeley, California 94720

Contract

Prepared for the
U.S. Department of Energy
Idaho Operations Office
Under DOE Contract No. DE-AC07-76IDO1570

ABSTRACT

This report examines six development projects that use low- [less than 90°C (194°F)] to-moderate [90-150°C (194-302°F)] temperature geothermal resources. These projects were selected from 22 government cost-shared projects to illustrate the many facets of hydrothermal development. The case studies describe the history of this

development, its exploratory methods, and its resource definition, as well as address legal, environmental, and institutional constraints. This report also provides a critique of procedures used in the developments and suggests recommendations for similar future hydrothermal projects.

ACKNOWLEDGMENTS

The publication of the case studies in this report is a result of a joint project between EG&G Idaho, Inc. and Lawrence Berkeley Laboratory. The project was funded through the Idaho Operations Office of the U.S. Department of Energy (DOE-ID). Dennis Goldman, Julie Martinez, and Max Dolenc of EG&G Idaho, and Sally Benson of Lawrence Berkeley Laboratory have made this

document possible. Technical support and review of these studies have been provided by EG&G's Geothermal Programs Office and Geoscience Branch, and by Lawrence Berkeley's Earth Sciences Division. The support for the project was provided through Dr. Leland L. Mink (DOE-ID) and Robert A. Gray (Division of Geothermal Energy, DOE).

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CASE STUDIES OF LOW-TO-MODERATE TEMPERATURE HYDROTHERMAL ENERGY DEVELOPMENT

1. INTRODUCTION

The development of geothermal energy resources for direct-use applications has been slow in the United States. This is because the geothermal energy data base is very limited. There is a lack of: (a) knowledge of the economical resource base; (b) inexpensive and reliable exploration and drilling techniques; (c) technical and economic data; and (d) established geothermal laws and regulations. To increase this data base, and thereby encourage increased private development of geothermal energy resources, the Division of Geothermal Energy of the U.S. Department of Energy (DOE) developed a program for sharing costs with developers of geothermal direct-use projects. In 1977 and 1978, DOE issued two Program Opportunity Notices (PONs). Developers were selected on a competitive basis. Twenty-two cost shared projects resulted. Each project was required to demonstrate the potential of the resource, provide technical and economic data, and address legal, environmental, and institutional issues.

The case studies discussed in this report, with the exception of one private development project, are part of the 22 PON projects and were chosen to represent varying direct-use applications and varying reservoir types. They are discussed in the text in order of their geographical location from east to west. (See Figure 1.) The projects represent low, less than 90°C (194°F), to moderate 90-150°C (194-302°F) temperature geothermal resources. The heat source for these resources is primarily the normal geothermal gradient of the earth 30°C/km (2.62°F/100 ft) which may or may not be increased by a positive temperature anomaly. Positive anomalies can be caused by: (a) higher than normal heat flow; (b) low thermal conductivity; (c) the presence of radioactive elements; (d) young magmatic intrusions; and (e) hydrothermal circulation.

Several major classifications of geothermal resources are known; however, not all (i.e., geopressured geothermal systems) are pertinent to direct-use applications. Those with potential for direct-use include hydrothermal convection

systems and deep regional aquifers. Hydrothermal convection systems occur when circulating ground water migrates downward along permeable zones, becomes heated, and rises. The circulation is caused by the density difference between hot and cold water. Permeable zones for migration may be either stratigraphic beds or networks of faults and fractures. The heat source in hydrothermal convection systems producing low-to-moderate resources is primarily dependent on the regional heat flow, the depth of water migration, and the residence time of water at depth. Recharge to a hydrothermal convection system is usually from precipitation over adjacent mountains and valleys.

Deep regional aquifers occur in downwarped, sediment-filled basins that collect and transmit ground water from adjacent highlands. The water is transmitted down dip and becomes heated from the thermal gradient of the earth. Geothermal reservoirs may occur within economic reach where the water is forced upward under artesian pressure or density differences. If the artesian pressure is high enough, the water may flow at the land surface.

In general, geothermal reservoirs occur in all rock types under varying conditions of porosity and permeability. The case studies presented in this report illustrate the essential differences. Geothermal reservoirs that occur in crystalline rock, i.e., igneous or metamorphic rock types, are primarily dependent on fracture flow because of low porosity. Permeability in these reservoirs then depends on the character of the fault system including the number of interconnections of faults, the nature of brecciated material along the faults, and the possibility of sealing of the fault zones.

Geothermal reservoirs in sedimentary basins, consolidated or unconsolidated, rely primarily on intergranular porosity for flow. Permeability in these reservoirs depends upon the size, sorting, cementation, and interconnections of the sedimentary particles. In some reservoirs, both intergranular and fracture flow may occur, resulting in a dual porosity system.

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Figure 1. General location map of all case studies.

2. ST. MARY'S HOSPITAL CASE STUDY

2.1. Introduction

The Division of Geothermal Energy of the Department of Energy (DOE) has funded three projects in South Dakota to evaluate the energy resource potential of the Madison Group Aquifer for direct-use application. This case study on the St. Mary's Hospital located in Pierre, South Dakota, illustrates the development of one project using the Madison Group Aquifer.

St. Mary's Hospital, a nonprofit organization, is a 138-bed facility providing medical services to the population in a 240 km (149 mi) radius of Pierre (Figure 2). Before retrofit, the hospital used two fuel-oil fired boilers to generate steam for space heating, cooling, and domestic water heating. The intended system design using geothermal water would satisfy 58% of the hospital's energy needs. A peak flow rate of 34.7 L/s (550 gpm) at 47°C (117°F) would be required by the hospital during the winter season, with an average yearly flow rate of 5.6 L/s

(88 gpm). A planned addition to the hospital complex would increase the required winter peak flow to 56 L/s (900 gpm) and the average yearly flow to 8 L/s (133 gpm). Any additional geothermal water from the well could be piped to the nearby Capital Lake Plaza, a three-story 2,048 m (22,000 ft) office building, to replace approximately 80% of the propane presently used for space heating and domestic water heating.

The St. Mary's Hospital project team consisted of the St. Mary's Hospital owner/manager, an architectural engineering firm, a consulting geologist, and a consulting reservoir specialist.

2.2 Background

2.2.1 Geology. The Mississippian Madison Group is a sequence of carbonates deposited in a broad seaway covering parts of Montana, Wyoming, western South Dakota, western North Dakota, and the northwest corner of Nebraska (Figure 3). Three distinct lithologic units are

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Figure 2. Location of Pierre, South Dakota.

Figure 3. Areal distribution of the Mississippian Madison Group.

present. The lower unit, the Lodgepole Formation, is dominated in the lower section by gray to gray-brown argillaceous limestone, chert and occasional interbeds of shale. A broad band of dolomite is present in the upper section. The middle unit, the Mission Canyon Formation, is comprised of tan, gray or brown limestone and dolomite, with anhydrite present in the upper section. The upper unit, the Charles Formation, is comprised of interbedded anhydrites and dense limestones.¹ The sequence in South Dakota thickens from 0 m on the east edge of the subcrop to 376 m (1,300 ft.) in the northwest corner of the state (Figure 4). The entire Madison Group is about 823 m (2,700 ft.) thick in the Williston Basin in North Dakota, and over 853 m (2,800 ft.) thick in the central Montana trough.²

After the Mississippian seas receded, erosion and dissolution of the limestone created a karst topography with surface relief of many meters. Insoluble materials remained forming a blanket of red residual clay.³ Deposition of new clays and reworking of the old clay effectively "sealed" the top of the aquifer system.² During the Laramide orogeny, the Madison Group was downwarped into the Williston Basin to the north, and uplifted and eroded in the Black Hills of South Dakota, exposing the formation.

2.2.2 Hydrology. Recharge to the Madison aquifer is through infiltration of rain and snowmelt in the Black Hills outcrop area, and from water loss to sinkholes in limestone creekbeds.² The potentiometric surface has a

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Figure 4. Thickness of the Madison Formation.

steep gradient near the outcrop area, but flattens radially outward (Figure 5).² Although it is known that slow circulation of water through the old solution network has continued to the present, the direction and rate of water movement within the aquifer is uncertain.²

The average porosity of the Madison Group in this area is 8%.⁴ This results from a combination of: (a) normal intergranular porosity; (b) joint and fracture systems; and (c) solution openings ranging in size from slightly enlarged joints to caverns.²

2.2.3 Geothermal. The geothermal potential of the Madison Group in South Dakota was initially demonstrated between 1910-13 when the first deep water well at Edgemont, Fall River County, flowed at 32 L/s (515 gpm) at 54°C (130°F). Deep water wells, as well as several hundred deep oil tests, provide data on the temperature, quality, quantity, and potentiometric surface of the Madison aquifer. A detailed study on the geothermal potential of the Madison Group aquifer in South Dakota was completed by J. P. Gries.²

Water temperature in Madison wells is a function of depth to the resource (Figure 6). Temperature gradients over most of the Madison Group are about 30°C/km (2°F/100 ft) of depth which is the average geothermal gradient for the earth. However, anomalous higher gradients exist in a large area of west central, and a small area in southwest, South Dakota (Figure 7).²

Water quality in the aquifer varies widely but, in general, is best near the outcrop area and decreases radially outward.² Total dissolved solids range from 1000 to 2000 ppm in western South Dakota and are as high as 6000 ppm near the North Dakota border.⁴ Evaporite units in the Charles Formation and at the top of the Mission Canyon Formation have an adverse effect on the water quality in the northern area.

Radium 226 has been detected in wells located in west central South Dakota in the area of the high-temperature anomaly. Dependent upon levels, disposal or secondary utilization of cooled Madison waters containing Radium 226 may require treatment. Although the total mineral content usually exceeds EPA standards for

drinking water, there are no dangerous levels of toxic elements. Therefore, in most areas, disposal or secondary utilization of Madison water is not a major problem.

Scaling and corrosion of pipelines and heat exchangers vary with the water quality in the Madison aquifer, but present little or no difficulty with the proper treatment. Scaling does not normally occur if pipelines carrying Madison water are not exposed to the atmosphere. If the water is allowed to cool and evaporate, mineral deposits of calcium carbonate, calcium sulfate, silica, or iron may occur.² Corrosion has occurred in pipelines installed at Midland and Philip, South Dakota. X-ray diffraction analysis of scale from these pipes shows the presence of copper sulfide and bornite. These indicate that hydrogen sulfide is present in significant amounts to do damage to the pipelines or heat exchangers. A corrosion inhibitor such as polyphosphate should control this problem.²

According to Gries,² the average expected discharge for a properly constructed and developed Madison aquifer well in western South Dakota is 31.5 L/s (500 gpm). This average is based on well yields ranging from 5 L/s (80 gpm) to over 63.0 L/s (1000 gpm).

2.3 Exploratory Programs

A low-temperature artesian system has been known to exist under the city of Pierre since the late 1800s when warm artesian waters were used for health baths. A deep well at the Pierre Satellite Airbase, a few miles from the St. Mary's Hospital, reportedly flowed about 69.4 L/s (1100 gpm) at temperatures from 43 to 47°C (110 to 117°F).⁵ Because the hospital site is 82 m (270 ft) lower in elevation, it was suspected that a well on the hospital property would have an increased pressure head of 813 kPa (118 psi) at a temperature near 47°C (117°F). Therefore, based on the known conditions of the Satellite Airbase well, and the characteristics of the Madison aquifer as reported by J. P. Gries,² the decision was made to drill on hospital property without any site-specific exploration. The well was sited to minimize surface preparation required for placement of the drilling rig (Figure 8).

Figure 5. Potentiometric surface of the Madison Artesian System.

Figure 6. Depth to the top of the Madison Group in South Dakota.

Figure 7. Isothermal map of the Madison Group in South Dakota.

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Figure 8. Location of St. Mary's Hospital well.

2.4 Production Drilling

Drilling began on March 27, 1979. The well, which was designed to allow a maximum flow of 94 L/s (1500 gpm), was completed and developed on May 30, 1979 (Figure 9). The well was drilled using a Spencer-Harris 600 rig. The drilling equipment included two mud pumps, 11.4 cm (4-1/2 in.) diameter drill pipe, and drill collars which were 20.3 cm x 3 m and 15 cm x 6 m (8 in. x 10 ft and 6 in. x 20 ft). The blowout preventer, designed to withstand anticipated high pressures, is shown in Figure 10.

A conductor hole was drilled to 24 m (80 ft) with a 25 cm (9-7/8 in.) bit, then opened to 60.9 cm (24 in.) with a 4-cone hole opener. A 41 cm (16-1/4 in.) conductor casing was set to 24 m (80 ft) and cemented. A 37 cm (14-3/4 in.) hole was drilled to 243 m (800 ft), cased with

27.3 cm (10-3/4 in.), 59 kg/m (40.5 lb/ft) casing and cemented to the surface. The well was then and cemented to the surface. The well was then drilled to a total depth of 663 m (2174 ft) with a 25 cm (9-7/8 in.) bit. A 17.7 cm (7 in.) liner was hung from 152 m (550 ft) to total depth and cemented in place.⁶

Mud was used as the drilling fluid for the entire hole. Mud weight was kept near 17 kg/L (10 ppg), viscosity near 40 s/qt until drilling reached 491 m (1611 ft). Mud weight was then raised to approximately 25 kg/l (14.5 ppg), viscosity to approximately 65 s/qt to control formation fluid from the Fall River Formation and was maintained to total depth.

Before completion, the well was logged by two geophysical logging companies. The following logs were run:

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Figure 9. Completion of St. Mary's Hospital well.

Figure 10. Blowout preventer during drilling of the St. Mary's Hospital well.

Dual Induction SFL	4-15-79
Compensated Neutron Formation Density	4-15-79
Gamma Ray-Cement Bond Log	4-19-79
Differential Temperature	4-25-79

After logging, the 17.7 cm (7 in.) liner was shot-perforated across porous zones in the Madison Formation. Six perforation runs, 13 shots/m (4 shots/ft) were made for a total of 232 perforations over a 17.6 m (58 ft) interval.

The well was allowed to flow at full capacity, producing at discharge rates of 15.7-16.7 L/s (250-265 gpm) at 41°C (106°F). Since this flow and temperature would not meet system-design requirements, the decision was made to perforate the section from 650 to 662 m (2134 to 2172 ft) and acidize the well. Acidizing would clean cement out of the perforations, and react with cement and mud that may have caused formation damage.⁷ After perforating, again using 13 shots/m (4 shots/ft), a 12-hour flow test before acid treatment indicated an increased flow to 17.8 L/s (283 gpm) at 41°C (106°F).

Using a small workover rig, a 17.7 cm (7 in.) fullbore cement packer was run on 7.3 cm (2-7/8 in.) tubing to a depth of 617 m (2024 ft). The acid treatment consisted of 30,303 L (8000 gal) of 20% hydrochloric acid, injected down the tubing at a rate of 9 barrels per minute under 10,342 kPa (1500 psi) pressure. The acid contained 75 L (20 gal) of corrosion inhibitor and 3,030 L (800 gal) of an additive to prevent scale on casing. Six hundred ball-sealers were injected to divert the fluid to all perforations. After four hours, the well was flushed with fresh water. The spent acid was neutralized with 362 kg (800 lb) of NaHCO₃. A 12-hour flow test, after acidizing, showed an estimated increase to an average 25 L/s (400 gpm) with a wellhead pressure of 34 kPa (5 psig).⁷

Drill cuttings analyzed indicate formations as shown in Figure 9.⁸

2.5 Aquifer Testing

Three short-duration flow tests were run on the St. Mary's Hospital well during completion as

previously discussed. No analyses in addition to the flow rate estimates were performed. The low flow rates led to the decision to add perforations and acidize the well.

After acidizing, an aquifer test was run from June 5-6, 1979 by EG&G Idaho, Inc.⁹ Water was discharged through an aluminum irrigation pipe 15.2 cm (6 in.) in diameter and 18 m (60 ft) long. A steel discharge pipe, 15.2 cm (6 in.) in diameter and 9.1 m (30 ft) long was connected to the end of the aluminum pipe. A 10.2 cm (4 in.) beveled orifice plate was attached to the end of the discharge line. The discharge rate was measured by the height of the water column in a manometer behind the orifice plate. The manometer was constructed from clear plastic tubing and two 91.4 cm (36 in.) measuring sticks. The discharge rate, which was checked only by the manometer, was controlled by a 20.3 cm (8 in.) gate valve near the wellhead. The valve performance was "adequate," but was not an optimal method for control because a large number of turns were necessary for flow rate adjustment. A 0-1000 psi Heise gauge with 1-psi increments was used to measure wellhead pressure. The temperature of the water at the wellhead was measured with a digital thermometer and a type J thermocouple.⁹

Testing consisted of two segments: pulse testing conducted on June 5 and production testing conducted from June 6-7. Pulse testing consisted of artesian flowing the St. Mary's Hospital well at four constant rates while recording temperature and wellhead pressure. After flowing approximately one hour for each pulse, the well was shut-in. Recovery wellhead pressure was measured until it had "stabilized," which in each case was longer than the duration of flow.⁹ The four pulse tests were conducted at rates of 26.5 L/s (420 gpm), 17.7 L/s (280 gpm), 13.6 L/s (215 gpm), and L/s (380 gpm). Test data from the 26.5 L/s (420 gpm) pulse was not quantitative due to a nonconstant discharge. A graph of wellhead pressure at each pulse rate versus the logarithm of production time is shown in Figure 11. The temperature at the wellhead stabilized at 41°C (106°F) for all pulses.⁹

Two production tests were conducted, allowing the well to flow at a constant rate while recording wellhead pressure and temperature. The well was flowed at 2.52 L/s (40 gpm) for 615 minutes prior to production testing to minimize fluid density effects. The first production test was at a rate of

Figure 11. Wellhead pressure versus production time of the St. Mary's Hospital well.

25.2 L/s (400 gpm) for 219 minutes. The well was shut-in at this time because of failure to maintain the desired 34 kPa (5 psig) wellhead pressure. The discharge valve was fully open during this test. This test was analyzed as a 22.7 L/s (360 gpm) test because of the 2.52 L/s (40 gpm) pretest flow. The second production test was at a rate of 23.7 L/s (375 gpm) for 824 minutes. Recovery data were collected for 25 minutes following shut-in.⁹ A graph of wellhead pressure versus the logarithm of production time is given in Figure 12. The temperature measured at the wellhead during production testing stabilized at 41.1°C (106°F). Pertinent data for the pulse tests and production tests are given in Table 1.

The wellhead pressure during the 23.7 L/s (375 gpm) production test appears to stabilize after 270 minutes (Figure 12). According to Niemi,⁹ if the recharge boundary is real, this well could supply 23.7 L/s (375 gpm) and maintain the required wellhead pressure for the life of the project. However, a barrier boundary, which would decrease the artesian capabilities of the well, is suggested by the facts that the well

penetrates the quartzite basement rock, and that the formation thickness thins to zero to the east of Pierre, South Dakota. The recovery data, which was graphically analyzed by two methods (Figures 13, 14, and 15) did not indicate either a recharge or a barrier boundary.⁹ A 10 to 14 day constant rate aquifer test was suggested by Niemi⁹ in order to more accurately confirm the presence of a boundary. This test has not been conducted.

Drawdown per log cycle of production time (s_{10}) and discharge rate divided by drawdown per log cycle of production time (Q/s_{10}) were calculated for each test (Table 2). Transmissivity which is calculated using the s_{10} values is inappropriate in geothermal reservoirs.¹⁰ Instead, Q/s_{10} is used, especially when there is fracture-controlled ground water flow within the aquifer, the thickness of the aquifer penetrated is uncertain, and when there is a chance that a boundary may occur before the test discharge rate and/or wellhead density remain constant.⁹ The Q/s_{10} values calculated range from 0.086 (L/s)/(kPa) log/cycle [(9.27 (gpm)/(psig))/log cycle] to 0.185 (Ls)/(kPa)/log

Figure 12. Wellhead pressure versus production time of the St. Mary's Hospital well.

Table 1. Initial and shut-in pressure^a

Discharge Rate		Initial Pressure		Shut-In Pressure		Test Length (min)	Variation in Discharge Rate (%)
(gpm)	(L/s)	(psig)	(kPa)	(psig)	(kPa)		
420	26.5	475	3275	0.2	1.4	60	15.0
280	17.7	471	3247	160	1103	61	7.5
215	13.6	473	3261	249	1717	60	9.3
380	24.0	472	3254	55	379	32	4.5
400	25.2	436 ^b	3006	1.3	9.0	219	3.5
375	23.7	474	3268	29 ^c	200	824	4.3

a. This data is from tests conducted between June 5-7, 1979.

b. Well was allowed to artesian flow at 40+ gpm for 615 minutes preceding 25.2 L/s (400 gpm) production test.

c. Artesian flow had decreased, allowing the wellhead pressure to increase from 186 to 200 kPa (27 to 29 psig).

Figure 13. Recovery data from pulse tests (June 1979) of the St. Mary's Hospital well.

Figure 14. Recovery data from production tests (June 1979) of the St. Mary's Hospital well.

Figure 15. Comparison of drawdown and calculated recovery data (June 5-7) from the St. Mary's Hospital well.

Table 2. Summary of test results

Discharge Rate (Q)	Coefficient of Determination (r^2)	Drawdown per Log Cycle (s_{10})	Data Used in Regression Analysis (t)	Discharge Rate Divided by Drawdown per Log Cycle (Q/s_{10})
280 gpm 17.7 L/s	0.9587	29.8 psig/log cycle 205 kPa/log cycle	1-60 min	9.40 [(gpm)/(psig)/log cycle] 0.086 [(L/s)/(kPa)/log cycle]
215 gpm 13.6 L/s	0.9806	21.3 psig/log cycle 147 kPa/log cycle	1-60 min	10.1 [(gpm)/(psig)/log cycle] 0.092 [(L/s)/(kPa)/log cycle]
380 gpm 24.0 L/s	0.9587	41.0 psig/log cycle 283 kPa/log cycle	1-32 min	9.27 [(gpm)/(psig)/log cycle] 0.085 [(L/s)/(kPa)/log cycle]
360 gpm 22.7 L/s	0.9627	17.8 psig/log cycle 123 kPa/log cycle	5.5-219 min	20.2 [(gpm)/(psig)/log cycle] 0.185 [(L/s)/(kPa)/log cycle]
375 gpm 23.7 L/s	0.9618	30.0 psig/log cycle 207 kPa/log cycle	1.3-90 min	12.5 [(gpm)/(psig)/log cycle] 0.114 [(L/s)/(kPa)/log cycle]

cycle[(20.2 (gpm)/(psig)/log cycle)] with a logarithmic mean of 0.107 (L/s)/(kPa)/log cycle [11.73 (gpm)/(psig)/log cycle].⁹

The recovery data from the pulse tests (Figure 13) and production tests (Figure 14) were analyzed by the Theis ratio method. The Theis ratio is

$$\frac{t + t'}{t'}$$

where t is the time of production, and t' is the time since shut-in. The data does not yield a linear portion which is required for quantitative analysis. According to Niemi,⁹ the data does indicate that well losses are slight and the acidizing increased the well efficiency.

Calculated recovery for each test was graphed versus the logarithm of time since shut-in (Figure 15). Data from the 25.2 L/s (400 gpm) production test and the 26.5 L/s (420 gpm) pulse test were not used because of nonconstant discharge rates and because the rates overstressed the artesian capabilities of the well. Data from the 23.7 L/s (375 gpm) production test are omitted for clarity because they graph in the same region as the 24.0 L/s (380 gpm) pulse test. Values of s_{10} and Q/s_{10} were derived using the linear regression of the calculated recoveries (Table 3).

Comparison of Q/s_{10} values calculated from drawdown and recovery (Tables 2 and 3) show a close resemblance. According to Niemi⁹ this resemblance indicates that no boundaries occurred in the portion of the aquifer affected by the producing well.

The graph of Q/s_{10} values versus flow rates indicates that Q/s_{10} is not dependent on the discharge rate (Figure 16). This indicates that the well behaved as a theoretically "ideal" well.⁹ The specific capacity values (Q/s), production rate divided by drawdown, ranged from 0.887 to 1.144 gpm/psig after 10 minutes of production and from 0.847 to 0.960 gpm/psig after 60 minutes of production (Table 4). The graph of specific capacity versus discharge rate (Figure 17) yields data points that are too closely spaced to establish a reliable productivity curve.

The drawdown and calculated recovery data (Figure 15) of three pulse tests indicate well losses of approximately 138 to 172 kPa (20 to 25 psig).

A Rapid City, South Dakota firm performed water analysis on samples from the St. Mary's Hospital well. Samples were collected before the well was acidized to avoid interference with the corrosion inhibitors that were used. The results of the water analysis are shown in Table 5. The values agree with the general model for the Madison Aquifer, in that water quality degrades away from the recharge area. The water does not meet "primary" (assumed EPA) drinking water standards because of the high level of total dissolved solids.¹¹ The calcium carbonate scaling index is + 0.2. Although this indicates a slight tendency toward scaling, it is unlikely to happen unless the water is aerated. Calcium carbonate scaling, if it did occur, could be controlled with acidification and/or polyphosphate treatment of the water.¹¹ Calcium sulfate and silica precipitation are both unlikely.

The water analysis indicates sulphide ion (HS^-) as the primary cause of corrosion of metals. Although the concentration of sulphide is higher than the value reported at the Diamond Ring Ranch (40 mi west), the corrosion rate is not higher. This is attributed to a lower water temperature at the St. Mary's Hospital well.¹¹ A radioactivity analysis completed by the Environmental Protection Agency showed 19 pCi/L of Radium 226.

2.6 Current Project Status

This project is currently in operation and a summary of it is provided in Table 6. The well has a temperature of 41.1°C (106°F) and artesian flows at 23.6 L/s (375 gpm) with a constant wellhead pressure of 200 kPa (29 psig). No water was available for use at the Capitol Lake Plaza. Heat is extracted from the water using three heat exchangers. The water is then discharged through a 20 cm (8 in.) polyvinyl chloride pipe approximately 29.6 cm (130 ft) to the Missouri River. There the water is dispersed through 39.6 cm (130 ft) of perforated pipe buried 7.6 m (25 ft) beneath the water surface. The diffusion and burial was required to dilute both the temperature (discharged at 23.8-26.6°C) and the Radium 226, and to prevent rapid ice melting in the river.¹²

Table 3. Summary of test results

Discharge Rate (Q)	Drawdown per Log Cycle (s_{10})	Time Since Shut-In (t')	Coefficient of Determination (r^2)	Discharge Rate Divided by Drawdown per Log Cycle (Q/s_{10})
280 gpm 17.7 L/s	29.4 psig/log cycle 203 kPa/log cycle	1-99 min	0.9695	9.51 [(gpm)/(psig)/log cycle] 8.72×10^{-2} [(L/s)/(kPa)/log cycle]
215 gpm 13.6 L/s	19.9 psig/log cycle 137 kPa/log cycle	2-60 min	0.9889	10.8 [(gpm)/(psig)/log cycle] 9.91×10^{-2} [(L/s)/(kPa)/log cycle]
380 gpm 24.0 L/s	44.1 psig/log cycle 304 kPa/log cycle	3-16 min	0.9924	8.62 [(gpm)/(psig)/log cycle] 7.89×10^{-2} [(L/s)/(kPa)/log cycle]
375 gpm 23.7 L/s	37.5 psig/log cycle 259 kPa/log cycle	3-25 min	0.9747	9.99 [(gpm)/(psig)/log cycle] 9.17×10^{-2} [(L/s)/(kPa)/log cycle]

Figure 16. Discharge rate divided by drawdown per log cycle (Q/s_{10}) versus discharge rate (Q) in the St. Mary's Hospital well.

2.7 Conclusion

The St. Mary's Hospital project, was successfully completed. However, no site-specific exploration was conducted because: (a) the Madison Aquifer is considered widespread in that area, and (b) there was a successful geothermal well located close by. The well was sited on hospital-owned property to minimize expense and piping distance. Because the Madison Aquifer is a deep intergranular permeable reservoir, an extensive exploration may not have been justified.

The drilling phase, with the exception of the well completion, was well conducted. The drill rig was satisfactory and was capable of handling the large wellhead equipment required by high flows and pressures. The well was completed with a 7 in. liner, cemented to total depth, and shot-

perforated. This completion technique was used in this case due to problems caused by sloughing of shale stringers. This is a typical oil-gas industry completion technique that is not recommended for geothermal wells because porous zones in the aquifer may have been cemented off. Completion by screen and gravel pack might have increased the completion cost, but eliminated the need for acid stimulation.

Artesian flow testing has been conducted on the St. Mary's Hospital well with the conclusion that the well sustain the flow rate and wellhead pressure required by the hospital heating system. A longer duration test and a pump test were recommended to determine drawdown in water level which would occur if higher flow rates should be required from the well. This additional testing has not been planned.

Table 4. Specific capacity of St. Mary's Hospital well

<u>Q</u> <u>(L/s)</u>	<u>10 Minutes</u>		<u>60 Minutes</u>	
	<u>s</u> <u>(kPa)</u>	<u>Q/s</u> <u>(L/s)/kPa</u>	<u>s</u> <u>(kPa)</u>	<u>Q/s</u> <u>(L/s)/kPa</u>
26.5	3265	8.11×10^{-3}	3274	8.09×10^{-3}
17.7	1744	1.01×10^{-2}	2144	8.25×10^{-3}
13.6	1297	1.05×10^{-2}	1544	8.81×10^{-3}
24.0	2730	8.79×10^{-3}	--	--
22.7	2641	8.60×10^{-3}	2930	7.75×10^{-3}
23.7	2710	8.75×10^{-3}	2975	7.97×10^{-3}

<u>Q</u> <u>(gpm)</u>	<u>10 Minutes</u>		<u>60 Minutes</u>	
	<u>s</u> <u>(psig)</u>	<u>Q/s</u> <u>(gpm/psig)</u>	<u>s</u> <u>(psig)</u>	<u>Q/s</u> <u>(gpm/psig)</u>
420	473.5	0.887	474.8	0.884
280	253	1.107	311	0.900
215	188	1.144	224	0.960
380	396	0.960	--	--
360	383	0.940	425	0.847
375	393	0.954	431.5	0.869

Q = discharge rate

s = drawdown at 10 and 60 minutes

Q/s = specific capacity at 10 and 60 minutes

Figure 17. Specific capacity versus discharge rate in the St. Mary's Hospital well.

Table 5. Water analysis

<u>Specie</u>	<u>PPM</u>
Total Dissolved Solids (TDS)	2084
HCO ₃ ⁻	124
Cl	75
SO ₄	1445
SiO ₂	27
Na	50
K	21
Ca	402
Mg	86
Fe	0.3
Mn	0.25
B	1.63
Cu	<0.1
Ag	<0.25
Pb	<0.8
Zn	<0.02
Cd	<0.05
Hg	<0.005
HS	0.7
O	<1.0

pH = 6.80
T = 106°F

Table 6. Summary of the St. Mary's Hospital case study

PROJECT TITLE:	Geothermal Direct Heat Application, St. Mary's Hospital Pierre, South Dakota
PRINCIPAL INVESTIGATOR:	James Russell, Administrator, (605) 224-5941
PROJECT OBJECTIVE:	To demonstrate to the public the geothermal potential of the Madison Aquifer by using the resource to provide space and water heating for the St. Mary's Hospital
LOCATION DESCRIPTION	Pierre, South Dakota
Population:	9,600
Area Activities:	Agriculture.
RESOURCE DATA	
Well Depth:	662 m (2176 ft)
Date Completed:	5/30/79
Completion Technique:	Casing cemented to total depth and shot perforated
Wellhead Temperature:	41.1 C (106 F)
Flow Rate:	23.7 L/s (375 gpm) artesian flow with a wellhead pressure of 200 kPa (29 psig)
Summary:	Warm artesian waters have been known in Pierre since the late 1800's. A deep well drilled a few miles from the St. Mary's site produced water at 43 to 47 C (110 to 117 F). The present well was drilled into the Madison Group Aquifer beneath the St. Mary's Hospital property.
SYSTEM FEATURES:	
Application:	Space and water heating
Heatload (Design):	5.55×10^6 Btu/hr
Yearly Maximum Use:	11.4×10^9 Btu/yr
Energy Replaced:	Fuel oil--435,275 L/yr (115,000 gal/yr)
Facility Description:	285 bed hospital
Disposal Method:	Discharge into the Missouri river through a perforated pipe 130 ft (39.6 cm) long.

Table 6. (continued)

SYSTEM FEATURES (continued):

Summary:

The St. Mary's Hospital was able to replace No. 2 fuel oil with geothermal water, representing a yearly savings in fuel costs of \$365,000. The system payback will take 6.3 years.

Status:

The St. Mary's Hospital is currently using the geothermal water produced from one well for space and water heating. No further development is planned.

3. WHITE SULPHUR SPRINGS CASE STUDY

3.1 Introduction

The First National Bank is the newest structure in the town of White Sulphur Springs, Montana. The town is a small agricultural community of about 1,400 located in Meagher County, approximately 120 km (75 mi) due north of Bozeman, Montana (Figure 18). The principle industry is stock raising. The town's only bank is a 603 m² (6500 ft²) structure, presently being heated by geothermal fluids.

Prior to the development of the town, the area was frequented by local Indians due to numerous thermal springs and seeps in an ~80 m² (20 acre) area. Weed¹³ visited the area around the turn of the century and reported that nine large thermal springs and several seepages whose combined flow was estimated at 13.7 L/s (217 gpm) was used for public baths at a temperature 51°C (123.5°F). In early 1970, the SPA Motel was built within 91 m (300 yards) of the main spring with the intent of using the thermal fluids. The motel is currently using the thermal fluids for a pool and space heating. The discharge was estimated in 1974 at 9.5 L/s (150 gpm) of 57°C (135°F) fluid.¹⁴ However, as the town was developed around the area most of the seepages stopped. In addition, it is the belief of the motel owner that the spring discharge has declined.¹⁵

The First National Bank building was built across the street from the SPA Motel, in an area of historic thermal seepage. The location was partially chosen to ultimately use thermal fluids in place of fossil fuel or electricity.

The project was initiated by the bank president, Mr. Mike Grove. He organized the following group of consultants to locate, develop and utilize the resource: Montana State University, a hydrology firm, a mechanical engineering firm, an architectural/engineering firm, and lastly, a geothermal engineering firm. The project was funded by the Montana State Department of Natural Resources and Conservation under grant No. RAE-503-GROVE-77.

3.2 Background

3.2.1 Geology. White Sulphur Springs is located in the Smith River Valley within the Rocky

Mountain physiographic province. The Smith River Valley is delineated on the east by a low drainage divide and the following mountain ranges on all other sides: Crazy Mountains to the south, Castle Mountains to the north, and the Big and Little Belt Ranges to the west.

The Smith River Valley consists of over 7927 m (26,000 ft) of sedimentary and igneous rocks ranging in age from Precambrian to Quaternary. In the vicinity of White Sulphur Springs, there is 9-21 m (30-70 ft) of Quaternary alluvium consisting of gravel, silt and clay deposits. The Greyson Shale underlies the alluvium in the area of the thermal springs. Exposures of this Greyson Shale lie immediately to the north of the city: a thick sequence of Precambrian shale, argillite, siltstone, and minor amounts of limestone and conglomerate (Figure 19). Outcrops of Tertiary sediments, consisting from mostly fine-grained siltstone and tuff beds to sand and coarse conglomerate of mud flows, lie to the east and west of the city. Exposures of Tertiary extrusives lie to the southeast and west of the city. A generalized stratigraphic section is presented by Groff.¹⁶ The major formations, in terms of thickness, consist of the Deep River and Fort Logan Formations (fine-grained siltstone and tuff beds to sand and coarse conglomerate); the Livingston Formation (andesitic sediments ranging from black marine shale to fairly coarse sandstone); the Colorado Shale (shale and siltstone); the Madison Limestone (massive Mission Canyon Formation to thin-bedded Lodgepole Formation); the Spokane Shale (mostly a red micaceous shale); the Greyson Shale (a sequence of shale, argillite, siltstone, and minor amounts of limestone and conglomerate); and the Newland Limestone (thin-bedded limey shale to platy siliceous limestone).¹⁶

The Smith River valley lies in a structurally complex region between the Big Belt Uplift, the Little Belt Uplift, and the Castle Mountains Dome. In addition, the Smith River valley is the apparent zone of intersection of the huge central Montana Arch (Big Belt, Little Belt, Big Snowy, Porcupine Uplift) and the famous Disturbed Belt (southeast-trending zone of imbricate thrust faulting), which extends from Canada to the Lombard-Three Forks area. Still another major structural feature, the Crazy Mountain Basin, extends into the southeastern part of western Meagher County.

Figure 18. General location map of First National Bank, White Sulphur Springs, Montana.

Figure 19. General geology of White Sulphur Springs, Montana.

Geologic structures of the area are complicated by extensive overthrust faults of considerable displacement. These were first described by Tanner.¹⁷ Their presence in this area indicates that the intricate thrust fault zone of the Disturbed Belt is present east of White Sulphur Springs. Evidence of major thrust faults extends from the southern edge of the area to its northwestern corner. High-angle reverse or normal faults more or less parallel the thrust system and the surface trace of the fault is marked in most places by silicification, brecciation, and red alteration products. Folding is most complex in the northwest corner of the area. Both folding and faulting seem related to at least two distinct orogenic phases and possibly a much older third phase.¹⁷

3.2.2 Hydrology. The principle aquifer in the area around White Sulphur Springs is Recent alluvium in the form of permeable gravel deposits. Wells in this area should be capable of providing water for irrigation through part of the irrigation season. However, very few wells exist in the local area. The town of White Sulphur Springs produces its water from the Trinity Springs which flows 158 L/s (2500 gpm) of water at 11°C (52°F).

There are numerous cold springs in Meagher County, mostly near the mountains. Most large springs appear to be related to cavernous limestone or thrust faulting.

3.2.3 Geothermal. The White Sulphur Hot Springs issue from a thin cover of Quaternary alluvium covering the Greyson Shale. A thrust plate, which crops out at the surface 4.8 km (3 mi) northeast of the town, dips underneath White Sulphur Springs).¹⁸ A north-south striking fault occurs near the First National Bank Property. Water, heated at depth, apparently rises along this fault to migrate laterally, along a zone and/or fractures of high hydraulic conductivity, possibly the thrust fault, near ground surface.¹⁹

Throughout the region, the emplacement of igneous rocks appears to have been controlled by major faults or joint networks. Highly silicified and otherwise altered zones are common along the major fault planes and may be the result of hydrothermal activity associated with the intrusions. The underlying Madison Group is of possible importance to the geothermal display. Wildcat oil and gas wells open to this formation show

fluids on the order of 49°C (120°F). Water chemistry does not suggest drastically differing fluids.¹⁶

Hot water had been found locally in the excavation of the local hospital 61 m (200 ft) northeast of the main springs, 152 m (500 ft) to the north in another excavation, and a natural seep 30 m (100 ft) north-northwest. This suggests that water circulation follows conduits (faults or fissure zones) made in the 46-76 m (150-250 ft) thick alluvial stratum.¹⁸

3.3 Exploratory Programs

A soil temperature survey at 0.6 m (2 ft) was conducted in over 60 locations in the 80 m² (20 acre) area of historic thermal activity. The surveys were conducted using copper-constantan thermocouples and a direct reading potentiometer. The thermocouples were inserted in the 0.6 m (2 ft) holes which were filled with soil and allowed to reach equilibrium. The survey showed a north-northwest trending zone of elevated temperatures. This zone extends from the bank property through the SPA Motel property and terminates in an area of sawmill waste fill 90 m (300 ft) to the east.²⁰

A resistivity survey was accomplished 300 m (1,000 ft) to the north of the bank. Two orthogonal profiles were run approximately 76 m (200 ft) and 229 m (750 ft) in length. The Wenner Array was used, which allowed for 40-50 m (131-164 ft) of penetration depth. No anomalies were identified by the apparent resistivity cross-sections.²¹

A reflection seismic survey was also run about 213 m (700 ft) to the north of the bank and just south of the bank. Three seismic profiles were run, each about 61-91 m (200-300 ft) in length. The profiles showed displacements of up to 10 m (30 ft) in the Greyson Shale. It appears that a major fault exists about 30 m (100 ft) east of the bank building.²²

Additional data concerning heat flow and geology were obtained when the Mountain View Hospital, located within the 80 m² (20 acre) thermal area drilled a test well to 67 m (220 ft). The lithology is basically a sandstone with some members more like a claystone from 4 m (13 ft) to total depth. Water temperature increases with

depth in a stepwise fashion. Nurse²³ interpreted the stepwise temperature gradient as suggesting impervious layers. The static water level declined and then rose with depth during drilling and was interpreted by Nurse²³ as suggesting poorly interconnected aquifers. The maximum bottom-hole temperature was estimated at 46°C (115°F).²³

3.4 Production Drilling

Selecting a site for production well drilling was made by the hydrogeologic consultant based on land ownership and geophysics. The well was located near the southeast corner of the bank property. This location was closest to a high soil temperature anomaly and as near as possible to the suggested fault in the seismic survey. The well was targeted to be drilled to 305 m (1000 ft). Target production rate was 5 L/s (80 gpm) of 46°C (115°F) fluid. Initially injection was planned to a shallower depth.

The well was drilled on a footage-rate basis. Drilling was accomplished with a Gardner-Denver 1500 rotary drill rig with a 25 cm (10 in.) rotary table and 6 cm (2-1/2 in.) mud lines. The drill pipe was 11 cm (4-1/2 in.) OD flush joint. No drill collars were used during drilling of the well. The drill fluid was planned as water, but natural bentonite in the formation resulted in the well being drilled with mud. A considerable amount of lost circulation material was also used in the drilling process.²⁴

The well was drilled with a nominal 38 cm (15 in.) bit to a depth of 10 m (30 ft). Schedule 40 steel casing, 30.5 cm (12 in.) in diameter, was installed and cemented in place. The well was then deepened to 29 m (95 ft), a nominal 29.8 cm (11-3/4 in.) in diameter. FibercaseTM casing, an epoxy ester pipe, 15 cm (6 in.) in diameter was inserted and cemented in place. The well as completed to 267 m (875 ft) using a 14.9 cm (5-7/8 in.) bit. Slotted FibercastTM casing, 7.6 cm (3 in.) in diameter, was hung from 27-104 m (90-340 ft) due to potential caving problems. The well was left open from 144 m (340 ft) to total depth of 267 m (875 ft). (See Figure 20.)

After completion of the well the drill fluids were circulated out. Air development was conducted until the well produced sand-free, clear fluids.

During drilling operations the hydrologic consultant recorded rate of penetration and drill fluid losses. A lithology log was produced during drilling based on 1.5 m (5 ft) samples and lithology changes. The material was predominately mudstone with varying amounts of silica-cemented quartz sandstone and considerable pyrite. At 144-152 m (480-500 ft) a yellow-orange clay was penetrated. The rock below 152 m (500 ft) was essentially all mudstone. Some of the pyrite showed well-developed crystal faces suggesting growth in open fractures. None of the subsurface material was found to be permeable.²⁵

Upon completion of the well a suite of borehole geophysical logs were run including temperature, natural gamma, spontaneous potential, wall-rock resistivity (single point) and a 3-arm caliper. The temperature logs, run at equilibrium and while pumping, showed a maximum temperature of 47°C (116°F) at a depth of 53 m (175 ft). The temperature decreased in all cases below this depth (Figure 21).

3.5 Aquifer Testing

In order to test the well, a 5-hp electric submersible test pump was set to a depth of about 4.6 m (15 ft). The discharge rate was regulated by a gate valve and measured by a bucket and stopwatch. For testing purposes the water was discharged to the Main Street gutter. Drawdown was measured with an electric tape.

A pump test at a discharge rate of 2.7 L/s (43 gpm) was begun, but due to difficulty in obtaining drawdown measurements was terminated after 10 minutes. The well was allowed to recover for 25 minutes. The test was restarted at 2.7 L/s (43 gpm) and run continuously for 605 minutes. The pumping rate was then increased to 5 L/s (79.5 gpm) for an additional 400 minutes. The discharge temperature was constant at 47-48°C (117-119°F). Recovery was measured for 69 minutes. The results of the production and recovery test are illustrated in Figures 22 and 23.

Transmissivities were calculated and the lowest value of 1982 (L/s)/m (103,000 gpm/ft) was assumed to be most correct.²⁵ The time versus drawdown curve shows only data scatter after 29 to 35 minutes. The consultant gave several possible explanations for this shape in the curve, but

Figure 20. Final construction diagram and lithology of the First National Bank production well, White Sulphur Springs, Montana.

Figure 21. Borehole temperature logs of First National Bank production well, White Sulphur Springs, Montana.

Figure 22. Drawdown for short-duration, multi-rate pump test of First National Bank production well, White Sulphur Springs, Montana.

hypothesized that an apparent recharge boundary was most reasonable. It was projected that drawdown at a discharge rate of 3.2 L/s (50 gpm) would cause only 0.4 m (1.22 ft) of drawdown. A recommendation to set the production pump at 4.6 m (15 ft) was made by the hydrologic consultant.

During the pump test, the SPA Motel thermal well and the discharge of the spring area were monitored. Nominal effects were seen at both locations. The consultant suggested that no adverse effects will be seen when producing the bank well at the required low rates.²⁵

3.6 Current Project Status

The geothermal well and heating system is currently in the second year of successful operation. No adverse effects have yet been determined. The 5 L/s (80 gpm) discharge is currently supplied to the SPA Motel at 47°C (116 °F) for their future use in additional space heating.

No cost savings or estimated investment pay-back period have been calculated due to limited data. Continued successful use is anticipated. A summary is provided in Table 7.

3.7 Conclusions

The White Sulphur Springs project had limited problems in the exploration and testing phases of development. Although site selection and exploration were based on space heating requirements at the existing bank structure, the bank was recently built on an area of historic thermal seepage with the intent to utilize the geothermal resource at a later date. This did limit site selection to an economical piping distance from the bank and to land ownership or unoccupied property. It would have been better to run the exploration program before purchase of the property and building the bank structure.

The testing phase encountered several difficulties. The long duration tests were too short

Figure 23. Recovery from short-duration, multi-rate pump test of the First National Bank production well, White Sulphur Springs, Montana.

Table 7. Summary of the White Sulphur Springs case study

PROJECT TITLE:	First National Bank of White Sulphur Springs
PRINCIPLE INVESTIGATOR:	Mr. Mike Grove, President, First National Bank (406) 586-6518
PROJECT OBJECTIVE:	Supply economical base load heating by using geothermal fluids
LOCATION DESCRIPTION:	White Sulphur Springs, Montana 120 km (75 mi) north of Bozeman, Montana
Population:	1400

Table 7. (continued)

Area Activities:	Agriculture and stock raising
RESOURCE DATA:	
Well Depth:	267 m (875 ft)
Date Completed:	July 1978
Completion Technique:	Slotted Fibercase TM casing
Wellhead Temperature:	47-48°C (117-119°F)
Flow Rate:	3.2 L/s (50 gpm) pumped
Summary:	No other geothermal wells exist in the local area. Several springs issue 57°C (135°F) fluids. The present well was drilled into Greyson Shale, a sequence of shale, argillite, siltstone, and small amounts of limestone.
SYSTEM FEATURES:	
Application:	Space heating a commercial bank
Heatload (Design):	2.5×10^5 Btu/hr
Yearly Maximum Use:	2.8×10^8 Btu/yr
Energy Replaced:	No. 2 Fuel Oil- 5.3×10^4 L/yr (14,200 gal/yr) Natural gas- 36.8 m^3 /yr (1,300 ft ³ /yr)
Facility Description:	603 m ² (6500 ft ²) commercial bank
Disposal Method:	Surface discharge to irrigation ditch
Summary:	The system was designed to provide 80% of the heatload.
STATUS:	
The system is currently in operation.	

for reliable extrapolation due to time-dependent density problems, apparent discharge-rate problems and the dual porosity nature of the reservoir. The time-dependent density problems could not be evaluated since only limited thermal

data were recorded. Thermal data should be collected on the same schedule as drawdown in order to correct and evaluate the test data. The quality of the well test data is unacceptable as a result of the apparent discharge rate fluctuations.

4. PAGOSA SPRINGS CASE STUDY

4.1 Introduction

Pagosa Springs, a small town of less than 1,500 people, is located in Archuleta County, Colorado, 448 km (278 mi) southwest of Denver and 106 km (66 mi) east of Durango (see Figure 24). The area of investigation includes 550 km² (211 mi²) centered on the city of Pagosa Springs. The city is located on the northeastern edge of the San Juan Basin approximately 24 km (15 mi) west of the Continental Divide, at an elevation of 2121 m (6957 ft).

Natural hot waters of the Pagosa Springs area have been used since the early 1800s. Indians named the area Pah-gosa, meaning "boiling waters," and used the hot springs for medicinal purposes and religious ceremonies. When white settlers came to the region in the late 1800s, they also used the springs for medicinal and recreational purposes. Often they would use the heat from the springs to cook meats during community celebrations. Between 1900 and 1910 the first hot water well was drilled in the community of Pagosa Springs, thus starting the use of natural hot water heating in the area.²⁶

The main hot spring is located south of downtown Pagosa Springs, across the San Juan River. This is the largest hot spring, in diameter, in Colorado with a discharge vent of 7-9 m (23-30 ft) in diameter. At 57.8°C (136°F), with a discharge of 19-44 L/s (300-700 gpm)^{27,28}, Pagosa Hot Springs has neither the hottest nor the highest discharge in Colorado.

During the early 1900s hot wells were drilled in the area to provide natural hot water for space heating. The first well drilled in Pagosa Springs was the well at Adobe Inn. Out of the 30 known hot wells in Pagosa Springs 13 are presently being used, seven are operational but not in use, and ten have been abandoned. Temperatures of these wells range from 34 to 67°C (93 to 153°F) with most wells averaging 55°C (131°F).²⁹ Depth of the hot wells range from 26 to 143 m (85 to 468 ft), with the average depth of the hot wells in Pagosa Springs being from 91 to 122 m (300 to 468 ft).²⁹ All hot wells produce from either the Dakota Sandstone or Mancos Shale. Many of the hot wells in downtown Pagosa Springs are being used to heat commercial businesses and public

buildings, while some wells are used to melt snow in the winter or provide tourist attractions.

The object of current development is to establish an extensive geothermal heating system within Pagosa Springs. The proposed system would provide hot water for space heating to about 10 public buildings (including schools), 54 businesses, and 63 homes. The system is intended to be operated by the town in cooperation with Archuleta County and the Colorado School District 50JT. The resource is proposed as an attraction around which future development can be built.

Pagosa Springs, Archuleta County, and School District 50JT, with the assistance of an architectural/engineering firm, a geology firm and a ground water firm responded to a Department of Energy, Project Opportunity Notice (PON ET-78-03-2047). Their project was selected for funding.

4.2 Background

4.2.1 Geology. Pagosa Springs is located in the San Juan Division of the Upper Colorado River Basin. The topographic boundaries of the basin consist of a series of uplifted earth masses that are deeply dissected by erosion, weathering, and glaciation. To the east and northeast, the San Juan Mountains serve as a boundary with elevations over 3950 m (1300 ft). Pagosa Springs is almost completely surrounded by the San Juan National Forest and lies only 24 km (1.5 mi) west of the Continental Divide. Its elevation, 2165 m (7085 ft), is due to the influence of the neighboring mountain range. The San Juan Division of the Upper Colorado River Basin is divided into two physiographic provinces. Pagosa Springs is located within the Southern Rocky Mountain Province.

In the Pagosa Springs area about 427 m (1400 ft) of Jurassic through Cretaceous sediments rest unconformably on Precambrian igneous and metamorphic rocks.³⁰ Most of these formations crop out in the Pagosa area. The local geology is characterized by the Mancos Shale formation overlying the Dakota Sandstone (Figure 25).

Figure 24. General location map of Pagosa Springs, Colorado.

Adapted from Steven and others, 1974

Qa	Alluvial deposits	Quaternary	Ti	Intrusive Rocks	Tertiary
Kl	Lewis Shale	Kmv	Mesa Verde Formation	Km	Mancos Shale
Kmu	Mancos Shale (upper part)	Kml	Mancos Shale (lower part)	Kdb	Dakota Sandstone and Burro Canyon Formation
Jmw	Morrison and Wanakah Formations	Jurassic

Explanation

- Qa — Alluvium, Quaternary
- Qt — Travertine, Quaternary
- Kmu — Mancos Shale (upper), Upper Cretaceous
- Kml — Mancos Shale (lower), Upper Cretaceous
- Kd — Dakota Sandstone, Upper Cretaceous
- Jm — Morrison Formation, Upper Jurassic
- Jw — Wanakah Formation, Upper Jurassic
- Je — Entrada Formation, Upper Jurassic
- Rd — Dolores Formation, Upper Triassic
- pεc — Crystalline Rocks, Precambrian

Index map

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Figure 25. Geologic map and cross section of Pagosa Springs, Colorado.

The Mancos Shale is subdivided locally into upper and lower members. The lower member is a dark gray to black shale with bentonite beds near the top and bottom. The total thickness is between 75-90 m (245-295 ft). The upper member includes white to gray bentonite interbedded with gray, fissile-bedded, calcareous shale. Thin silty zones and septarian concretions are also common. The total thickness of these members is about 335-520 m (1099-1706 ft).³¹ The Dakota Sandstone is a fine- to coarse-grained, parallel-bedded and cross-laminated quartz sandstone, interbedded with dark gray to black carbonaceous shale. Much of the Dakota Formation around Pagosa Springs is quartzitic.

These sedimentary units dip northeast at 8 to 10 degrees as the result of the Archuleta Anticlinorium, a regional tectonic feature. Pagosa Springs is situated on its eastern flanks. Ryder³⁰ states that the anticlinorium is characterized by: (a) west to northwest-trending, upright and inclined, plunging, cylindrical folds; (b) northwest-trending longitudinal faults; and (c) northeast-trending transverse faults. The Anticlinorium is 120 km (75 mi) long and from 9.7 to 26 km (6 to 16 mi) wide. This complex zone of faults and folds is the northward continuation of the Nacimiento and San Pedro mountains of New Mexico.³² Southwest of Pagosa Springs are the Sunetha and Stinking Springs anticlines (Figure 25), which are smaller fold features trending in the dominant N 40° W direction.

The major fault system is situated 3 km (2 mi) southwest of town. This fault has been called the Nacimiento Fault Zone or the Eight Mile Mesa Fault.³³ Though the fault zone trends from northwestern New Mexico, and has up to 91 m (300 ft) of vertical displacement, the fault trace is relatively unaffected by topography, suggesting a near vertical orientation. Displacement along near-vertical normal faults in the Pagosa Springs area ranges from less than 3 m (10 ft) to 91 m (300 ft), which is relatively insignificant compared to the overall lengths of these fault systems. However, locally, the Nacimiento Fault uplifts the Dakota Sandstone into fault-contact with the overlying Mancos Shale. Minor faulting occurs in several directions from the Nacimiento Fault. It is projected that one of these splay faults may trend through the town of Pagosa Springs and be a conduit for the hot spring waters; however, there is no surface manifestation of such a fault.

4.2.2 Hydrology. The major drainage is the San Juan River. Its headwaters are located to the east, on the western slope of the Continental Divide. The West and East Forks of the San Juan River flow through areas little disturbed by human activity, with the West Fork providing the domestic water supply for the Town of Pagosa Springs. The San Juan River at Pagosa Springs has been classified by the Colorado Department of Health as a Class B₁ river.³⁴ McCabe Creek that originates about 5 km (3 mi) north of the town joins the San Juan River at mid-town Pagosa Springs. McCabe Creek is the only other significant stream within the town boundaries.³¹

The near-surface ground water regime is dominated by the San Juan River and by local structures. The relatively abundant surface water and poor water quality in the shallow aquifers has resulted in limited ground water development. Within and adjacent to Pagosa Springs, alluvial deposits along the flood plain of the San Juan constitute the most productive ground water aquifers. The aquifers yield several hundred L/s (several thousand gal/min).³⁵ The Mancos Shale and Dakota Sandstone are two additional aquifers that are exploited in the Pagosa Springs area.

Most of the wells in Pagosa Springs are completed in either the Mancos Shale or the overlying alluvium and are less than 61 m (200 ft) deep. Ground water flow in the Mancos Shale is the result of both fracture and intergranular porosity. Many of the discontinuous sands yield moderate amounts of water under semi-confined conditions. The phreatic surface map suggests areas of local recharge to the west, north, and east of Pagosa Springs. A local discharge area occurs about 0.6 km (1 mi) south of Pagosa Springs along the San Juan River. Recharge to the San Juan River may occur along much of its course through the Mancos Shale, but because of limited data, this cannot be verified.

Galloway³³ states that yields and specific capacities of wells in the Mancos Shale are highly variable ranging from 0.06 to 2 L/s (1 to 30 gpm) and from < 0.01 to 41 (L/s)/m (0.01 to 41 gpm/ft), respectively. Many of the higher values are based on reported drawdowns of zero, which may be in error. Estimated coefficients of transmissivity, assuming a storage coefficient of 0.2, range from less than 30,000 (L/s)/m to

900,000 (L/s)/m (100 gpd/ft to 30,000 gpd/ft). Some of the wells with high specific capacities may be partially completed in alluvium.

Ground water flow in the Dakota Sandstone is the result of fracture porosity and is confined. At least, two semi-independent aquifer (fracture) systems probably exist; they are separated by black shale sequences.³³ Areas of recharge, as defined by the piezometric surface map correspond to exposures of Dakota Sandstone. Along the San Juan River south of Pagosa Springs, ground water from the Dakota Sandstone may be recharging the San Juan River. The Dakota Sandstone is not exposed in town, suggesting that discharge may occur through fractures and/or faults into the Mancos Shale. The delineation of the discharge area is uncertain.

Ground water quality of the Mancos Shale is generally poor. Total dissolved solids range from 1000 to 2500 mg/L with particularly high concentrations of sodium, calcium, iron, and sulfate. Dissolved hydrogen sulfide is also common. However, there are undocumented claims of relatively good quality ground water from the Mancos Shale. These may be wells completed in relatively clean discontinuous sands which may be in hydraulic connection with alluvium.

4.2.3 Geothermal. The geothermal reservoir in the area is probably restricted to fractures in the Dakota Sandstone and lower Mancos Shale.³³ There are no geologic indications of intrusives providing heat to the Pagosa Springs geothermal system. The youngest known intrusives are the late Miocene dikes of the Archuleta dike swarm and a 26 to 28 m.y. old subvolcanic batholith, postulated by Lipman.³⁶ The lack of adequate young intrusives suggests that heat may be provided to the geothermal system by relatively deep circulation and a slightly enhanced regional geothermal gradient.

One of the major questions regarding the nature of this thermal system is whether the thermal water flows laterally through the Dakota Sandstone and Mancos Shale, or is fed only vertically via fractures.

During 1975 and 1976, the Colorado Geological Survey sampled all the known hot springs and wells in the state on a regular basis. In Pagosa Springs, they sampled the main hot springs: the Courthouse Well, and the

Spa Motel-1 well. The Colorado Geological Survey analyzed the water samples for a complete suite of metals, trace elements, irons, and dissolved minerals. Then the Survey applied several standard chemical geothermometer models³⁷ to the chemical analyses from the hot waters in Pagosa Springs. The results of the geothermometer models yielded calculated reservoir temperatures at depth ranging from chalcedony-silica at 76-81°C (169-178°F) to Na/K at 207-211°C (404-412°F). The conclusions of the Survey were that the Na/K and a Na-K-Ca model were anomalously high as the result of massive calcium-carbonate (travertine) deposition throughout the spring area. The state's best guess as to subsurface reservoir temperatures was calculated at 80-150°C (176-302°F). The maximum temperature experienced in any spring or well in the Pagosa Springs area has been 67°C (153°F) from the Adobe Inn Well and the Montroy Well.

Two isotopic determinations for oxygen-18 and deuterium were done on geothermal fluids from the Colorado Geological Survey test wells.³³ If values are plotted on a graph, the points fall on the trend of meteoric and slightly heated ground waters, as defined by Craig,³⁸ indicating the geothermal fluids at Pagosa Springs are of meteoric origin and were not trapped in place for several million years. The results of a tritium analysis on samples from state wells P-1 and O-2 imply that the geothermal fluids have a residence time greater than 25 years.

4.3 Exploratory Programs

Dipole-dipole and dipole-bipole electrical resistivity surveys have been conducted over a 3 km (2 mi) radius from town. The dipole-bipole survey resulted in background resistivities ranging from 150 to 300 $\Omega \cdot m$ or more. These resistivities are relatively high for a sedimentary sequence, and probably reflect the presence of relatively fresh waters in the sedimentary sequence. A striking feature of the reconnaissance resistivity survey is the region of anomalously low resistivity, less than 30 to 50 $\Omega \cdot m$ mapped at the town of Pagosa Springs. The lowest resistivity values are just southeast of and near the main hot springs. A second anomaly is weaker (average resistivity of 50 $\Omega \cdot m$) and is northwest of Pagosa Springs at the cemetery. Keller³⁹ felt these areas of low resistivity probably reflect the limits of the reservoir in which thermal waters are present. The area of low

resistivity appears to terminate abruptly along a northwest-southeast trending line along the southwestern edge of the town. The regions of lowest resistivity tend to be elongate to the northeast. The most noticeable feature from the dipole-bipole survey is the N 30° E orientation of the low resistivity zones; this approximates the strike of mapped splay faults from the Nacimiento fault. In summary, both the shallow and deep penetration resistivity surveys indicate a well-defined zone of low resistivity which probably represents the area of the reservoir feeding the hot springs.³⁹

The Colorado School of Mines conducted a vibroseis survey of Pagosa Springs to delineate major faults, structures, and depth of indicator horizons under the town.³⁹ The results and interpretations projected by the study are questionable.⁴⁰ A major east-west fault is interpreted as passing through the central portion of Pagosa Springs, although no surface indications are expressed. The interpretation of the vibroseis survey gives anomalous depths to several indicator horizons. According to Callan,⁴⁰ if projected depths of these indicator horizons are compared with surface geology, and correlated with nearby oil well tests, depths differ by several kilometers.

Forty soil samples around Pagosa Springs were analyzed for concentrations of mercury. Slightly anomalous concentrations of soil mercury at Pagosa Springs (30 to 40 ppb) may indicate relatively low temperature geothermal resources. Three km (2 mi) southeast of town, samples begin to yield anomalously high concentrations of soil mercury in excess of 200 ppb. Though more data are needed southeast of Pagosa Springs, these high concentrations may indicate elevated subsurface heat. The mercury soil survey failed to delineate any anomalous areas within Pagosa Springs.⁴¹

In 1977, the Colorado Geological Survey contracted the drilling of six temperature gradient wells (heat flow holes) at Pagosa Springs³⁷ (see Figure 26). These wells were drilled to depths of about 92 m (300 ft) and temperatures were recorded at 3 m (10 ft) intervals (Figure 27).

Many of the heat flow holes at Pagosa Springs have gradients in excess of 100°C/km (6.5°F/100 ft). Nearly all heat flow holes have twice the normal heat flow values.⁴¹

4.3.1 Test Drilling. The objective of the Colorado Geological Survey's test drilling^{33,41} program at Pagosa Springs was to confirm the existence of a geothermal reservoir at depth and to evaluate the reservoir with respect to various hydrologic characteristics. Locating the test well sites proved to be a difficult problem. Geophysical, geological, hydrological, and heat flow surveys were not definitive, but indicated that an anomaly did exist and was restricted to an area of approximately 1.3 km² (0.5 mi²) centered under the downtown area.

The difficulties in locating a deep well were land ownership and physical space to drill. A legal agreement was reached among the owner of private land behind the Archuleta County courthouse, the county, city, and school district regarding the ownership of geothermal wells, and the sale and distribution of any produced water. This land would provide easy access to the river for both the disposal and the pumping of water needed in the drilling program, as well as, being sufficiently close to existing wells to permit pressure monitoring during drilling and testing.

Observation well 0-1 is a slim 610 m (2000 ft) observation well. The well was drilled using a Speedstar 5S-22 rotary drill rig. Large boulders, unconsolidated soil, sand, and gravel required installation of 7.25 m (23.8 ft) of 27.3 cm (10-3/4 in.) conductor pipe. Drilling continued rapidly through the Mancos Shale with air until about 19 to 32 L/s (300 to 500 gpm) of 56°C (133°F) water was encountered at a depth of 27.4 m (90 ft). Drilling continued to the top of the Dakota Sandstone at 72 m (235 ft) with a 22 cm (8-5/8 in.) bit. Surface casing was installed and cemented. A 25 cm (10 in.) gate valve and a single-stack blowout preventer were installed. An air-percussion hammer was used to drill through the Dakota Sandstone and into the Morrison Formation. The available compressed air was insufficient to lift the large volumes of geothermal water encountered in the Dakota Sandstone and to maintain good footage rates. During a break in drilling, severe caving occurred between 177 and 213.8 m (580 and 700 ft). Attempts to blow caving material from the hole failed. Mud could not be used because of the relatively high pressure of high volume geothermal water at such shallow depths. Casing could not be installed because the hole diameter would then be too small to proceed to the intended total depth. Instead of completely

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Figure 26. Detailed location map of Pagosa Springs production wells, test wells, and private hot wells.

abandoning 0-1, it was decided to designate it 0-2, a shallow observation well, and proceed with a larger diameter well.

Well P-1 was to be a test production well. Initially 3.7 m (12 ft) of 55.9 cm (22 in.) diameter culvert was installed to avoid potential problems with unconsolidated gravels and boulders, as those found in well 0-2. Drilling continued with a 51 cm (20 in.) rotary bit and 10.7 m (35 ft) of 41 cm (16 in.) conductor pipe was installed and cemented. Heavy collars, a reamer, and stabilizer were added to avoid some of the problems encountered in drilling 0-2. It was intended to drill through the caving zone of the Morrison Formation, cement casing, and continue to the Precambrian basement. At a depth of 76 m (250 ft), a fault was encountered which yielded between 95 to 126 L/s (1500 to 2000 gpm) of water at 60°C (140°F). This flow had such a significant

effect on the spring that the well had to be cased immediately precluding any testing. Casing was run from the surface to a depth of 81 m (265 ft) and cemented. After drilling through the same caving zone as encountered in well 0-2, the hole was cased with 174 m (511 ft) of 22.6 cm (8-7/8 in.) casing and cemented. A 20 cm (7-7/8 in.) hole was drilled to the top of the Precambrian at 418 m (1371 ft) where another large flow of 63 to 95 L/s (1000 to 1500 gpm) at 45°C (113°F) was encountered. A 16.8 cm (6-5/8 in.) casing was installed from the Precambrian basement to within 9 m (30 ft) of the surface and cemented. A 15 cm (6 in.) air-hammer was used to drill to 500 m (1475 ft) in crystalline rock. In view of the lower temperatures of 45°C (113°F), lateness of the season (local people were starting to depend on their private wells for heat), and a lack of funds, drilling was terminated. The wells were logged commercially (Density, BHC

Figure 27. Temperature gradient profiles for hot water wells at Pagosa Springs, Colorado.

Sonic, Neutron, Gamma, Induction). The wells were also logged by the Colorado Geological Survey equipment for temperature (Figure 27).

During drilling, many private geothermal wellhead pressures and the main spring level were monitored. At various depths and flows, some wells and the spring were affected by drilling activity. Details as to which wells were affected and the magnitude of effects are not available.

4.4 Production Drilling

Two geothermal wells were to be drilled to approximate depths of 91 m (300 ft). The targeted production rates from each well were 13 L/s

(500 gpm) of 57°C (135°F) fluids. The target reservoir was the Dakota Sandstone; as previous drilling showed the Mancos Shale did not yield adequate flows and had significant impact upon private wells in town. The wells PS-3 and PS-4 were first sited by land ownership and second by the success of the state drill program (wells 0-2 and P-1). The wells were located in a line with the state wells, 0-2 and P-1, parallel to the San Juan River (Figure 26). Well PS-4 is located 200 m (656 ft) S 45° W from well 0-2. Well PS-3 is located 61 m (200 ft) N 45° E from well P-1.

The wells were drilled on a day-rate basis. A consulting team consisting of an architectural

engineering firm, a hydrology firm, and a drilling specialist provided supervision to the driller. Drilling was accomplished with a Speedstar SS-20 rotary drilling rig. The drill pipe used was 7.3 cm (2-7/8 in.) diameter and the drill collars were 12.7 cm (5 in.) diameter. In general, the wells were drilled approximately 6 m (20 ft) through the boulders of the San Juan River alluvium with a 66 m (26 in.) hole and 51 cm (20 in.) conductor casing. This zone caused considerable difficulty and delays due to the river gravels and boulders.⁴² The wells were then drilled to approximately 24 m (80 ft) with a 44.5 cm (17-1/2 in.) bit and surface casing of 34 cm (13-3/8 in.) was set and cemented in place. The surface casing was set in a competent section of the Mancos Shale, before any major thermal flows were encountered. The wells were then scheduled to be drilled to the top of the Dakota Sandstone with a 31 cm (12-1/4 in.) bit and 24 cm (9-5/8 in.) casing cemented in place. The high flows expected to be encountered in this interval could be controlled by heavy drilling mud [1.7 kg/L (14+ lb/gal) of gel was actually used]. Finally, a 22 cm (8-3/4 in.) hole was to be drilled using water to a depth of 91 m (300 ft). A typical well construction can be seen in Figure 28.

Because the required flow rate and temperature were not encountered at PS-4, reservoir testing was not conducted. Cumulative flow rates of 6 L/s (228 gpm) at 48°C (118°F) were encountered during drilling operations. The well was thus considered a "dry hole" and was plugged and abandoned.

Because of inadequate total geothermal production, a third well, PS-5, was drilled to 84 m (274 ft). It was located on the same basis as wells PS-3 and PS-4, but near an existing high-capacity town well to ensure the required flow. The well was drilled and constructed similarly to wells PS-3 and PS-4.

During drilling, cuttings were sampled at 3 m (10 ft) intervals and at noticeable lithology changes. Although no geolograph was used, a record of drill penetration rate was kept to show an average penetration rate for each zone, and for use in future drilling to determine necessary casing points.

Excessive wear on bits during drilling and slow drill rates in the Dakota Sandstone was a function of poor drill supervision and improper equipment. The bits used were designed to drill with more

weight than could be applied, due to the short length of hole and the small diameter of drill pipe and drill collars. Air rotary bits were at first being used while drilling with water. Finally the mud pumps on the drill rig could not compete with the formation production, causing cuttings to be redrilled.

4.5 Aquifer Testing

During test drilling well P-1, the resource was evaluated. A test was organized during drilling of the uppermost water bearing zone in P-1 at 27 to 30 m (90 to 100 ft). Two adjacent wells were monitored for a period of approximately 2 hours. Air lifting fluids from P-1 resulted in an intermittent discharge. Responses were analyzed in the two observation wells and aquifer properties were calculated; however, test conditions and assumptions made about the aquifer question the validity of the hydraulic properties obtained. Transmissivity values ranges from 3×10^{-4} to $7.8 \times 10^{-3} \text{ m}^2/\text{s}$ (2400 to 54,000 gpd/ft) and storage coefficient ranged from 10^{-3} to 10^{-7} . The test clearly indicated interference drawdown of more than 30 psi at a distance of 46 m (150 ft). No further testing was done at P-1 while test drilling.³³

After completion of test drilling, a test was run with 0-2 used as a production well. The spring level and six private wells were monitored. Several days before the beginning of testing, all the monitor wells were shut-in. Prior history of operations were not recorded. Limited data were available on monitor well completion or construction. Four 1-hour pulse tests were run at rates of 12.6, 25, 44, and 63 L/s (200, 400, 700, and 1000 gpm). The well was unable to sustain 63 L/s (1000 gpm) for one hour. Results of the pulse testing were not reported.⁴³

The 24-hour 38 L/s (600 gpm) flow test was accomplished and results were analyzed assuming an isotropic, homogeneous aquifer system. Calculated transmissivity values from observation wells ranged from 1×10^{-3} to $3.7 \times 10^{-3} \text{ m}^2/\text{s}$ (7750 to 25,500 gpd/ft) with a storage coefficient of 10^{-2} to 10^{-5} . The consulting hydrology firm concluded that no boundary conditions were apparent in the observation well responses. Monitor well response suggested hydraulic connection between the Dakota Sandstone and the Mancos Shale. No effect was seen at the hot spring during the flow test.

Figure 28. Completion and casing profiles of well PS-3, Pagosa Springs, Colorado.

The tests at PS-3 and PS-5 were designed as natural artesian flow tests for 12 and 72 hours per well and a 7-day combined flow. For testing purposes 100 psi pressure gauges were installed at PS-3, PS-5 and six observation wells (County No.1, Town, Buhler, Edmonds, Superior Automotive and Methodist Church wells). In addition, the main hot spring was monitored by means of a staff gauge in the main pool. Discharge was regulated by gate valves and measured by an orifice plate with free discharge and a manometer tube. Temperature was measured by a glass mercury thermometer in the discharge line at unspecified "reasonable time intervals."⁴³

A step test was performed on wells PS-3 and PS-5 for 1-hour duration per step. No details or results were reported.

Independent 12-hour flow tests were run at wells PS-3 and PS-5. The discharge rates were 38 and 72.6 L/s (600 and 1,150 gpm), respectively. During the test at PS-5, it was necessary to open the gate valve completely to maintain a constant flow rate near the end of the 12-hour test. A plot of the logarithm of time versus drawdown for well PS-5 is presented in Figure 29. Subsequently, independent 72-hour tests were run at PS-3 and PS-5. The discharge rates were 27 and 50 L/s (425 and 800 gpm), respectively. A plot of the logarithm of time versus drawdown for well PS-3 is presented in Figure 29. Finally, a 7-day multi-well test was run with discharge rates of 13 and 44 L/s (212 and 700 gpm) at wells PS-3 and PS-5, respectively. A plot of the logarithm of time versus drawdown for wells PS-3 and PS-5 is presented in Figure 30.

It was recognized that the standard aquifer parameter of transmissivity did not apply in the strict sense of the definition. This is due to the definite fracture control of the reservoir system. However, for lack of a better term, the transmissivity parameter was calculated in the standard water well fashion. The system responds as a porous media on a macroscopic scale. Locally, the flow probably is controlled by fracture size, frequency and extent of interconnection. Furthermore, temperature data suggest that the system is complicated, since the wells show an average temperature difference of 10°C (18°F) over a linear distance of only 43 m (141 ft). This difference suggests that each production well, although hydrologically interconnected, is deriving its water from a local fracture network

that may have a different hot water source or a complex mixing phenomenon at depth.

A summary of the results of the 12- and 72-hour test is seen in Table 8. A summary of the interference effects during testing is seen in Table 9. The pressure reductions at the observation wells were determined to be dependent on the flow rate of the production wells, the distance from the production well to a given observation well, and the length of the flow test. However, a clear correlation between these factors could not be seen because of the unknown nature of the shallow reservoir system (i.e., Mancos Shale) and the lack of information on the depths of several hot water wells in the town.

The average storage coefficient was calculated to be on the order of 9×10^{-4} , which confirms that the reservoir exists under confined conditions. It was projected that PS-3 could be discharged at 25 L/s (400 gpm) for 100 years by natural artesian flow. It was projected that well PS-5 could be discharged at 44 L/s (700 gpm) for a minimum of 25 years before a pump must be installed.

4.6 Current Project Status

Development of the planned heating system is proceeding and will be operational during the 1981-82 heating season. A summary of activities is seen in Table 10.

4.7 Conclusions

The Pagosa Springs project had only minor problems in each of the development phases. The site selection and exploration programs were based on locating a resource close to the town of Pagosa Springs. This limited the well location to an economical piping distance from town. In addition, land ownership further restricted site selection. However, within this distance, only limited land was available for development. Although the geology and hydrology surveys produced a reasonable general description of the hydrogeologic environment, a site-specific target model was not detailed due to the fractured nature of the shallow thermal system. However, with current reasonably priced technology, no additional surveys would have clarified the target model.

Figure 29. Drawdown for 72-hour 27 L/s (425 gpm) test of PS-3, and for 12-hour 72.6 L/s (1,150 gpm) test of PS-5 at Pagosa Springs, Colorado.

Figure 30. Drawdown for 7-day, multiwell, flow test of PS-3 and PS-5 at Pagosa Springs, Colorado.

The drilling phase was hampered by a driller and drilling consultant that were neither familiar with the particular type of formations encountered nor with the drilling procedure. Difficulties were encountered in the boulder section of the alluvial material and in the Dakota Sandstone.

A typical ground water problem was encountered in the testing phase which does not have a simple solution. The monitor wells had limited, if any, data concerning construction. In addition, control of discharge from these wells was not possible. The result was data that cannot be readily interpreted.

Table 8. Calculated values of aquifer characteristics based on data from 12- and 72-hour flow tests at wells PS-3 and PS-5^a

Well Name	Well Type	Length of Test (hrs)	Pumping Rate		Transmissivity		Leakage Coefficient (Dimensionless)	Method of Analysis
			(L/s)	(gpm)	(m ² /s)	(gpd/ft)		
PS-3	Test	12	38	600	3.5 x 10 ⁻³	24,369	--	Jacob Semi-Log
PS-3	Test	12	38	600	2.8 x 10 ⁻³	19,317	N/A	Theis Recovery
PS-3	Test	72	27	425	1.6 x 10 ⁻³	11,327	--	Theis Log-Log
PS-3	Test	72	27	425	2.0 x 10 ⁻³	14,025	2.0 x 10 ⁻²	Jacob Semi-Log
PS-3	Test	72	27	425	2.2 x 10 ⁻³	15,583	N/A	Theis Recovery
PS-5	Observation	72	27	425	2.3 x 10 ⁻³	15,711	1.2 x 10 ⁻³	Theis Log-Log
PS-5	Observation	72	27	425	3.0 x 10 ⁻³	20,778	4.4 x 10 ⁻⁴	Jacob Semi-Log
PS-5	Observation	72	27	425	2.3 x 10 ⁻³	16,500	N/A	Theis Recovery
PS-3, -5	Observation	72	27	425	2.6 x 10 ⁻³	17,810	1.1 x 10 ⁻³	Distance Drawdown
PS-5	Test	12	73	1,150	2.2 x 10 ⁻³	14,976	--	Theis Log-Log
PS-5	Test	12	73	1,150	3.0 x 10 ⁻³	20,536	1.0 x 10 ⁻³	Jacob Semi-Log
PS-5	Test	12	73	1,150	3.1 x 10 ⁻³	21,770	N/A	Theis Recovery
PS-3	Observation	12	73	1,150	6.0 x 10 ⁻³	41,184	2.9 x 10 ⁻³	Theis Log-Log
PS-3	Observation	12	73	1,150	2.9 x 10 ⁻³	19,914	1.6 x 10 ⁻⁴	Jacob Semi-Log
PS-3	Observation	12	73	1,150	3.3 x 10 ⁻³	22,661	N/A	Theis Recovery

Table 8. (continued)

Well Name	Well Type	Length of Test (hrs)	Pumping Rate		Transmissivity		Leakage Coefficient (Dimensionless)	Method of Analysis
			(L/s)	(gpm)	(m ² /s)	(gpd/ft)		
PS-5	Test	72	50.5	800	2.3×10^{-3}	15,807	--	Theis Recovery
PS-5	Test	72	50.5	800	4.6×10^{-3}	32,000	4.0×10^{-5}	Jacob Semi-Log
PS-5	Test	72	50.5	800	3.0×10^{-3}	20,706	N/A	Theis Recovery
PS-3	Observation	72	50.5	800	3.0×10^{-3}	20,836	8.2×10^{-4}	Theis Log-Log
PS-3	Observation	72	50.5	800	2.8×10^{-3}	19,200	1.4×10^{-3}	Jacob Semi-Log
PS-3	Observation	72	50.5	800	2.7×10^{-3}	19,027	N/A	Theis Recovery
PS-3, -5	Observation	72	50.5	800	4.5×10^{-3}	31,289	4.7×10^{-5}	Distance Drawdown

a. See Reference 44.

Table 9. Pressure reductions at selected observation wells and water levels in Pagosa Springs during hydrologic testing program^a

Well/Spring Name	PS-3				PS-5					
	12-Hr Test		72-Hr Test		12-Hr Test		72-Hr Test		Multiwell Test	
	(kPa)	(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)	(psi)
Town	27.6	4.0	36.5	5.3	86.9	12.6	74.5	10.8	88.3	12.8
Methodist Church	26.9	3.9	33.8	4.9	51.0	7.4	44.1	6.4	68.9	10.0
Superior Auto ^b	--	--	53.1	7.7	95.8	13.9	82.7	12.0	106.2	15.4
Edmonds	30.3	4.4	34.5	5.0	53.8	7.8	48.3	7.0	74.5	10.8
Buhler	40.7	5.9	42.1	6.1	62.1	9.0	53.1	7.7	81.4	11.8
Texaco	--	--	--	--	48.3	7.0	--	--	--	--
County No.1	18.6	2.7	21.7	3.1	--	--	33.8	4.9	57.9	8.4
Giordanno No.1	--	--	--	--	--	--	--	--	46.9	6.8
Giordanno No.2	--	--	--	--	--	--	--	--	--	--
Pagosa Hot Springs (E) ^c	31	12-3/8	27	10-5/8	Dry	Dry	--	--	Dry	Dry
Pagosa Hot Springs (W) ^d	67	26-3/8	63	24-5/8	33	13-1/2	--	--	42	16-3/8

Table 9. (continued)

Well/Spring Name	PS-3				PS-5					
	12-Hr Test		72-Hr Test		12-Hr Test		72-Hr Test		Multiwell Test	
	(kPa)	(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)	(psi)
PS-3	434.4	63	351.6	51	--	--	117.2	17	--	--
PS-5	117.2	17	206.8	30	303.4	44	427.5	62	--	--

a. See Reference 44.

b. Well flowing throughout each test.

c. Measured in units of cm (in.). Static level in east spring = 36 cm (14 in.).

d. Measured in units of cm (in.). Static level in west spring = 71 cm (28 in.).

Table 10. Summary of the Pagosa Springs case study

PROJECT TITLE:	Pagosa Springs Geothermal Distribution and Heating System
PRINCIPAL INVESTIGATOR:	Fred A. Ebeling, Planning Administrator, Pagosa Springs, Colorado (303) 264-5851
PROJECT OBJECTIVE:	Provide the community with a means of using its natural hydrothermal resource for space heating
LOCATION DESCRIPTION:	Pagosa Springs, Colorado (48 km) 30 miles east of Durango, Colorado
Population:	1500
Area Activities:	Lumbering and agriculture

RESOURCE DATA:

	<u>Well PS-3</u>	<u>Well PS-5</u>
Well Depth:	(91 m) 300 ft	(84 m) 275 ft
Date Completed:	7/2/80	7/31/80
Completion Technique:	Open hole	Open hole
Wellhead Temperature:	(55°C) 131°F	(64°C) 148°F
Flow Rate:	(38 L/s) 600 gpm for 12 hr test	(51 L/s) 800 gpm estimated

Summary: The geothermal resource in Pagosa Springs has been used since the early 1900s. Nearly 30 wells have been drilled for heating and recreation purposes. These wells are drilled to depths of less than 500 ft (152 m) and produce waters ranging in temperature from 130-170°F (54 -77°C). The hydrothermal fluids are produced from a Dakota Sandstone aquifer.

SYSTEM FEATURES:

Application:	District heating
Heatload (Design):	27 x 10 ⁶ Btu/hr (7.9 MW)
Yearly Maximum Use:	28.6 x 10 ⁹ Btu/Yr (0.96 MW/yr)
Energy Replaced:	Natural gas-1.16 x 10 ⁶ m ² /yr (40.8 x 10 ⁶ ft ³)
Facility Description:	Ten public buildings, 54 businesses and 63 residences

Table 10. (continued)

Disposal Method:	The State of Colorado has agreed to allow discharge of the geothermal fluid to the San Juan River.
Summary:	The system will provide heating for users located along U.S. Highway 160. For the proposed closed distribution system, two independent loops have been designed. The initial system will utilize (57 L/s) 900 gpm but will be capable of expansion to (113 L/s) 1800 gpm.
STATUS:	The preliminary design has been completed and the production wells drilled. The system will be operational during the heating season of 1981-82.

5. UTAH ROSES CASE STUDY

5.1 Introduction

Utah Roses, Inc., is a 23,268 m² (6 acre) greenhouse facility that wholesales roses. The facility is located 22.6 km (14 mi) south of Salt Lake City, in the suburb of Sandy, Utah (Figure 31). With a population of 58,000, Sandy is rated as the fastest growing municipality in the metropolitan Salt Lake Region.⁴⁵ The greenhouse location is on the western edge of Sandy about 184 m (600 ft) from the Jordan River.

There are no surface manifestations of a thermal resource within about 10 km (6.2 mi) of the greenhouse. However, within a 3 km (1.9 mi) radius there exist three thermal wells. The closest well, 138 m (453 ft) distant, is 244 m (800 ft) deep and reportedly produced 24°C (75°F) fluid at the surface during a 1966 pump test.⁴⁶ A maximum downhole temperature of 34°C (93°F) at a pumping rate of 3788 L/m (1000 gpm) in 1979 was recorded on this well.⁴⁶

The high cost of heating the greenhouse using natural gas and oil prompted an effort to develop a hydrothermal resource. Utah Roses, Inc., with the assistance of an architectural and engineering firm and a resource development firm responded to a Department of Energy Project Opportunity Notice (PON ET-78-N-03-2047) and was selected for funding.

The geothermal energy from the well drilled on Utah Roses property will be used for floral industry process heat. The annual fuel consumption (natural gas) for process space heat will be cut from 70,000 million Btus to about 5000 million Btus, plus electrical power usage additions equivalent to \$24,000 (800,000 kWh) annually.⁴⁷

5.2 Background

5.2.1 Geology. The proposed geothermal site is within the Jordan Valley, a structural valley in the Basin and Range physiographic province. The valley occupies about 1036 km² (400 mi²) with Salt Lake City located in the north and east portion of the valley. Utah Roses is near the southern end of the valley.

The valley is topographically and structurally bounded on the east by the Wasatch Range, with

peaks higher than 3353 m (11,000 ft) above sea level and a local relief of about 1829 m (6000 ft). On the south, the valley is topographically and structurally bounded by the Traverse Mountains, whose relief is about 610 m (2000 ft). On the west are the Oquirrh Mountains with a relief of 1219 m (4000 ft). The northern boundary of the valley is the Great Salt Lake and a low east-west salient from the Wasatch Range. The valley floor is relatively flat and gently sloping toward the northwest.

The surface geology of the Jordan Valley consists principally of unconsolidated deposits laid down by streams, lakes, and winds in Quaternary time. There are also extensive outcrops of Pre-quaternary rocks located generally in areas where pediments formed at the base of the mountains (Figure 32). The history and sequence of deposition is complex with no single stratigraphic sequence applicable to the valley as a whole. The principal rock types in the valley fill consist of interbedded clay, salt, sand, gravel, tuff, and lava. The thickness of the fill material is on the order of 915 m (3000 ft) in the vicinity of the Utah Roses property.⁴⁶

The Wasatch Mountains to the east are characterized by folded sedimentary strata and intruded granite. Several steep-sided eastwest canyons open out into the valley proper. These canyons are the direct result of glaciation, faulting, and/or differential erosion depending on the individual canyon.⁴⁸ The Traverse Mountains to the south are folded and fractured Paleozoic limestone and quartzites, mantled in places by Tertiary volcanics and Quaternary sediments of varying origins.⁴⁹ The part of the Oquirrh Mountains that borders the Jordan Valley to the west is composed of Paleozoic rocks, principally of the Permian-Pennsylvanian Oquirrh Formation, but including Mississippian rocks, and sedimentary, intrusive, and extrusive rocks of Tertiary age.⁴⁸

The deposits and erosions of Lake Bonneville are among the most impressive aspects of the landscape of the area. Tremendous embankment deposits of gravel and sand are at the mouths of many canyons and at the Jordan Narrows. Sharp shorelines of Lake Bonneville are etched in bedrock and in pre-Lake Bonneville alluvial fans all around the valley.

Figure 31. General location map of Utah Roses, Sandy, Utah.

Qal Quaternary alluvium

Qag Quaternary colluvium and alluvium

Qb Quaternary-Bonneville related sediments

Qgm Quaternary glaciated ground and moraines-undifferentiated

TQu Tertiary-Quaternary deposits-undifferentiated

Tsi Tertiary-Salt Lake Group

Ti Tertiary intrusives

Tv Tertiary volcanics

PPO Permian and Pennsylvanian Oquirrh Formation

Pu Paleozoic sedimentary units-undifferentiated

PEu Precambrian sedimentary units-undifferentiated

Fault:

— Well exposed

- - - Inferred

..... Covered by alluvium

Thrust fault-barbs on upper plate of thrust sheet

Fault-inferred from geophysical evidence

Figure 32. Geology and generalized cross section of Utah Roses.

The Jordan Valley is a graben that lies at the intersection of three major tectonic features: (a) the Uinta Arch, (b) the Rocky Mountain Overthrust Belt, and (c) the Intermountain Seismic Zone.⁴⁹

The Uinta Arch, a broad anticlinal structure, is a westward continuation of the anticlinal structure of the Uinta Mountains. The axis of the fold in the Wasatch Mountains is exposed along the Wasatch Front just north of the mouth of Little Cottonwood Canyon.⁵⁰

West to east thrusting occurred during the Laramide orogeny and is represented in the Salt Lake area by three recognized thrust sheets. Interpretation of thrusting in the Salt Lake area places both the Traverse Ranges and the Oquirrh Mountains on a thrust plate, and explains the differences in geology between the Wasatch and Oquirrh Ranges.⁵⁰

The Intermountain Seismic Belt, a 100-km (62 mi) wide zone of relatively high seismicity, coincides locally with the Wasatch Front Fault zone. This zone parallels the eastern margin of the Basin and Range physiographic province. Seismic studies by Smith et al.,⁵¹ and Slear et al.⁵² suggest the zone is an active rift system with the tensional axis oriented in an east-west direction.

The Wasatch Fault Zone and associated faults are currently active. Movement along the fault zone resulted in more than 53 earthquakes above Richter magnitude 3 since 1850.⁵³ The latest movements on the Wasatch Fault is that of normal upthrusting, with the mountain block being uplifted. The total vertical displacement along the Wasatch Fault Zone is difficult to estimate because of the amount of sedimentation that has accumulated in the valleys and the covering of many of the fault lines. Normal high angle faults have been hypothesized to exist in the valley parallel to the front⁴⁸ and perpendicular to the front fault.⁴⁶

5.2.2 Hydrology. The principal source of surface water in the Southern Jordan Valley is the north-flowing Jordan River and six major creeks that drain the Wasatch Range. Most of these creeks drain from about 16 km (10 mi) back from the mountain front and flow westward through deep canyons. When the streams exit from the mountain range they flow westward across

deposits of coarse unconsolidated material at the edges of the valley, losing their flow by influent seepage.⁵⁴

The sediments that filled the Jordan Valley were deposited by several environments resulting in ground water aquifers that range widely from place to place in permeability and storage capacity. The discontinuous aquifers have been characterized into six categories based on geology, water-bearing properties of the deposits, and the quality of the ground water.⁴⁸

The ground water in the Jordan Valley occurs in three general divisions: a shallow unconfined aquifer, local perched water, and a deep artesian aquifer. All of the unconsolidated water-bearing materials of the valley are hypothesized to be connected hydraulically to some degree. The shallow unconfined aquifer, composed principally of clay, silt, and fine sand is usually less than 15 m (49 ft) thick. The transmissivity ranges from 120 m²/day to 372 m²/day (1289 ft²/day to 3992 ft²/day) with a storage coefficient ranging from 0.1 to 0.2. The confined aquifer, composed of clay, silt, sand, and gravels, ranges in thickness of greater than 300 m (984 ft). The transmissivity ranges from less than 93 m²/day (1000 ft²/day) to greater than 4600 m²/day (49,425 ft²/day) with a storage coefficient on the order of 0.5 to 0.0001.⁵⁴

Large thicknesses of well-sorted gravels interbedded with lake-bottom clays underlie the Sandy area. There are also numerous channel gravels of ancient perennial streams. The ground water moves generally northwest. Many wells exist, most less than 46 m (150 ft) in depth. The deeper wells are often artesian. Specific capacities range from 1 to 42 (L/s)/m (5-222 gpm/ft) of drawdown with an average of 9.4 (L/s)/m (45 gpm/ft) of drawdown.⁴⁸

The chemical quality of surface waters is dependent on their source and location within the valley. Water from the Wasatch front (i.e., Little and Big Cottonwood Creek) displays a total dissolved solids (TDS) level of ~150 mg/L at their mouth and a TDS level of ~500 mg/L at their confluence with the Jordan River. Water from the Jordan River reflects the chemical quality and thus the inflow, outflow, and evaporation in Utah Lake. In addition the water quality within the valley reflects the activities of man (irrigation and storage) more closely than natural conditions.⁵⁴

The water quality of the unconfined and confined aquifers varies areally and with depth. In general, the shallow unconfined system has a higher TDS than the deeper confined aquifer. The TDS levels in the confined aquifer range from 100 to 2000 mg/L.⁵⁴

5.2.3 Geothermal. The surface temperature of ground water as measured and reported in the Jordan Valley ranges from 70 to 59°C (46 to 139°F). The temperature of the water in most wells and springs, however, range from 11 to 15.6°C (52 to 60°F). The temperature of the ground water exceeds 15.6°C (60°F) in two principle areas of the valley. One of these areas extends from Point of the Mountain northward to the area around Sandy. The highest temperature recorded in this area is 59°C (139°F) at Crystal Hot Springs near the State Prison, with the ground water temperature apparently decreasing away from this spring. The other area of high temperature ground water occupies much of the northern part of the Jordan Valley. The eastern margin of this northern area is marked by several hot springs which rise along the Warm Springs Fault. The warmest temperature measured was 55°C (131°F) at Beck's Hot Springs.^{54,55}

There are nine thermal springs within the Utah Roses general area, mostly associated with the Wasatch Front. All of the springs appear to be associated with a fault zone. A trend of degrading water quality of the thermal springs appears to occur from south to north. Geochemical thermometers indicate 66 to 250°C (150 to 482°F) reservoir temperatures.⁴⁷

The thermal anomalies within the immediate Utah Roses are as follows:

1. A 360 m (1150 ft) deep city well (Sandy), 3 km (2 mi) south of Utah Roses, with a reported surface temperature of 32°C (90°F).
2. A county well, Salt Lake County conservancy well, 244 m (800 ft) deep, within 138 m (450 ft) of the Utah Roses property. The well reportedly produced 24°C (75°F) fluids during a 1966 pump test.⁴⁶ A maximum downhole temperature of 34°C (93°F) while pumping at 3788 L/m (1000 gpm) in 1977 was recorded.⁴⁶

Sodium/potassium/calcium geothermometry indicates 57°C (135°F). Silica geothermometry indicates 70°C (158°F).

3. A 23°C (73°F) city-owned (Midvale) well, 3 km (2 mi) to the north of Utah Roses.
4. Crystal Hot Springs, 9.7 km (6 mi) south, 58°C (136°F) surface temperature with geochemical indicators of 136°C (277°F) for the reservoir.¹⁴
5. The Utah State Forestry No.1, 9.7 km (6 mi) south, in April, 1978, delivered 75°C (167°F) water from a 79 m (260 ft) depth. Geothermometry indicate 157 to 177°C (315° to 350°F) reservoir temperatures.⁴⁹

5.3 Exploratory Programs

An aeromagnetic survey was run in the Southern Jordan Valley by Books of the USGS in 1954. The data were plotted on a map (unpublished) prepared by the American Smelting and Refining Company (ASARCO)⁵⁶ in July, 1954. The map shows the magnetic gradient of the valley floor. The contours show a relatively steep magnetic gradient trending eastward that passes just south of Sandy and the Utah Roses property. This suggests an eastwest-trending fault zone.⁴⁶

Numerous thermal studies^{55,57,46,49} have shown the fault-related presence of a thermal resource in the Jordan Valley. Thermal gradients were measured in the only available well: the Salt Lake conservancy well (Figure 33).

A gravity survey of the Traverse Mountains⁵⁸ did encompass the area of interest. However, no anomalies were suggested.

5.4 Production Drilling

Utah Roses, Inc., with their resource development firm, decided to drill a geothermal production well. Site selection was based on land ownership, known thermal wells in the vicinity and a suspected fault in the area. The well is located approximately 30 m (100 ft) from the east end of the greenhouse.

Drilling was accomplished with a rotary Wilson 75 drill rig. The drill pipe used was

Figure 33. Temperature gradient profiles of Utah Roses production well and a nearby county well.

11.4 cm (4.5 in.). The drill collars were 20.3 cm and 15.9 cm (8 in. and 6.3 in.). The well was drilled to 715 m (2345 ft) with gel [mud weight 1.08-1.13 kg/L (9.0-9.5 lb/gal)] and to total depth of 1526 m (5123 ft) with water. Drilling of the upper section was accomplished in 5 days at rates of 4 to 16 m per hour (13 to 52 ft/hr). Drilling of the lower section took 7 days at rates of 11 to 17 m per hour (36 to 56 ft/hr).⁵⁹

At a depth of 810 m (2657 ft) all three cones were lost from the tri-cone bit. A basket and magnet recovered the junk in less than 6 hours. The hole became unstable at a depth of 76 m

(250 ft) and surface pipe had to be cemented in. A minor lost circulation zone was encountered at 1335 m (4379 ft), but was handled with plug clay and mica.⁵⁹

The hole was completed with 51 cm (20 in) surface casing to a depth of 11.3 m (37 ft). A 34 cm (13.38 in.) H-40, 18 Kg (40 lb) threaded casing was cemented to a depth of 74 m (243 ft). A 21.9 cm (8.6 in.), K-55, 14.5 Kg (32 lb) threaded liner was inserted to a depth of 684 m (2244 ft). The well was drilled with a 44.5 cm (17.5 in.) bit, a 28 cm (11 in.) bit and a 20 cm (7.9 in.) bit to total depth (Figure 34).

(All depths referenced to Kelly Bushing)

INEL-A-18 622

Figure 34. Final well construction and lithology at Utah Roses production well.

The well was logged by a DOE experimental logging truck from Grand Junction, Colorado, for temperature, natural gamma, resistivity and SP, and neutron porosity. An analysis of the logs was made by the resource consulting firm.⁶⁰ A geologist record was made, but no interpretations have been reported. Drill cuttings were obtained every 9 m (30 ft) or changes in lithology. Chip logs interpretations were reported. The general geology, as specified in the drillers log, is sandstone (Figure 34).

After drilling the well was "stimulated" with air from the rig, a 2-1/2 hour "flow test" was run by letting the well flow artesian at rates from 0.32 to 0.57 L/s (5 to 9 gpm). The rig was demobilized. The surface discharge temperature was recorded at 41°C (106°F).

5.5 Aquifer Testing

Ten days after the rig was released, a temperature log was run. However, the temperature probe could not penetrate below the 866 m (2840 ft) depth. The well was apparently bridged at that point, and it was suspected that the flow was originating from the region just below the casing, 684 m (2244 ft), to the bridged region at 866 m (2840 ft). Temperature at 866 m (2840 ft) was 50°C (122°F). Temperature of the flow at the wellhead was 40.6°C (105°F).⁶¹

The well was pump-tested, using a turbine shaft powered by a diesel motor, rated at about 38 L/s (600 gpm) with a 107 m (350 ft) head. Bubbler tubing of 0.95 cm (0.4 in.) in diameter was strapped to the pump in 6 m (20 ft) threaded lengths. The 6-hour test was planned for a steady 9.5 L/s (150 gpm), but the well would not sustain that pumping rate and by the end of the test the flow was approximately 6.9 L/s (110 gpm). A rough analysis of these data indicated that a flow of 5.7 to 6.3 L/s (90 to 100 gpm) might be sustained throughout a normal heating season.⁶²

Because of the poor flow, a Cabot workover rig moved onto the site to remove the bridge. Using a power swivel, the bridge at 853 m (2800 ft) was cleaned out and the rest of the hole to 1526 m (5008 ft) was conditioned. A liner of 14 cm (5.5 in.), K55 6.4 Kg threaded casing was hung at the 634 m (2080 ft) level in the 20 cm (8-7/8 in.) production casing. This liner extended to 1184 m (3885 ft) and was not cemented. The casing

hanger was a Brown Oil Tool Hydroflo, with a weighted set packer. The workover rig verified that the remainder of the hole was still open.⁶³ The rig was discharged after 3 days.

The modified Utah Roses well was test pumped again in March 1980. The same turbine shaft pump and bubbler tube was set to a depth of 160 m (525 ft). The test started at a flow rate of 28.4 L/s (450 gpm), but the well drew down 152.4 m (500 ft) within 5 minutes. The pump rpm was then reduced to maintain a drawdown of about 140 m (460 ft). The well was pumped at a rate of about 11.4 L/s (180 gpm), with a reported 140 m (460 ft) drawdown for over 4 hours. The well was then allowed to recover for about 2 hours. Following the short recovery the well was pumped at a flow rate of 7.3 L/s (115 gpm), with a reported 88 m (290 ft) drawdown for another 4 hours. The maximum pump outlet temperature was 49°C (120°F).⁶³

The well was pump-tested again in April 1980 with the pump and tubing set to a depth of 229 m (750 ft). Flow was 17.7 L/s (280 gpm) with a drawdown of 210 m (690 ft). Maximum discharge temperature was reported 50.6°C (123°F). No duration of pumping was reported.⁶⁴

Air lifting was used to stimulate the well. Compressed air was injected into the well at a level of 610 m (2000 ft) unloading the well to that depth. The air lift was continued for approximately 8 hours. A borehole temperature log showed little change from previous logs. Also, the artesian flow of the well appeared unchanged after the air-lift procedure.⁶⁵ To correct the low specific capacity, the liner was shot perforated with 8.9 cm x 28 gr (3.5 in. x 432 grain) jet charges by Petro Log, Inc. The liner was perforated from 936-966 m (3070-3168 ft) (200 shots), 1103-1119 m (3618-3670 ft) (100 shots) and 1143-1158 m (3749-3798 ft) (100 shots).

The diesel-powered-turbine shaft pump and bubbler tubing was again set by Petersen Brothers to a depth of 229 m (750 ft). The flow was measured via an in-line orifice plate and differential pressure gauge 34.5 kPa/division (5 psi/division) and was backed up by a 208 L (55 gal) drum. Three pulse tests were run at rates of 5.2, 10.4, and 14.9 L/s (82, 165 and 236 gpm) for 150, 85, and 42 minutes, respectively. The pulse tests produced questionable data, as the well produced sand.

Upon clearing, a 12.6 L/s (200 gpm) test was run for 24-hours. Flow rate difficulties produced questionable data beyond 300 minutes. The well drew down ~76 m (250 ft) within the first minute and then declined at a slower rate. The well was allowed to recover for 400 minutes. Another test, at 9.5 L/s (150 gpm) was run for 1200 minutes. The well again drew down ~76 m (250 ft) within the first four minutes. Both tests have been plotted in Figures 35 and 36. The discharge temperature for both tests was ~51°C (124°F). A downhole temperature (Figure 33) suggests that most of the fluids must be coming from the uppermost perforations and possibly from behind the liner.

5.6 Current Project Status

Based on the pump test results and a maximum operation time of six months, a permanent pump setting of 335 m (1100 ft) is required to discharge 12.6 L/s (200 gpm). Disposal into the nearby Galena Canal has been granted and the thermal

fluids will provide a base load for the greenhouse (peak heating will be by existing fossil fuels). Plans are to be operational for the 1981-82 heating season. A summary is provided in Table 11.

5.7 Conclusions

The Utah Roses project illustrates problems that can be expected when small-scale projects are implemented with a limited budget in a highly developed area. The site selection was based on space heating requirements at an existing greenhouse structure. This limited site selection to an economical piping distance from the greenhouse. In addition, land ownership further restricted site selection to the developer's existing property. No surficial manifestation of a geothermal resource was evident on the Utah Roses property reducing the odds of a usable shallow depth resource. The geology, hydrology, and geophysical surveys were oriented toward a regional interpretation. No site-specific surveys to

Figure 35. Drawdown for 24-hour 9.5 L/s (150 gpm) and 24-hour 12.6 L/s (200 gpm) pump test of Utah Roses production well.

Figure 36. Recovery for 24-hour 9.5 L/s (150 gpm) and 24-hour 12.6 L/s (200 gpm) pump test of Utah Roses production well.

delineate lithology, structure, or hydrology were accomplished. One site was considered as good as any other, since exploration and drilling was restricted to the Utah Roses property. However, this approach should be questioned, since any geothermal system at this locale would be fracture controlled. A site-specific-resistivity survey and local-gradient drilling should have been the minimum accomplished. A target model was apparently not developed due to land ownership restrictions and the limited site-specific data. The probability of drilling one well to successfully find a resource was low.

The only difficulty involved in the drilling phase was the limited amount of well development

accomplished. Although the well was drilled with water in the production zone and air lifted, it was later "mudded-up" to insert the liner. Additional well development could have cleaned out the drill fluid and may have removed "fines" near the borehole creating a higher permeability. Although final construction was not optimal for a high production well, only previous test drilling knowledge could have corrected the situation.

The testing phase of development encountered several difficulties. The testing instrumentation was inadequate. It would have been better to use a continuous bubbler tube and pressure gauges that had 0.5 kg (1 lb) increments. Early-time pulse testing was meaningless, as the well was producing

Table 11. Summary of the Utah Roses case study

PROJECT TITLE:	Floral Greenhouse Industry Geothermal Energy Demonstration Project
PRINCIPAL INVESTIGATOR:	Ralph M. Wright, Chairman of the Board Utah Roses, Inc., Sandy, Utah (801) 295-2023
PROJECT OBJECTIVE:	Demonstrate to the public the potential offered by geothermal space heating in a highly populated area, by using geothermal heating in a commercial application.
LOCATION DESCRIPTION:	Sandy, Utah 21 km (13 mi) south of Salt Lake City
Population:	51,227
Area Activities:	Agriculture, light industry and commercial development
RESOURCE DATA:	
Well Depth:	1527 m (5009 ft)
Date Completed:	12/8/79
Completion Technique:	Slotted liner
Wellhead Temperature:	49°C (120°F)
Flow Rate:	17.6 L/s (280 gpm) with pumping
Summary:	Several wells in the area of Utah Roses have shows of warm water, including one within 91 m (300 ft) of the site, which has 34°C (93°F) water. The present well was drilled into loosely consolidated sandstone formations beneath the Utah Roses property.
SYSTEM FEATURES:	
Application:	Greenhouse space heating
Heatload (Design):	4.9×10^6 Btu/yr (1.44 MW) estimated
Yearly Maximum Use:	17.1×10^9 Btu/yr (0.57 MW/yr) estimated
Energy Replaced:	Fuel oil-150,000 L/yr (39,612 gal/yr) Natural gas- 3.3×10^5 m ³ /yr (11.5×10^6 ft ³ /yr)
Facility Description:	24,300 m ² (six acre) commercial greenhouse

Table 11. (continued)

SYSTEM FEATURES (continued):

Disposal Method: Surface discharge into adjacent canal is proposed.

Summary: The Utah Roses facility, in a rapidly growing suburb of Salt Lake City, used \$130,000 of fossil fuels during the winter of 1979-80. It is anticipated that the well will provide 25% of the heating for the greenhouse which produces cut roses for the national floral market.

STATUS: The startup date is presently planned for the heating season 1981-82.

a considerable amount of sand. All of the testing was too short for reliable extrapolation, due to time-dependent density problems and discharge rate problems. The quality of testing and the resultant test data should be scrutinized carefully

as part of the analysis. The pump setting was selected on the basis of extrapolating test flow data to a full heating season plus a 100 ft outgassing allowance and a 200 ft contingency reserve.

6. MONROE CASE STUDY

6.1 Introduction

Monroe is a small, predominantly agrarian central Utah community with a population of ~2,000. It is located about 250 km (155 mi) south of Salt Lake City in the Sevier River Valley (Figure 37). Two large tufa mounds from which springs discharge up to 24 L/s (380 gpm) of 70°C (158°F) warm water are located within 600 m (2000 ft) of the town's eastern boundary. The hot spring water since 1864 was piped into town for bathing and irrigation through wooden, wire-wrapped pipes.⁶⁶

The proximity of the resource and heavy demands on the town-owned electric utility prompted the development of energy from hydrothermal fluids. Monroe City, supported by an architectural/engineering and geotechnical firm, and the University of Utah, responded to a DOE Project Opportunity Notice (PON EG-77-N-03-1553) and was selected for funding.

The specific objective of this funding was to provide a city-wide district space heating and domestic water heating system. The district heating system was to be developed in phases. The plans were to include space heat and domestic water heating for the high school, an elementary school, a junior high, the LDS chapel, and 73 residences.

6.2 Background

6.2.1 Geology. Monroe and its neighboring areas are part of the High Plateau of Utah, a transition area between the Colorado Plateau and the Basin and Range provinces. The High Plateau is divided into the Sevier Valley and the Sevier Plateau (Figure 38). The Valley and the Plateau are essentially divided by the Sevier Fault. It is along this fault zone, in the area of Monroe, that the thermal springs are designated as a Known Geothermal Resource Area (KGRA).

The Monroe KGRA constitutes the eastern flank of the Central Sevier River Valley which is bound to the east by the steep, deeply dissected monocline of the Sevier Plateau and to the west by the Pavant Range. The Antelope Range, a series of low hills, crosses the valley about 10 km (6 mi) south of Monroe City.

Monroe and its vicinity constitute lands developed dominantly by slope-wash, stream deposits, mud flows, and alluvial fan materials deposited largely by floods of high energy but of short duration.⁶⁷ The thickness of the alluvium has been calculated by Mase et al.⁶⁸ at 1.5 km (4900 ft). The source of these alluvial deposits is apparently from the Late Tertiary Volcanics of the Bullion Canyon assemblage to the east (Figure 38). These volcanics consist of latite flows, tuffs, breccias, and volcanic conglomerate, intermingled with small inclusions of quartz.⁶⁹ Beneath the Bullion Canyon Volcanics lies the Arapien Shale, thought to be a confining layer, and the Nugget Sandstone, thought to be the source of the thermal fluids (Figure 38). Travertine or tuffa deposits occur in many places, the most prominent being the large mounds along the Sevier Fault on the east side of Monroe.

The rock alterations within the KGRA consist of yellow, earthy patches that stand out against the light purple to light gray volcanic host rock. The alteration of the rock in the southwest corner of the area is clearly visible from the town of Monroe. These patches are generally distributed in distinct linear patterns and for the most part trend northeast, following the major range front faults.⁶⁹

The Bullion Canyon Volcanics have been separated into three units each marked by an unconformity. Test hole lithologies indicate a sequence of sinter deposits in the shallow subsurface underlain by altered Quaternary alluvium, consisting primarily of quartz latite fragments derived from the volcanic range to the east and more consolidated volcanic bedrock at the base.⁷⁰

The Sevier Valley occupies a synclinal trough modified by a graben structure: the Sevier Fault to the east and the Elsinore Fault to the west⁷¹ (Figure 38). This region is typified by high angle normal faulting. Miller⁶⁹ divides the faulting and fracturing affecting the Monroe area into three main sets: northwest-northeast-, and north-trending. The northwest and northeast sets display considerable vertical displacement. Hydrothermal alteration is controlled by north-trending fractures and dikes in the northern resource area and by the northeast-trending features in the southern portion.⁷² The Sevier Fault Zone, the local major

Figure 37. General location map of Monroe, Utah.

From Kilty et al., 1978

INEL-B-18 710

Figure 38. General geologic map and cross section of the Monroe-Red Hill geothermal resource area, Utah.

structure, is mostly buried beneath alluvium, landslide debris, and travertine deposits.

The assumed fault strike is N 10° W, and the dip of the Sevier Fault Zone has been computed to be W 67° ± 3°. This dip is shallower than that deduced from the geophysics and may indicate step faulting.⁷³ The vertical displacement is reported to be ~1800 m (5900 ft) in the Monroe area.⁷¹

The Sevier Fault area is considered to be relatively active seismically. There have been some recorded adjustments along the fault zone in recent years. Five seismic events of some significance have been recorded since 1921, ranging in intensity from VIII to IX (Modified Mercalli-Scale). Although those earth movements were noted, the epicenters were not necessarily located on the Sevier Fault. Geologically, the most recent movements have occurred along the Dry Wash Fault⁷⁴ (see Figure 38).

6.2.2 Hydrology. The surface waters in the Monroe area all contribute to the Sevier River. The Sevier River drainage comprises approximately 2 million hectares (5 million acres) of mountainous land in southern and central Utah. The Sevier drainage is hydrologically closed. Locally, all surface waters drain into Monroe Creek, a perennial stream. Monroe Creek produces power at the Monroe City Power Station, provides culinary water to city residents, and also provides a limited amount of irrigation water. The general hydrology of the area is given in USGS Water Supply Paper 1787.⁷¹ Unconsolidated coarse sands and gravels of the valley fill are the source for most of the ground water for wells and springs. The recharge of sedimentary aquifers occurs in the mountainous areas which receive an average 75 cm (30 in.) of water or more per year as precipitation. The aquifers are recharged directly from surface precipitation wherever they outcrop; otherwise, their recharge depends on available fractures and faults in the overlying volcanic rocks.⁷⁵ The aquifers are also recharged by the Sevier River, its tributaries, and irrigation canals and ditches.

Mundorff⁵⁵ described the geochemistry of both the cold water aquifer and the hot springs of the area. The concentration of dissolved solids of the Monroe Hot Springs discharge was measured at

2,780 mg/L with the major constituents being: Silica 54 mg/L, Calcium 282 mg/L, Sodium 562 mg/L, Bicarbonate 354 mg/L, Sulphate 898 mg/L, and Chloride 630 mg/L. The local ground water has a concentration of 500 mg/L of total dissolved solids.

6.2.3 Geothermal. Surficial evidence of the geothermal system includes three significant warm springs, intermittent warm water seeps, and travertine deposits. The springs are located within two large travertine hills, the Monroe and Red Hill mounds, east of Monroe. The springs issue from the Sevier Fault at temperatures ranging from 61-76°C (142-169°F).⁷⁶ Approximately 3 km (1.9 mi) south of Monroe, the Johnson Hot Springs also issue from the Sevier Fault.

The Monroe-Red Hill Hot Springs occur at changes in the strike of the Sevier Fault. These areas may be the only places of sufficient permeability through which hot water may rise to the surface. The springs discharge from the Monroe Mound at two major points. The largest spring issues 64°C (147°F) water at 3.2 L/s (47 gpm) from the center of a tuffa mound. Additional water at 41°C (106°F) discharge from an orifice at the base.⁵⁵ The total discharge including that of several small springs amounted to 9.5-12.6 L/s (140-186 gpm).⁵⁵ Only one spring issues from the north-central part of the Red Hill mound at 75°C (167°F) with a discharge rate of 9.5 L/s (140 gpm).⁵⁵ Ground water temperatures at intermittent seeps along the Sevier Fault are often warm; a temperature of 35°C (95°F) was recorded at the mouth of Sands Canyon.⁶⁹ Miller analyzed the Monroe and Red Hill Hot Spring waters. Using these data and the Na-K-Ca geothermometer calculations of Fournier and Truesdell,⁷⁷ W. T. Parry calculated the geothermal reservoir temperatures as 197 and 193°C (387 and 379°F), respectively. Measured temperatures of the springs were 65 and 76°C (149 and 169°F), respectively.⁷⁸ Recent geothermometry interpretations listed in "Assessment of Geothermal Resources of the United States—1978," suggests that the Monroe-Red Hill Hot Springs maximum source temperature is between 79°C (174°F) (chalcedony geothermometry) and 114°C (237°F) (Na-K-Ca, Mg—corrected geothermometry) with the most likely reservoir temperature of 109°C (228°F) (quartz conductive geothermometry).

6.3 Exploratory Programs

Rock alteration studies have been completed by Miller.⁶⁹ The most striking feature of the alteration within the KGRA is yellow, earthy patches that stand out against the light purple to light gray Bullion Canyon Volcanic host rock. These patches are generally distributed in distinct linear patterns and for the most part trend northeast, following the major range front faults.

Magnetic data for the Monroe Area are available on the aero-magnetic map of the State of Utah.⁷⁹ The University of Utah conducted a more detailed ground magnetic survey of the Hot Springs area which has not been extensively interpreted. Both Mase et al.⁶⁸ and Halliday and Cook⁸⁰ recognized strong magnetic gradients parallel to the Sevier Fault zone. A magnetic high is associated with the Sevier Valley alluvium and a low is associated with the Bullion Canyon Volcanics.

The regional gravity data taken prior to development of the resource is of a reconnaissance nature.^{81,82,83} Additional work has been completed by Halliday and Cook. A gravity low exists in the center of the Sevier Valley. Additional gravity data suggest the possibility of an intrusive body in the Northern Sevier Plateau. The data do not fit a model of a steeply dipping contact along the Sevier Fault. Mase et al.⁶⁸ suggested an en echelon fault system with $70^\circ +$ fault planes. In addition, Mase et al.⁶⁸ interpreted the lower density material near the fault as hydrochemically altered or fractured volcanics.

A dipole-dipole resistivity survey was conducted by the University of Utah.⁶⁸ The results of the survey outlined a resistivity zone ($< 30 \Omega \cdot m$) which represents the trace of the Sevier Fault and contains all surface geothermal manifestations. Within this zone is an area of low resistivity ($< 10 \Omega \cdot m$) which represents the near surface extent of the hotter portions of the convective hydrothermal system, and which follows the trend of hydrothermal springs in the Monroe-Red Hill area. A northwest trend of low resistive values, away from the Monroe-Red Hill Springs, has been assumed to be evidence of brine leaking northwestward from the convective hydrothermal system along the trend. Upward leakage was apparent by two plumes coincidental with the

Monroe and Red Hill Springs. The data suggest that the dip of the Sevier Fault must be $W 70^\circ +$.

Eleven thermal gradient holes (Figure 39) were drilled by the University of Utah (M-1—M-6 and RH-1—RH-5) to a maximum depth of 100 m (325 ft).^{68,75} Six of these holes were drilled in the vicinity of the Monroe Mound and five in the vicinity of the Red Hill. Temperature profiles (Figure 40) across the Monroe geothermal field reveal the extent and characteristics of the temperature field and indicate a maximum bottom-hole temperature of $63^\circ C$ ($145^\circ F$) recorded in gradient hole M-3. The lithologic logs from the thermal gradient holes identify the fault location as somewhere between gradient holes M-3 and M-4 and RH-1 and RH-4. A high-angle fault plane would be consistent with the data. Temperatures observed in the test holes and the thermal gradient holes indicate a strong convective system rigorously confined along a fault zone. Thermal data suggests leakage of the thermal fluids into the alluvium to the west. Temperatures at 300 m (984 ft) were extrapolated to be approximately $120^\circ C$ ($248^\circ F$).

6.3.1 Test Drilling. Two test holes (Figure 39) were drilled prior to finalizing the production well location and well design (MC-1 and MC-2). Intersection of consolidated volcanics in the drill holes were deduced from the drill logs (drilling rate, caliper, natural gamma) and lithologies. The dip of the Sevier Fault Zone determined from encountering more consolidated volcanic bedrock at depths of 95 m (312 ft) in MC-1 and 186 m (610 ft) in MC-2 was $W 67^\circ \pm 3^\circ$. This value was calculated from the relative location of the wells and assumes a fault strike of $N 10^\circ W \pm 10^\circ$. The computed dip of 67° is slightly shallower than the dip deduced from geophysical modeling and may indicate en echelon faulting.⁸⁴

Temperatures observed in MC-1 and MC-2 after drilling indicated the central part of the Monroe system is near isothermal at $74^\circ C$ ($165^\circ F$) between depths of 50 and 250 m (165 and 820 ft).

Both MC-1 and MC-2 flowed artesian. Initial artesian flow of approximately 13 L/s (206 gpm) from MC-2 is attributed to production from a fracture within the volcanic bedrock. This fracture has been suggested previously by the caliper and natural gamma logs.

Figure 39. Detailed location map of the Monroe-Red Hill production well, test wells, and thermal gradient holes.

Figure 40. Temperature profiles of the production well, test wells, and thermal gradient holes at Monroe, Utah.

A monthly hot spring monitoring program was initiated in September, 1978. The program includes measuring of hot spring discharges and temperatures, and water sampling and analyzing of major element constituents. A small increase in total discharge and corresponding slight decrease in temperature is evident during the spring and early summer. This probably is due to an increase in the shallow, cold ground water component of the discharge. Harrison⁷⁰ concluded that the hot water component remains approximately constant throughout the year.

Seismically, this area is probably the second-most active area in Utah during historic time. Five large earthquakes (1901, $I_0 = IX$; 1921, $I_0 = VIII$, VII, VIII; 1967, $I_0 = VII$) occurred in the Elsinor-Monroe-Marysville area (modified Mercalli Scale).⁸⁵

6.4 Production Drilling

Penetrating fractures and inducing production from depth was the principal goal of the production drilling.⁷⁰ Flow rates up to 38 L/s (600 gpm) were required to service the planned district heating; therefore, a large diameter surface casing was planned to accommodate the appropriate flow/pump requirements. The well was designed and located on the basis of the geometry inferred from the test hole drilling and was intended to intersect the volcanic bedrock at 275-335 m (900-1100 ft). Production from 335 m (1100 ft) and below offered the advantage of minimizing any influence of colder hydrologic conditions.

The well was drilled on a footage-rate using a 1500 Midway rotary drilling rig. The rig was equipped with a 13 cm x 20 cm (5 x 8 in.) Gardner-Denver pump. Additional pumping capacity was provided by a rented 12.7 cm x 25.4 cm (5 in. x 10 in.) Gardner-Denver mud pump. The combined pumping capacity was approximately 28.4 L/s (450 gpm) at 600 psi. Drilling of a 25 cm (10 in.) hole, using a moderate weight mud and collecting cuttings every 3 m (10 ft) proceeded as planned until a "hard" formation was intersected at approximately 210 m (689 ft). Because of "hard drilling" the work was changed to a day-rate basis. The cuttings from this zone consisted primarily of 80% calcium and 20% quartz, possibly a lacustrine formation resulting from ancient ponding against the fault.⁸⁴ Fear of hole failure, as experienced in

exploration well MC-2 (although of different depth and lithology), by the driller and the geotechnical consultant prompted the use of a heavier mud to total depth (TD) [~ 1.2 kg/l (~ 10 lb/gal)]. Hard drilling persisted to 400 m (1312 ft), although a number of clay stringers were encountered (interpreted by drill rate of 0.5-3 m/hr (1.5-10 ft/hr). It was questionable whether clay could be identified when ~ 1.2 kg/L (~ 10 lb/gal) mud was used.

The bit was expected to wear out at a depth of approximately 372 m (1220 ft). However, drilling continued since there was a possibility that the targeted depth of 396 m (1300 ft) could eventually be the total depth for the well. In addition, the bit manufacturer had reported that this type of sealed bit generally exhibited long-bearing life. However, due to bearing failure, all three cones were lost from the bit at the 400 m (1312 ft) depth.

Since the drilling between 209 m and 400 m (685 ft and 1312 ft) had been "hard," and in view of the high cost of 38 cm and 51 cm (15 in. and 20 in.) button reamers, it was decided to set the 41 cm (16 in.) casing at 213 m (700 ft) instead of 305 m (1000 ft) as originally planned. In addition, it was concluded that the softer zones could be potential water-bearing zones which could enhance production. Reaming to 51 cm (20 in.) and running and cementing the 41 cm (16 in.) casing to 213 m (700 ft) went smoothly. Geophysical logs could not be run prior to running casing due to the high viscosity of the drill mud.

The well was cleaned by circulating mud for approximately seven hours at 400 m (1312 ft) and logging was attempted. Again, the heavy viscosity of the mud did not allow geophysical tools to descend the borehole. The well was circulated with "lighter" mud. Artesian flow was steady at about 5.4 L/s (86 gpm) with a shut-in wellhead pressure of 159 KPa (23 psig). The artesian flow was disappointing considering the over 183 m (600 ft) of open hole below the casing (mud still in the hole). Injecting one borehole volume of cold water at the wellhead was attempted in an effort to stimulate greater artesian production by cleaning the well, and to identify high permeability zones. A temperature survey conducted immediately after pumping indicated that most of the cold water entered the formation just below the casing.

In view of the disappointing artesian flow and the fact that a number of clay zones had been

identified while drilling the 209-400 m (686-1312 ft) interval, the decision was made to continue drilling with a 20 cm (8 in.) bit, using water, to 457 m (1500 ft) in the hope of finding a good producing fracture in the volcanics. The alternative would have been to let the rig stand by while well testing was performed and to increase the rig time by 10 to 14 days. In addition, there was concern over the potential for the borehole collapsing when the well was pumped.

Before drilling could resume, the cones had to be recovered by making four trips with a finger basket and two trips with a magnet. The bottom 57 m (187 ft) was drilled with water, as the mud consumption at 427 m (1400 ft) was excessive. The artesian flow improved from 8.2 L/s to 11 L/s (132 gpm to 174 gpm) at the conclusion of drilling.

The lithology between 209 m and 400 m (686 ft and 1312 ft) was not completely understood and the desire to avoid borehole collapse or sedimentation in the well prompted the installation of 213 m (700 ft) of 20 cm (8 in.) liner. The bottom 107 m (350 ft) were slotted. A final construction diagram is shown in Figure 41. Mud pump suction hose tests and short artesian flow tests (4 min/rate step), before and after the liner was run, indicated little loss in delivery. It should be noted that flow rate was determined by flowing pipe pressure and a v-notch plywood weir in a ditch.

Geophysical logging was performed by the geotechnical consultant and by the Idaho National Engineering Laboratory. Logging consisted of single point resistivity/SP, caliper, temperature, and natural gamma suites. Mud logging was done by the University of Utah.

The drilling program lasted 58 days, exceeding the 30-day period originally planned. This was due in part to the change in hole specifications. However, it was evident throughout the drilling program that the rig was somewhat small for the job. Breaking out and assembling drill string was time consuming due to difficulties in handling the heavy pipework (especially the bottom hole assembly and drill collars). The drillers were not equipped with power tongs. These would have facilitated faster breaking of pipe joints when tripping out. In addition, the rented supplemental mud pump proved unreliable and was not used for

most of the program. The additional capacity would have resulted in more effective cleaning of the hole and quicker penetration.

6.5 Aquifer Testing

An artesian flow test was conducted first.⁷⁰ The well was allowed to flow at 6.3 L/s (100 gpm) for 500 minutes. Continual adjustment of the control valve was necessary to maintain a constant rate. No temperature was recorded. Flow rate was measured with an annubar, and wellhead pressure was measured with a mercury manometer. Analysis of the data was not successful due to poor data quality.

A 25 Hp turbine shaft electric pump was set to ~61 m (200 ft). A series of pulse tests ranging from 30 to 40 minutes were run. The well was allowed to recover for 45 minutes between each pulse. A bubbler tube was installed to 48 m (157 ft) to measure drawdown. No temperature data were recorded. Problems with the power generator during testing caused discharge rate fluctuations. No quantitative analysis of the data was possible.

A 70-hour test at 20.5 L/s (325 gpm) was run using the same pump setting, discharge, and instrumentation equipment. Drawdown and recovery data from the 70-hour pump test for the production well and monitor wells are shown in Figure 42. The temperature of the discharge fluid rose to 73°C (163°F) within five minutes of initiation of pumping and remained between 73 and 74°C (163 and 165°F) throughout the test. All available wells and springs were monitored (Figure 39). All the springs on the Monroe Mound were affected by the pump test. There was no apparent influence on the monitor wells or hot spring at Red Hill. Computed storage coefficients suggested that confinement increased with depth. Theis (1935) type curve analysis of the data gave transmissivities of 2.5 and 1.7 m²/hr for MC-1 and MC-2, respectively.⁷⁰

The rapid initial drawdown (Figure 42) in the production well was interpreted as caused in part by formation damage near the wellbore. The leveling off in drawdown after approximately 12 minutes suggested the presence of a high permeability or recharge zone, perhaps a water-carrying fracture, between 12 and 20 m (40 to 65 ft) from the wellbore. The difference in

Figure 41. Final construction diagram and lithology of production well MC-3 at Monroe, Utah.

Figure 42. Drawdown and recovery for 70-hour 20.5 L/s (325 gpm) test of Monroe MC-3.

drawdown and recovery at various rates, and the change in slope, were interpreted as boundaries.

In an attempt to stimulate the well, compressed air was pumped into the well for 2-3 minutes. When wellhead pressure reached ~65 psi the well was opened. This was repeated until no flow improvement could be seen. An improvement in specific yield was apparent. The artesian flow rate improved from 10 to 16 L/s (150 to 253 gpm).

A short (~2 hour) pump test was conducted after the well had been treated with compressed air. The well was initially pumped at ± 25 L/s (396 gpm) but declined to ± 23 L/s (364 gpm) during the test. No temperature was recorded.

Maximum temperatures of only 75°C (167°F) had been realized at the wellhead during the previous pump testing. This was below the 82°C (180°F) measured in the bottom of the hole. It was concluded that swabbing the lower portion of the well would increase productivity from the lower horizons. Artesian flow rates improved to 18 L/s (285 gpm) after the swabbing treatment; however, there was no increase in delivery temperature.

A 150 Hp electric turbine shaft pump was installed at 152 m (499 ft). Pulse testing at ~40 minutes/pulse at rates of 39, 48, and 56 L/s (618, 760, and 887 gpm) was conducted initially to define an optimum pumping rate for the expected 30-hour test. Drawdown and recovery data for the 30-hour pump test, during which the well was pumped at 39 L/s (618 gpm) $\pm 6\frac{1}{2}\%$, were plotted in Figure 43. The first recording of temperature was 2-1/2 hours after the start of the test.

The apparent transmissivities and storage coefficients obtained from the drawdown and recovery data for the monitor wells were consistent with those from the previous pump tests. The apparent nearby recharge zone, which was evident in the previous 70-hour test was not indicated in this test.

The interpretation of the testing is as follows:

1. Natural flow from behind the slotted liner [287 to 400 m (941 to 1312 ft)] and the open hole section [400 to 457 m (1312 to 1500 ft)] resulted in a 16.4 L/s (260 gpm) artesian flow rate. This rate compares with

the 12 L/s (190 gpm) at 48 to 70°C (118 to 158°F) natural seepage at the Monroe Mound.

2. The resource temperature is less than marginal for district heating purposes because the district is too disperse. The system is essentially isothermal at 74°C (165°F) between 152 and 457 m (499 and 1500 ft). Significantly higher temperatures could only be expected below the point where cold water influx may occur. A portion of the district could use this resource.
3. Pumping of the production well at moderate flow rates had a pronounced effect on monitor wells and springs in the vicinity. Production over a period of time would reduce flow from the Red Hill Hot Springs and dry up the Monroe Hot Springs.
4. Drawdowns of greater than 122 m (400 ft) could occur during periods of peak pumping. Drawdowns in the surrounding monitor wells could exceed 61 m (200 ft) during these periods. The large cone of depression may induce near-surface cold water into the thermal aquifer after a prolonged period of pumping.
5. The effects of long-term pumping on the production well are unclear. The thermal anomaly exhibits clear boundaries at the surface. However, no aquifer boundaries were evident in the drawdown data collected during the pump tests.
6. It appears from the information assembled to date that the Monroe geothermal resource has a limited capacity and could not be expected to service a large development.

6.6 Current Project Status

The proposed district geothermal heating system at Monroe, Utah is not economical at present due to: (a) wellhead temperatures [74°C (165°F)] which are lower than predicted based on original resource assessment; (b) the cost of pumping as a result of the low artesian flow rate;

Figure 43. Drawdown and recovery for 30-hour, 39 L/s (618 gpm) test of Monroe MC-3.

(c) the large area/low density population distribution in Monroe; and (d) the cost of piping to a reinjection site. Alternate applications for the resource are being investigated by Monroe. A summary sheet of the project is seen in Table 12.

6.7 Conclusions

The selection of a drill site was restricted to a location within an economical piping distance from the town. Although the geology and hydrology surveys produced a reasonably correct target model, one misinterpretation was evident. This was the extrapolation of the 40-80 m (131-262 ft) thermal gradient data to a depth necessary for the end-use temperature requirements making no allowance for a well being isothermal within the thermal reservoir. The first hint of this should have been the 100 and 180 m (328 and 591 ft) test wells, which show this phenomenon. This response should be expected in shallow hydrothermal reservoirs which are fault-controlled.

The drilling phase had difficulties of either inadequate drilling equipment and/or insufficient capabilities on the part of the driller and drilling consultant. The results were additional costs and a delay in completion. Heavy weight mud should not have been used to reduce artesian flow and stabilize the wellbore. The 4.5 kg (10 lb) mud used should have created about 9070 kg [20,000 lb or 786 kPa (114 psi)] of pressure greater than a borehole of water on the formation at 400 m (1312 ft). This would probably be well above hydrostatic pressure in the reservoir, opening

microfractures and forcing drill mud deep into the formation. In addition, the concern of hole collapse, based on difficulties in the 180 m (591 ft) test well, caused the well to be constructed with a slotted liner in a section of limestone and volcanic latite that may have been sufficiently competent to remain open. A definitive answer could have been obtained by circulating out the heavy mud in the 287-400 m (942-1312 ft) of the borehole and determining the necessity of a liner. If the hole had partially collapsed, it could have been cleaned or redrilled at nominal cost. Lastly, the only well development accomplished was the use of compressed air at the wellhead. This was considered a remedial action, rather than a preplanned operation. It would have involved nominally greater cost to improve the well by surging or swabbing the well until sand free, then air-lifting from depth and finally rawhiding with a high-capacity pump. This would have removed more of the drill fluid which had infiltrated the intergranular permeable formation and possibly created a proper natural pack around the slotted zone.

The testing phase also encountered difficulties. The early testing has poor discharge rate control and inadequate thermal measurements. A step test was run, but no temperature was recorded at each discharge rate. Thus, the steps could not be related. In addition, the durations of each step and of the long-term test were too short for reliable extrapolation in a dual porosity reservoir. Finally, during the long-term testing only limited thermal data was recorded resulting in interpretations of time-dependent borehole density problems and thermal boundaries as reservoir boundaries.

Table 12. Summary of the Monroe case study

PROJECT TITLE:	Direct Utilization of Geothermal Resources--Field Experiments at Monroe, Utah
PRINCIPAL INVESTIGATOR:	Mr. Duane Nay, Mayor Monroe, Utah (801) 527-3511
PROJECT OBJECTIVE:	Use geothermal fluids from well near local hot springs to heat high school, city hall, and fire stations; install nucleus of district heating system for private and commercial use
LOCATION DESCRIPTION:	Monroe, Utah 260 km (160 mi) south of Salt Lake City, Utah
Population:	2000
Area Activities:	Agriculture
RESOURCE DATA:	
Well Depth:	457 m (1500 ft)
Date Complete:	4/10/79
Completion Technique:	Slotted liner
Wellhead Temperature:	74°C (165°F)
Flow Rate:	32.9 L/s (600 gpm) with pumping
Summary:	The Sevier Fault is located approximately 610 m (2000 ft) east of the eastern boundary of Monroe. The Monroe KGRA is situated along this fault and is characterized by two large tufa mounds. The Monroe and Red Hill Springs collectively discharge approximately 24 L/s (380 gpm) of 65-76°C (149-169°F) water
SYSTEM FEATURES:	
Application:	A district heating system was originally proposed. Alternate uses are being sought.
Heatload Design:	9.6×10^6 Btu/hr (2.8 MW) maximum proposed in preliminary design of system
Yearly Maximum Use:	6.6×10^9 Btu/yr (0.22 MW/yr) based on "near term" loads from preliminary design

Table 12. (continued)

SYSTEM FEATURES (continued):

Energy Replaced: Approximately 272 155 kg (300 tons) per year of coal; approximately 126,400 L (33400 gal) of fuel oil and 689000 kW/hr of electricity

Facility Description: The original system included three schools, a church, and 73 residences.

Disposal Method: The Utah Water Pollution Committee approved plans for a 107 m (350 ft) injection well.

Summary: The system's design and cost analysis indicate that due to the lower-than-expected resource temperature, high pumping and maintenance costs, and the large area/low population density the district heating system is uneconomical.

STATUS: The project is currently being reassessed. Alternate applications for the resource are being sought by Monroe.

7. SUSANVILLE CASE STUDY

7.1 Introduction

Susanville is located in Lassen County in north-central California. The city has undertaken a project to heat 14 public buildings with geothermal fluids. Hydrothermal fluids were discovered about 50 years ago when managers of a lumber mill began drilling for water to cool the mill equipment. Some of the wells drilled were subsequently abandoned because the water was hot. Eventually, the thermal water was used to fill the mill pond, keeping it ice free in the winter and extending the mill operating season.

The city plans to develop one or two production wells to provide 31.5 L/s (~ 500 gpm) of 82°C (180°F) geothermal brine.

7.2 Background

7.2.1 Geology. The city of Susanville is located at the intersection of three major physiographic provinces: the Modoc Plateau, the Sierra Nevada, and the Basin and Range (see Figure 44). Plio-Pleistocene volcanic rocks form a dissected plateau north and west of the city. These volcanics have been identified as members of the Warner Basalt, a collective unit of petrographically and structurally similar lavas found throughout the Modoc Plateau.⁸⁶ South of Susanville lie the Jurassic-Cretaceous quartz monzonite and quartz diorite of the Sierran batholith. Extending east and southeast from Susanville is the graben-like structure of Honey Lake Valley, filled in part by Pleistocene sediments of extinct Lake Lahontan.

The Susanville geothermal exploratory wells penetrate Holocene alluvium and Pleistocene Lake Lahontan sediments, interbedded with Plio-Pleistocene basalts and andesites. These same lithologic units are penetrated by water wells in the Susanville-Johnsonville area and provide good yields of ground water. The respective amounts of water produced from either the basalt or the sediments are not well understood.⁸⁷ Meteoric water permeates through fractures and joints in the basalt and along vesicular and scoriaceous zones at the top and bottom of the basalt units. The Lake Lahontan sediments thicken to the east of Susanville. To the south, they interfinger with

coarser, near-shore Lahontan deposits. These near-shore deposits outcrop along the base of Diamond Ridge.

7.2.2 Hydrology. Hydrologically, the near-surface Lahontan deposits have a dual role. They are usually highly permeable and provide a path for ground water recharge of interfingering Lahontan sediments and, in some cases, recharge to underlying basalt units. In saturated zones, such as along the base of Diamond Ridge, near-shore deposits are important shallow ground water aquifers.

7.2.3 Geothermal. There are no surface manifestations of the geothermal anomaly at Susanville, California. The nearest hot springs occur approximately 40 km (25 mi) east of Susanville in the Wendel and Amedee areas, near Honey Lake. The first awareness of the thermal anomaly in Susanville resulted from the drilling of several warm water wells in the 1920s.

7.3 Exploratory Programs

7.3.1 Exploratory Wells. Twenty-four temperature gradient holes and warm wells have been drilled in Susanville to date.⁸⁸ Five temperature gradient holes, with a target depth of 40 m (131 ft), were drilled for preliminary resource identification. Subsequently, 12 exploratory bores, with depths of 135 m (443 ft) to 640 m (2,000 ft), were drilled in an attempt to outline the areal extent of the geothermal anomaly. Lithologic and geophysical logs were obtained for each of these wells. Well locations are shown in Figure 45.

Standard heat-flow completions were used for most of the exploratory bores. To accomplish this, a 6.5-in. hole was drilled to total depth (TD). A 2-in. pipe (PVC or steel) was emplaced in the hole, capped at the bottom, and filled with water. The remaining bores were completed for possible use as observation wells in future reservoir tests. These were also drilled 6.5-in. in diameter, and a 2-in. pipe with a screen and wellpoint was installed at the bottom of each one. The holes were gravel-packed several hundred feet above the bottom, and then cemented to the top. One of the holes, Suzy 6, was completed with a 6-in. blank casing to 32 m (105 ft). A 6-in. diameter slotted liner with

Figure 44: Location map of Susanville geothermal anomaly.

Figure 45. Location map of wells drilled to date in Susanville.

gravel-pack to TD was inserted so that the well could be used as a production, injection, or observation well during aquifer testing. Table 13 outlines detailed information of the well completions, locations, depths, elevations, and static water levels.

During the drilling of each bore, a geologic well log was compiled by recording descriptions of cutting and drilling operations as described by a well-site geologist. After drilling was completed, geophysical well logs were run to investigate the petrophysical nature of the lithologic units penetrated by the wells. The standard suite recorded in most of these holes was as

follows: SP, caliper, resistivity, neutron, gamma-gamma ray, natural gamma ray, and temperature (SP, caliper, and resistivity were not run in the cased holes). Temperature surveys have been run periodically in each hole since completion.

Six wells had been drilled prior to this investigation: the Naef well, the Davis well, the Church of Jesus Christ of the Latter Day Saints well (LDS Church well), the Roosevelt swimming pool well, the Lassen Lumber and Box No. 2 well, and the Wirth well. Some of these wells have been used intermittently since the 1920s for space heating. The swimming pool well heats the Roosevelt swimming pool. Because these wells were drilled

long ago, little detailed information on total depth and well completion is available. The available information is summarized in Table 13.

7.3.2 Interpretation of Subsurface Logs. Two basalt beds were identified as marker units on the natural gamma ray and geologic logs. Correlations between wells drilled in these two units inferred the structural relationships of the lithologic units penetrated. One of the basalt beds is typically penetrated within the first 30 m (98 ft) of drilling. The second bed is encountered between 90 m (295 ft) and 150 m (492 ft). The basalt beds are absent or ill-defined on the Suzy 3 log; the upper basalt unit is not evident and there is a poorly-defined basalt bed between 42 m (138 ft) and 70 m (230 ft). In Suzy 9, 9A, and 11, the upper basalt bed is present but the lower bed is andesite rather than basalt.

On the basis of the subsurface log correlations, the Susanville geothermal prospect has been divided into five structural units (Figure 46). Cross sections have been constructed to illustrate the structural relationships between the various units (Figures 47 and 48). Except as noted in the text, the Susanville wells typically penetrate 3 to 5 m (10-16 ft) of Holocene alluvial deposits, 6 to 21 m (20-69 ft) of basalt, 91 to 121 m (299-397 ft) of interbedded Lake Lahontan sediments and Pleistocene basalt lenses, and 30+ m of Plio-Pleistocene basalt.

To the west, Suzy 3 in Block 1 penetrates 40 m (131 ft) of clays, sand, and gravels interbedded within basalt lenses, 30 m of basalt with minor clay, and 550 m (1804 ft) of sand and clay with minor gravel beds. Block 2, east of Block 1, is penetrated by wells Naef and Suzy 4 and is downfaulted by approximately 42 m (138 ft), assuming that the 27 m (89 ft) thick basalt unit in Suzy 3 is the same unit as the lower basalt in Naef and Suzy 4. Block 3, south of Block 2, is downfaulted from Block 2 by at least 80 m, based on offset of the lower basalt section. The upper basalt units indicate an offset of approximately 21 m (69 ft) and could be indicative of Holocene faulting. Suzy 5, 6, and 7 penetrate Block 3. Block 4 is upfaulted about 54 m (177 ft), relative to Block 3 and downfaulted about 30 m (98 ft) relative to Block 2. Cumulative offset between blocks may vary because of variations in basalt flow thicknesses, formation of uneven erosional surfaces, and minor intra-block faulting.

Suzy 2 and Suzy 8 penetrate Block 4. Examination of the logs from these holes suggests that the top of the lower basalt unit is offset by less than 7 m (23 ft) between these wells, and the bottom of the upper basalt unit does not appear to show any offset. Such apparent offset of the lower unit can be explained by phenomena other than faulting, e.g., variations in the thickness of the basalt flow, differential topographic and erosional patterns, or jointing and erosion of the basalt. The lithologic units are inferred as being generally undisturbed between Suzy 2 and Suzy 8.

A fifth structural unit, Block 5, has been inferred by the lithologic change in the lower volcanic unit between Suzy 8, Suzy 9, and Suzy 9A. The lower basalt unit evident in Suzy 8 is replaced by a thick andesite unit in Suzy 9. On the basis of this lithologic unconformity, a fault or series of faults is inferred to separate a northerly block containing wells Suzy 9, 9A, and 11 from Block 4 to the east and Blocks 1 and 2 to the south.

7.3.3 Temperature Distribution of the Anomaly. Temperature profiles obtained from the wells are shown in Figure 49. Examination of the temperature logs indicate several trends:

1. The temperature profiles are characteristically similar for wells within each block outlined by the structural study (Figure 46).
2. In wells with temperature reversals, the maximum temperatures were recorded in a zone immediately above or below the contact between the Lake Lahontan sediments and the lower basalt or andesite unit.
3. Temperatures are generally warmest in Blocks 2, 4, and 5.

Maximum temperatures in the wells range from 35 to 83°C (95-181°F). The hottest wells are Suzy 9, 9A, and 11. Unlike the wells in the southern portion of Susanville, these three wells have no temperature reversals, indicating the possibility of higher temperatures with depth.

Subsurface temperatures are contoured at three subsurface elevations [1250 m (4101 ft), 1200 m (3937 ft), and 1150 m (3773 ft)] in Figure 50. As illustrated, at shallow depths (elevation 1300 m; 50 m below average ground surface), the anomaly

Table 13. Well completion data

Well	Location	Elevation (m)	Total Depth (m)	Cased Depth (m)	Casing Size (in.)	Open Interval		Static Water Level (m)	Comments
						(m)	(m)		
Suzy 1	N393,794 E2,375,183	1273.4	271.0	266.0	2	61-90	30.5 ^b	2.3	Perforated 61-90 m, Gravel pack 149-171 m, and Well point 266-271 m
Suzy 2	N394,304 E2,374,716	1276.0	512.0	512.0	2	114-129	15.2 ^b	5.8	Perforated 114-129 m
Suzy 3	N394,298 E2,372,571	1289.0	636.0	636.0	2	73-104	30.5 ^b	15.2	--
Suzy 4	N393,964 E2,373,944	1279.0	234.0	232.0	4	232-234	2 ^b	4.6	Well point 2 in. and Slotted liner 2.4 m
Suzy 5	N373,278 E2,376,886	1271.0	225.0	222.6	2	85-106	21 ^b	8.2	Well point 2.4 m and Gravel pack 152-225 m
Suzy 6	N392,883 E2,375,452	1273.0	190.0	189.0	6	32-190	158 ^b		Slotted liner 32-190 m
Naef	--	1288.0	127.0	114.0	8 (0-74) ^a 7 (74-114) ^a	--	--	14.0	Well drilled--1930 ^c
Davis	N393,113 E374,112	1276.0	192.0	--	--	--	--	4.4	Well drilled--1929 ^c
LLB No. 2	N392,029 E2,376,569	1273.0	152.0	--	--	--	--	4.0	Well drilled--1930 ^c
Swimming Pool	--	1295.0	335.0	--	--	--	--	8.5	Well drilled--1930 ^c
LDS Church	--	1268.0	175.0	--	12 (0-71) ^a 10 (71-127) ^a 8 (127-172) ^a	--	--	5.5	--
Suzy 7	N392,359 E2,374,642	1275.3	224.0	223.1	12 (10.7-well point) ^a	152	--	--	--
Suzy 8	N396,668 E2,373,994	1276.8	160.9	159.4	2 (159.4) ^a	None	None	--	Bottom of pipe sealed and filled with clear water
Suzy 9	N396,276	1283.2	135.6	135.6	2	None	None	--	Bottom of pipe sealed and filled with clear water
Suzy 9a	N396,288 E2,372,122	1283.2	249.3	249.3	2	None	None	--	Bottom of pipe sealed and filled with clear water

Table 13. (continued)

Well	Location	Elevation (m)	Total Depth (m)	Cased Depth (m)	Casing Size (in.)	Open Interval		Static Water Level (m)	Comments
						(m)	(m)		
Suzy 10	N406,625 E2,372,595	1291.4	197.4	197.4	2	None	None	--	Bottom of pipe sealed and filled with clear water
Suzy 11	N397,306 E2,371,270	1305.8	243.2	243.0	2	None	None	--	Bottom of pipe sealed and filled with clear water

a. Cased interval in meters.

b. Length of open interval in meters.

c. Completion data not available.

Figure 46. Division of the Susanville geothermal prospect into five structural units.

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Figure 47. Cross sections showing relationships between various structural units (as indicated by the natural gamma logs). Each verticle division equals 100 ft.

INEL-A-19 374

Figure 48. Cross sections showing relationships between various structural units (as indicated by the natural gamma logs). Each verticle division equals 100 ft.

A.

B.

C.

INEL-A-19 356

Figure 49. Temperature profiles from wells: Suzy 1 through 7; Suzy 8 and 9, the Davis, Naef, Lassen Lumber and Box No. 2, and Roosevelt Swimming Pool wells; and Suzy 9A, 10, and 11.

Figure 50. Subsurface temperature contours at 1250 m elevation, at 1200 m elevation, and at 1150 m elevation.

is centered around the Davis and Naef wells. At greater depths the anomaly becomes asymmetrically shaped around a northwest-trending axis. The anomaly deepens to the northwest. The anomaly is sharply bounded to the west, indicating a hydrologic and/or geologic discontinuity, e.g., a fault, or a fracture zone. To the east and north, the thermal boundary is gradual; to the south, it is more abrupt. Analyses of cores and geophysical data suggest that cooler ground water from shallow saturated strata may be mixing with geothermal fluids in these areas. The asymmetrically shaped thermal anomaly and the noticeable temperature reversals in the southern portion of the field suggest that heated fluids are upwelling along a northwest-trending fault (or at the intersection of several faults). They then apparently enter the reservoir by flowing through the most permeable strata.

7.3.4 Well Testing. From December 10, 1978 to January 8, 1979, a well test was conducted in Susanville. The well test consisted of four segments. The first segment involved the measuring of background data prior to pumping the Davis well. However, because of the extremely cold weather, the LDS Church well was being produced for space heating at the time. To avoid or minimize any pressure transients associated with the Church well flow, the rate was held constant at approximately 5.6 L/s (90 gpm) throughout both the background data collection period and the subsequent pumping of the Davis well. The second segment of the test consisted of pumping the Davis well at a rate of 15.75 L/s (250 gpm) for a period of 9 days. The well was then shut in and the pressure buildup was observed. Several days after the Davis well was shut in, the Church well was shut in for 12 hours and then pumped continuously for the duration of the test. During the last segment of the test, the Roosevelt Swimming Pool well was pumped at a rate of 18 L/s (275 gpm) for 3 days and then shut in.

The producing wells were flowed using existing (installed) pumps. Because the LDS Church well had no flow-measurement device, a 5-gallon bucket and stop watch were used for estimating the flow rate. The elapsed time to fill the 5-gallon bucket varied between 2.9 and 3.4 s (110-90 gpm) with $\pm 10\%$ accuracy on the time measurements. These measurements yielded maximum and minimum flow rates of 5.51-5.0 L/s (120-80 gpm). A 5.6 L/s (90 gpm) flow rate was

assumed for analysis. The Roosevelt Swimming Pool well also had no flow-measurement device, so flow rates were obtained from pump curves which were supplied by Reno Pump and Supply Company in Reno, Nevada. This company installed the pump in 1975.

Pressure data were recorded at eight observation wells and one production well (Davis well). Four of the Suzy wells were perforated (Suzy 1, 2, 3, and 5) for use as observation wells in an interference test. Selection of the perforation interval was based on the maximum measured temperatures and estimated porosities as determined from the well logs obtained during drilling and completion. Because of several complicating factors, the perforation job was considered to be successful only in Suzy 3. The pressure data obtained from five of the observation wells are shown in Figures 51 through 55. Since the casing was of small diameter (2 in.), pressure data in all but three of the observation wells were obtained by lowering a nitrogen-filled capillary tube into the wells. At the surface, the tubing was connected to a wellhead pressure transducer. Downhole pressure transducers were used in Suzy 4 and the Lassen Lumber and Box well (Paroscientific and Hewlett-Packard, respectively). The Naef well was instrumented for background data in July 1978 with a continuously recording water-level device. This device was also used to obtain water-level data during the interference test. Table 14 summarizes the instrumentation used for the well testing.

The magnitude of drawdowns at the observation wells in this test ranged from 0.3 to 1.5 m (0.4 to 2.5 psi). Readings from the wells instrumented with nitrogen-filled tubing (Suzy 1, Suzy 2, Suzy 3, and Suzy 5) were strongly affected by daily temperature and atmospheric pressure changes. The background noise obscured both the initial pressure and the drawdown caused by the production well(s), and rendered the data unsuitable for analysis.

The Suzy 4 and the Lassen Lumber and Box wells had drawdowns of 2.0 psi and 0.5 psi, respectively. These wells showed two peculiar features as compared to other wells (see Figures 52 and 53). Both showed a gradual pressure decrease several days before the Davis well was turned on, and both showed a pressure buildup several days before the Davis well was shut in. Because the

Figure 51. Davis well pressure and flow rate data.

Figure 52. Suzy 4 interference test data.

Figure 53. Lassen Lumber and Box No. 2 interference test data.

Figure 54. Suzy 3 interference test data.

Figure 55. Naef well interference test data.

reason for this behavior is not known, the data from these wells were not considered suitable for a complete analysis.

Since both the Lassen Lumber and Box and the Suzy 4 wells experienced drawdown due to the Davis well production, it can be inferred that the pressure is affected by the Davis well production and by an external source, e.g., atmospheric pressure, ambient temperature, or an influx of fluids to the reservoir from some unknown source(s).

7.3.5 Analysis of Well Test Data. Pressure data in the Davis well were obtained for the duration of the test. However, because of instrumentation problems, only data from the drawdown (December 10 to 19, 1978) are considered reliable. These data were analyzed by the Miller-Dyes-Hutchinson (semi-log) technique.⁸⁹ The data are shown plotted on semi-log paper in Figure 56. After the first several hundred minutes, the data fall on a single straight line, indicating that no boundary is influencing the pressure response. The calculated transmissivity is 7.3×10^5 md-ft/cp.

A plot of wellhead temperature versus time during production of the Davis well is shown in Figure 57. The temperature declined from an initial value of 66 to 59°C (151-138°F) over several

days of production. The discharge temperature appeared to stabilize at 59°C (138°F). The production temperatures may indicate the influx of cold water to the well (during production). Flowing temperature and spinner surveys could provide information about how and where this temperature degradation is taking place.

Pressure data obtained from an observation well which is affected by the production of more than one well or by variable flow rates requires computer-assisted analysis methods. The nonlinear, least-squares computer matching program, ANALYZE, was used to analyze observation data from the Naef well.⁹⁰ The program employs the line source solution (Theis), which calculates pressure drawdowns assuming an isotropic, isothermal, homogenous porous medium of constant thickness. The production well is modeled as a line source which fully penetrates the reservoir. The program can be used to search for vertical reservoir boundaries (impermeable or constant potential). Vertical boundaries are modeled using the method of images. These assumptions (isothermal, homogeneous, etc.) are far too simple to accurately model the Susanville reservoir; however, the program was employed for a preliminary analysis.

The interference data from the Naef well were first analyzed using the production data from all

Table 14. Instrumentation

Well	Test Classification	Measurement Parameter	Instrumentation	Resolution
Naef	Observation	Water level	Leupold-Stevens Type A water level recorder owned by Burec	0.1 ft
Comments: Clear evidence of communication between Davis well, LDS Church well, and the Roosevelt Swimming Pool well. Accuracy of data uncertain between 12/16/78 and 12/20/79 due to sticking of water level recorder.				
Davis	Production-Observation	Pressure	Forty-ft of tubing in pipe-pump annulus, connected to Paroscientific pressure transducer	0.01 psi
		Wellhead temperature	Platinum RTD	0.1 F
		Flow	Orifice and pitot tube	20%
Comments: After 12/19/79 probable nitrogen leak in tubing which caused subsequent pressure change. Clear evidence of communication with the Church well.				
LDS Church	Production	Flow	Flow measured using container and stopwatch	20%
Lassen Lumber and Box No. 2 Well	Observation	Pressure Temperature	Hewlett-Packard pressure probe Gearhart-Owen temperature tool 0.1°F set at 425 ft	0.01 psi
Suzy 1	Observation	Pressure	Fifty-foot tubing connected to Paroscientific pressure transducer.	0.01 psi
Comments: The perforation job was not successful. No pressure change due to flowing well was recorded.				
Suzy 3	Observation	Pressure	Two hundred and fifty-foot tubing and chamber connected to Paroscientific pressure transducer	0.01 psi
Suzy 4	Observation	Pressure	Down-hole Paroscientific transducer set at 500 ft	0.01 psi
Suzy 5	Observation	Pressure	Two hundred-foot tubing and chamber connected to Paroscientific pressure transducer	0.01 psi
Comments: Did not respond to the reservoir pressure due to unsuccessful perforation job.				
Roosevelt Swimming Pool	Production	Flow	Private communication	20%

Figure 56. Semilog plot of Davis well drawdown versus time.

three producing wells (the Church well, the Davis well, and the Roosevelt Swimming Pool well) by the computer technique described above. This analysis revealed that the reservoir is heterogenous because an acceptable match of the pressure data could not be obtained with one set of reservoir parameters (kH/μ , ϕcH , geometry). For this reason, the data were analyzed in two parts. The drawdown caused at the Naef well by the Davis well was analyzed assuming that the production of the Church well had no pressure transients associated with it during the Davis well production. Analysis yields a value for kH/μ of $2.3 \times 10^6 \text{ md-ft/cp}$ and a value for ϕcH of $7.2 \times 10^{-4} \text{ ft/psi}$. Figure 58 shows the best match obtained between the observed and calculated response. The best match of observed and calculated values indicates that the pressure response was influenced by an impermeable boundary. The low storativity values obtained may be an indication that secondary (fracture) permeability is controlling the fluid flow in these wells.

The drawdown caused at the Naef well by the Swimming Pool well was analyzed assuming that

the pressure transient caused by the Davis and the LDS Church wells were negligible compared to the drawdown caused by the Swimming Pool well. Analyses of drawdowns caused by the Swimming Pool well are complicated by several factors. The Swimming Pool well is thought to be 335 m (1099 ft) deep. If the entire wellbore length of the lower zones are producing fluids, complications such as partial penetration and/or a multilayered system will affect the results of the analysis. If the lithology, open interval, and producing zones were known, we could account for these in the analyses, but this information is not available. Using standard techniques, a transmissivity value of $3.4 \times 10^6 \text{ md-ft/cp}$ and a storativity of $4 \times 10^{-3} \text{ ft/psi}$ were obtained. The value of storativity obtained was substantially larger than that obtained from the analysis of drawdowns caused at the Naef well by the production of the Davis and the LDS Church wells. The meaning of this difference is difficult to interpret because of the complications mentioned above.

The ultimate goal of any well test is to extract the reservoir permeability k , thickness H ,

Figure 57. Davis wellhead temperature.

porosity ϕ , and production zone geometry from the lumped parameters, transmissivity (kH/μ) and storativity (ϕcH). Interpretation of the reservoir parameters obtained is complicated by several factors. First, no stabilized shut-in pressure was obtained prior to production of the Church well. Second, flow rates were low, resulting in small drawdowns that were subject both to the sensitivity of the instrumentation and to pressure transients caused by ambient temperature, atmospheric pressure, and precipitation. Interpretation of the analysis is ambiguous because of the lack of available data on the open intervals, well completions, well depths, and well lithology of the older wells monitored in the area. Average results, however, are still useful for an overall (average) estimation of resource parameters. Table 15 presents a summary of the values obtained from the well tests and possible indications of reservoir boundaries.

Pressure data indicate hydrologic continuity between all of the observation wells and produc-

tion wells. Preliminary analysis indicates that the reservoir has a permeability of several darcies. Porosity values extracted from the reservoir storativity, ϕcH (where ϕ is porosity), are ambiguous; however, low storativity values obtained indicate that secondary permeability (fracture permeability) may play a major role in fluid movement throughout this section of the reservoir.

7.3.6 Airlift Test, Suzy 9A. In order to obtain a preliminary assessment of the permeability of the northern portion of the reservoir, Suzy 9A was recompleted and airlifted.⁸⁶ Suzy 9A was recompleted in the following manner. The 2-in. steel pipe was pulled from the well. The well was cleaned by running a 6.5-in. rock bit to the bottom of the hole and circulating clean water. A 4-in. steel pipe was then lowered into the well to a depth of 101 m (331 ft). A shirttail packer was used to seal the upper portion of the well from the wellbore.

Figure 38. Match of calculated and observed values for the drawdown of the Naef well due to production of the Davis well.

Table 15. Summary of well test values and indications of reservoir boundaries.

Observation Well	Pumped Well	Transmissivity (KH/μ)	Storativity (ϕch)	Indication of Reservoir Boundaries
Naef	LDS Church	$3.6 \times 10^6 \frac{\text{md-ft}}{\text{cp}}$	$2.3 \times 10^{-4} \text{ ft/psi}$	Barrier boundary
Naef	Davis	$2.3 \times 10^6 \frac{\text{md-ft}}{\text{cp}}$	$7.2 \times 10^{-4} \text{ ft/psi}$	Barrier boundary
Naef	Roosevelt Swimming Pool	$3.4 \times 10^6 \frac{\text{md-ft}}{\text{cp}}$	$3.9 \times 10^{-2} \text{ ft/psi}$	None
Davis	Davis	$7.3 \times 10^5 \frac{\text{md-ft}}{\text{cp}}$	Not obtained	None

To airlift the well, a 1.5-in. pipe was inserted into the well through the 4-in. tubing to a depth of 162 m (532 ft). A 750 ft³/min, 250 psi air compressor was used to supply the compressed air. The fluid from the well was discharged into a pipe through a 4-in. pipe. Flow rates were measured with a 5-gal bucket and stop watch.

The well was airlifted continuously for 7 hours. The brine temperature stabilized at 74°C (165°F) at a flow rate of 10 L/s (160 gpm). Brine samples, for chemical analysis, were obtained. The results of the analysis are discussed in the following section.

7.3.7 Water Quality. Well Suzy 9A was flowed in March 1980. Chemical samples were obtained and a water quality analysis was performed. The results of these analyses are shown in Table 16. The analyses indicate that the total dissolved solids stabilized at approximately 800 ppm. Samples obtained from the southern portion of the resource have somewhat low salinities, indicating that more ground water mixing is taking place.

7.3.8 Conceptual Model. The Susanville geothermal anomaly appears to be related to a northwest-trending fault. Temperature contours and temperature profiles suggest that heated fluids upwell along the fault and then enter the highly permeable agglomerate-basalt interface and/or permeable zones within the fractured volcanic sequence. Areal confinement of the shallow thermal anomaly has been established for three sides of the resource (west, east, and south). The northwestern boundary of the thermal anomaly has not been completely defined. In the southern portion, the thermal anomaly is vertically confined at or near the agglomerate-basalt interface, as indicated by a temperature reversal. No temperature reversal occurs in the temperature gradient holes in the northern part of the anomaly. However, temperatures at depths below 300 m (984 ft) are not known. The maximum temperature measured, 84°C (183°F) was in well Suzy 9A.

Analyses of interference and production test data from the southern portion of the anomaly give high permeability values. Storativity values are low, suggesting a low porosity aquifer. This information is consistent with geologic data indicating a fracture-dominated hydrologic system. Wells in the northern portion of the

resource have not been sufficiently tested to make estimates of the reservoir size and parameters.

Preliminary estimates of the amount of hot water recharge into the system have been made. A simple model for fault-charged reservoirs was applied to the Susanville system. By comparing the observed temperature distribution of the resource to a theoretical temperature distribution based on a simple model, it is possible to estimate a recharge of 2.25×10^{-2} m³/s along a 2500 m (8202 ft) fault zone.⁹¹

7.4 Production Drilling

In October of 1980, Susan 1 (not shown in Figure 45) was spudded approximately 5 m (16 ft) to the northeast of well Suzy 9A and 15 m (49 ft) southwest of Suzy 9.⁹² The well site for Susan 1 was chosen for the following reasons: the proximity to the hottest well in the field, the moderate flow rate expected in a fractured basalt and the absence of a temperature reversal in well Suzy 9A.⁹³ A Failing JED-A reverse-circulation drill rig was used to drill the well. Water was used as the sole drilling fluid in order to avoid formation damage.

The well was drilled to a depth of 283.5 m 927 ft. The drilling and completion schedules are as follows:

A 26.5-in. drag bit was used to drill the first 15.24 m (50 ft). A 20-in. conductor pipe was then cemented into the hole. Below 15.24 m (50 ft), a 17.5-in. rock bit was used to drill to a depth of 164 m (538 ft). A 12.5-in. bit was used to drill to the final depth. After the well was drilled, a combined string of solid and slotted casing was run to 164 m (538 ft). The annulus between the casing and the hole was gravel packed to a depth of 97.5 m (320 ft) below the surface. The remainder of the annulus was cemented. After the 26-in. conductor casing was pulled, a 8 5/8-in. slotted casing was run in the interval between 158 m (520 ft) and 282 m (922 ft). The lower casing string was neither gravel packed nor cemented. Figure 59 shows the completion of well Susan 1.

Lost circulation and well caving caused substantial difficulties during drilling. River gravels which were penetrated at depths of 73 to 80 m (240 to 262 ft) began to cave in on the drill string. A

Table 16. Chemical analysis of a water sample^a

<u>Date</u>	<u>pH</u>	<u>Temperature (F)</u>	<u>Ca</u>	<u>Mg</u>	<u>Na</u>	<u>K</u>	<u>CO₃</u>	<u>HCO₃</u>	<u>SO₄</u>	<u>C</u>	<u>B</u>	<u>NO₃</u>	<u>Total Solids</u>
02/15/80	8.1	165	26	2	215	5	0	34	320	120	2.000	--	825
02/27/80	8.4	165	32	1	205	6	1	37	294	120	3.080	--	810
02/27/80	8.4	165	30	1	203	6	1	35	294	119	2.460	--	797
02/27/80	8.2	165	36	1	207	6	0	35	307	120	3.040	--	795
02/27/80	8.3	165	34	1	205	6	0	37	301	119	3.040	--	807

a. See Reference 85.

Figure 59. Completion of Susan 1.

cement plug was set to stabilize the hole. At 144.8 m (475 ft) a total loss of circulation occurred. Circulation was lost throughout the remainder of the drilling operation. An estimated 10,600,000 L (2,800,000) gallons of cold water was lost in the well.

A total of 48 days was spent in drilling, logging, and completing well Susan 1. Much of that time resulted from the severe drilling conditions caused by well caving and lost circulation.

The subsurface lithology penetrated in Susan 1 is similar to that encountered in Suzy 9A. From examination of drilling logs, drill cuttings, and geophysical logs, the following stratigraphic sequence has been identified:

Alluvial section:	0-22 m (0-72 ft)
Lake beds (?):	22-85 m (72-279 ft)
Tuffs (?):	85-213 m (279-699 ft)
Lake beds (?):	213-228 m (699-748 ft)
Basaltic andesite:	228-248 m (748-814 ft)
Lake beds (?):	248-272 m (814-892 ft)
Basalt:	272-278 m (892-912 ft)
Lake beds (?):	278-283 m (912-929 ft)

Two major permeable zones have been identified, the first one from 106 to 144 m (348-472 ft) and a second one near the bottom of the well in the lake bed deposits.⁹³

7.5 Aquifer Testing

During drilling, several geophysical logs were run by a commercial logging company.⁹³ These included caliper, spontaneous potential, resistivity, gamma ray, and neutron logs. Temperature logs were also run at various times.

The caliper log identified two washout zones: 68.58 to 82.29 m (225-270 ft) and 214.88 to 225.55 m (705-740 ft). These have been identified as lake-bed units. Several other zones show a slightly enlarged wellbore; these are interpreted to be caused by fractures 102 m to 145 m (335-476 ft).

In general, the electric and nuclear logs did not provide much differentiation between lithologic units, indicating (a) that drilling fluid and formation fluid were relatively similar, and (b) that the volcanic rock has a fairly uniform chemical composition.

No stabilized temperature log has been obtained from well Susan 1. However, since it is so close to Suzy 9A, it can be assumed that the formation temperature will be nearly identical. The temperature surveys obtained were used to locate the permeable zones mentioned in the previous section.

A preliminary pump test was performed on Susan 1 in December 1980.⁹³ The well was pumped at several rates over a two-day period, 15.7 L/s (250 gpm), 22 L/s (350 gpm), 9.5 L/s (150 gpm), and 44 L/s (700 gpm). Figure 60 shows a productivity plot of the stabilized drawdown versus flow rate for several rates. An average productivity index of 10 gpm/ft (drawdown) was obtained.

Buildup data after the 15.7 L/s (250 gpm) and 22 L/s (350 gpm) periods were analyzed using a Horner plot. One case is shown in Figure 61. The average transmissivity (kH/μ) obtained was 1.5×10^6 md-ft/cp. This is in fair agreement with the transmissivity values obtained in the southern portion of the field.

7.6 Current Project Status

The well Susan 1 could be used to supply the entire 315 L/s (500 gpm) of brine required to heat the 14 building complexes. A reinjection will be used to dispose of the produced brine. A second supply well may also be drilled, but this is not definite.

GeothermEx, Inc. has recommended that an interference test, with a minimum duration of 30 days, be run. Simultaneously, a comprehensive model of the reservoir should be constructed so that long-term reservoir potential can be predicted. This data, along with the interference data will be used to determine the optimal location for the second production well (if one is to be drilled) and the reinjection well. A summary of this project is provided in Table 17.

Figure 60. Deliverability of Susan 1.

7.7 Conclusion

The Susanville project demonstrates that the risk in selecting the drill site location and predicting the reservoir lifetime can be minimized if a fairly extensive reservoir assessment program is undertaken before development is initiated. Susanville was fortunate insofar as the majority of the reservoir exploration program was done by the

former U.S. Bureau of Reclamation, now the Water and Power Resources Service. The large cost of drilling 12 exploratory bores would most likely have been prohibitive for the city. But it is clear that because of this extensive exploration program, the Susanville project has a much larger chance of success than it would have had otherwise. A startup of the project is planned for the 1981-82 heating season

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Figure 61. Pressure buildup test—15.7 L/s (250 gpm) case.

Table 17. Summary of Susanville case study

PROJECT TITLE:	Susanville Energy Project--Direct Utilization of Geothermal Energy
PRINCIPAL INVESTIGATOR:	Philip A. Edward (916) 257-7259
PROJECT OBJECTIVE:	To displace fossil fuels and create employment. Program will heat public building complexes. Effluent fluids will be cascaded through an industrial park.

Table 17. (continued)

LOCATION DESCRIPTION: Susanville, California

Population: 6,500

Area Activities: Logging and agriculture

RESOURCE DATA:

Well Depth: 283.5 m (930 ft)

Date Completed: 12/02/80

Completion Technique: slotted casing

Wellhead Temperature: 82°C (180°F)

Flow Rate: 31.5 L/s (500 gpm)

SUMMARY:

Extensive exploration was carried out which provided insight into the geohydrology of the area. Conclusive results are still uncertain but it appears the one well will satisfy the total design demand.

SYSTEM FEATURES:

Application: Space heating, cascading effluent fluids of (120°F) through an agri-industry park

Heatload (Design): 8.5×10^6 Btu/hr

Yearly Maximum Use: 15.9×10^9 Btu

Energy Replaced: Fuel oil 537,389 L/yr (142,000 gal/yr)

Facility Description: Fourteen public buildings

Disposal Method: Injection with backup to an irrigation canal

Summary: Exceeded requirements with one well and will meet entire heat demand required

STATUS:

The startup date is presently planned for the heating season 1981-82.

8. CRITIQUE

Any development project using new technology involves a degree of risk. Geothermal projects are no exception. All six of the case studies discussed in this report received some government funding for the express purpose of assuming the front-end financial risk and promoting the use of geothermal energy.

In the course of preparing this report, some similarities were noted in the application of exploring, drilling, and reservoir engineering techniques that resulted in a few projects not meeting all of their original objectives and full development potential. This critique attempts to highlight techniques that may assist the development or future projects.

The major similarity in each case study was that the resource site was selected because it was in close proximity to a facility that could be retrofitted. In general, sites were chosen with only a minimal amount of exploration. Such a selection method is consistently successful only in an areally-large resource, such as the Madison Aquifer. Detailed exploration, for the typical geothermal resource will, significantly improve the chances of encountering a viable resource. A good example is Susansville, where exploration led to the selection of a prime well site. This well had higher than originally expected temperatures and flows; it resulted in one well satisfying what was originally conceived as a two-well project.

In fault-controlled systems, site selection raises questions such as: will the site exploit the optimal resource flow rate and temperature? Or will the project scope be compromised by settling for a marginal flow rate and temperature in favor of land ownership and pipeline distance to the retrofit facility? Future projects of this nature should focus on additional exploration. Surface geologic mapping, thermal, gravity, electrical, and seismic exploration techniques are available to assess subsurface reservoirs and identify the optimal location for drilling.

A second similarity was that more emphasis should be placed on drilling preparations. Before drilling a well, rigs and other equipment should be carefully selected by consultants familiar with drilling techniques for the resource area. Inappropriate rig sizing or equipment can result in

costly delays and even hamper the completion of a well. In addition, since geothermal development uses both ground water and petroleum techniques, dependent on the resource, a decision must be made as to what technique is most appropriate to the specific resource.

A third similarity entailed the use of inappropriate lost circulation materials, and heavily weighted drilling muds. Both should be used with extreme caution since they can severely damage the wellbore and adjacent pores and fractures. Lost circulation materials used in the case studies may have plugged-off zones of usable fluid; however, no tests were run to prove this factor. The use of heavily-weighted muds in fracture-controlled systems, can damage the fractures to the point where geothermal production is severely inhibited without application of special cleanout techniques. Whenever possible, water, air, or foam should be employed as the drilling media. Although the use of water will result in a natural mud being formed, the fluid weight will be low and not as damaging to the formation and fractures system as a commercial, water-swelling, clay bentonite.

A fourth similarity in each case study was in well completion and development. Slotted liners, gravel packs, or open-hole completions allow for maximum productivity and should be used whenever possible. Wellbore conditions, in unconsolidated formations or in highly-fractured rock, can be controlled for production if gravel pack (behind a screen) or slotted liner techniques are employed. Perhaps these techniques were not necessary in the case studies described, but they should be considered in future work. In the case studies, only low productivity sites accomplished any well development. A good well cleanup, either air-lifting or rawhiding, is a necessity to ensure maximum wellbore productivity.

A fifth similarity was concerned with the need to emphasize well testing and analysis in some of the case studies. Many of the case studies showed that there was inadequate instrumentation to truly assess the reservoir system. Fluid discharge rate control was poor in a few cases, making it difficult to evaluate any long-term well capability. The lack of baseline data from monitor wells, or no monitor well data whatsoever, makes it difficult to

determine what effect drawdown will have on the aquifer systems of the area. The development of standardized instrumentation, test procedures, and analysis is necessary to assist future projects.

A sixth similarity was that test duration was often too short to evaluate the true nature of the reservoir, i.e., will the thermal system be affected by cold water aquifer infiltration, or will nearby boundary effects drastically affect long term drawdown? Since the majority of developments were intended to be relatively small one-well projects, the project teams were not interested in total reservoir capability and interpretation. This fact is obvious from the limited test data which makes it difficult if not impossible to develop conceptual reservoir models.

A seventh similarity involved analytical techniques and units that were not uniformly applied.

The mix of petroleum analysis and ground water analysis in interpreting geothermal data has led to much confusion. Variations, such as use of Q/s_{10} (fundamentally the same as kH/μ), have not been accepted as standard techniques. This area is one of the objectives of the program under which these case studies were funded and will hopefully be addressed in future projects.

Since these projects were the first of their kind they were understandably deficient in some areas. It is the goal of the Low-to-Moderate Temperature Reservoir Engineering Program to advance the current state-of-the-art into a second generation of testing and analysis of such thermal systems. Accordingly, these case studies and this critique are presented to address the state-of-the-art of a developing energy industry, which holds great promise for the future.

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