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RESOURCE DEVELOPMENT; SYSTEM DESIGN, CONSTRUCTION, AND OPERATION FOR GEOTHERMAL DIRECT USE APPLICATIONS

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ABSTRACT

This report discusses topics important to potential investors in geothermal direct-use applications. The topics are: geothermal resource development; and direct-use system design, construction and operation. These topics cover the phases of project development which follow the initial geothermal resource assessment. The resource assessment process is described in a companion report (DOE/ET/12099-3). Potential development problems are indicated and guidance is given to investors in how to decrease risk, increase resource utilization and minimize the investment payback period. The objective of this report is to provide readers with (i) introductions to each of the major subjects addressed, (ii) descriptions of the application-project experience related to each subject, and (iii) references where the reader can seek additional information.

Experience for this report was obtained from some 23 Department of Energy (DOE) sponsored Program Opportunity Notice (PON) projects and from the geothermal literature. The goal of each DOE project was to build and monitor the initial operation of a direct use geothermal heat system for an appropriate application. This report summarizes data from these projects.

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This report was co-authored by ICF, Inc. and EG&G Idaho, Inc. Generally, the EG&G authors addressed the detailed resource development aspects while ICF generated the overall outline and addressed the system economics.

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**RESOURCE DEVELOPMENT, SYSTEM DESIGN, CONSTRUCTION
AND OPERATION FOR GEOTHERMAL DIRECT-USE APPLICATIONS**

1. INTRODUCTION

1.1 Purpose of Report

This is one of a series of three reports prepared by ICF Incorporated for the Idaho Operations Office of the Department of Energy (DOE). The reports discuss the following topics important to potential investors in geothermal direct heat applications:

1. Resource assessment
2. Resource development by well drilling, direct-use system design, construction, and operation
3. Economics of selected projects.

The activities described in this report follow that of a companion report on resource assessment which involved drilling site selection and estimating the probability of finding geothermal energy based on a study of available resource characteristics.¹ In this report, geothermal resource development; and direct-use system design, construction and operation are addressed. The report indicates potential development problems, and offers guidance to investors on how to decrease risk and increase resource utilization and payback. For the potential developer, who has completed the resource assessment phase and determined that the geothermal resource can be economically exploited the next phases are:

- o The resource development phase: drilling, development, and stimulation of the well followed by testing to characterize the geothermal well and reservoir

- o the system design and construction phase: design and construction of the system to use the geothermal energy directly
- o the system operation phase: the operation, maintenance modifications and long-term monitoring of the system(s).

Whenever possible, the discussion cites actual experience gained from 23 geothermal direct-use application projects sponsored by the Department of Energy, Division of Geothermal and Hydropower Technologies (DOE/DGHT) through its Program Opportunity Notice (PON) Program. The report also provides the reader with references of sources of additional information.

Applications or uses of geothermal energy are commonly divided into two categories: (a) direct use of the energy for purposes of agriculture, aquaculture, water and space heating, and industrial processing, and (b) indirect use for generating electric power. Projects to which geothermal energy can be applied directly require wellhead temperatures usually between 100-200°F. Electric power generation (an indirect-use application) usually requires much higher resource temperatures. With a binary wellhead electric generator, temperatures as low as 190°F have been used, but economics improve with increasing temperature. Steam-dominated reservoirs in the 500-700°F range are preferred but rarely found. Heat pumps and adsorption refrigerators can also be used with low temperature geothermal resources.

1.2 Reasons for Potential Interest in Geothermal Resources

The rise in imported oil and natural gas prices and the likelihood of further eventual increases, especially for natural gas,² have enhanced the desirability of developing domestic resources. Domestic demand for energy, declining domestic production of crude oil, and environmental problems limiting the expanded use of other domestically available conventional energy resources have also stimulated the search for viable

alternatives. In addition, the national security implications associated with reliance on imported oil and natural gas support the increased use of domestic resources to reduce our dependence on imports.

Environmental problems have limited expansion of domestic coal, offshore oil, and nuclear power production. Interest has intensified in the development of unconventional energy technologies, most of which are not economically feasible at this time. Limited applications of geothermal energy, however, have demonstrated that this source of energy can be economically viable. In a companion report, nine of the direct-use PON projects were analyzed to determine what factors contributed to their economic attractiveness.³

The commercial attractiveness and reliability of geothermal systems has been enhanced by using existing conventional energy systems. Typically, the existing conventional heating system in a retrofitted structure is used only for peak loads and/or as backup for the geothermal system.

Once a geothermal well has been drilled and developed, its long-term resource capability can be projected from short-term flow tests. The longer (and more expensive) the short-term flow test, the lower the risk that the resource will fall significantly short of its long term production projection. Usually short-term flow tests of 2-4 weeks are sufficient to quantitatively define the well capability; however, monitoring of the developed resource is recommended to verify predicted performance and environmental effects. The rate at which energy can be extracted is then dependent on known parameters. Except for downhole pumps in non-artesian wells, unforeseen supply interruptions are likely to be infrequent and probably less common than interruptions from foreign energy supplies.

1.3 Overview of Geothermal Development Process

The major barrier to geothermal development is the lack of confirmed reservoirs. Confirmation of geothermal reservoirs by drilling is costly, so maximum return on investment requires the rejection of all drilling

sites which do not appear to be very promising from the compiled predrilling data. In addition, economic, engineering, and environmental limitations should be reviewed at each stage to prevent additional investment in an area which can not be profitably developed.

The first problem is resource identification up to the point of well drilling. This encompasses the first three phases in the development process⁴ which is shown in Figure 1. Potential direct-heat users cannot, in general, afford to do the regional geologic work or geothermal data compilation that is needed to identify those local sites where reservoir confirmation studies are most likely to succeed. But, they can obtain valuable information from the United States Geological Survey (USGS) and from the individual states. State universities may also be consulted. These organizations have inventoried various surface manifestations such as hot springs and fumaroles,^a and they have records on thermal wells. In some areas, it is possible to obtain an estimate of the expected temperature, and this information can be used in feasibility studies aimed at the prospective application.

If there appears to be a match between 1) evidence of a geothermal resource in the area, 2) an application for the energy that is co-located with the resource, and 3) very preliminary economic and engineering analyses of the proposed project that look favorable, it is appropriate to proceed with the next step. This step involves hiring a geological consultant for the site specific geological analysis. The consultant (preferably one recommended by the USGS or the State) can give valuable assistance for an update of the economic and engineering analysis by providing expert opinion on probable well depth, temperatures and flow rates. In addition, the consultant can either assist in the environmental assessment or recommend someone else who can help.

a. Fumarole--Hole, vent or geyser which emits considerable quantities of gases, vapor or steam.

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Figure 1. Phases of Geothermal Direct Use Development

Permitting requirements for various aspects of the project may start with resource assessment (exploration), and can be expected to continue throughout much of the development stage. They may even continue after the project becomes operational if temporary permits have been issued or if renewals of permits are necessary for aspects such as the discharge of fluid to surface waters.

The resource development phase, Figure 1, involves production well drilling, well development and testing to evaluate the hydraulic characteristics and thermal behavior of both the well and geothermal resource. These activities usually represent the first major commitment of funds to the project. If, upon completion of the well, actual wellhead temperatures, fluid production rates, and well fluid pumping levels or pressures are lower than those necessary for the project to be economically viable, this does not mean that the investment is irrevocably lost. However, a decision on whether to commit additional funds, in an attempt to improve well performance, is required. While considering cost versus probability of success, these remedial options should be considered:

- o Undertake additional well development to reduce hydraulic "well losses" and thus increase well discharge productivity by decreasing pumping lifts, increasing wellhead pressure and/or increasing the discharge rate
- o Stimulate the well using acid or hydraulic fracturing techniques to decrease pumping lifts or increase wellhead pressure
- o Modify well construction by methods such as additional perforation of the casing in production zones to decrease pumping lifts or increase wellhead pressure
- o Install, at a deeper level, a larger horsepower pump capable of pumping at the necessary rate, but with a greater than anticipated pumping lift or lower wellhead pressure

- o Modify the heat exchanger system such as increasing the heat exchanger area to be more thermally efficient, or incorporate a heat pump and thus require less than anticipated flow rates/ wellhead temperature
- o Manage the resource to minimize long-term geothermal fluid withdrawals, thus minimizing pumping lifts
- o Recover mechanical energy (if the discharge pressure of the spent geothermal fluid is sufficiently high) to decrease project electrical costs
- o Modify well construction to prevent or minimize inflow from cold water producing zones (shallow or deep) thus resulting in an increased wellhead temperature for the geothermal fluid
- o Deepen the well if elevated temperatures can be expected and additional producing zones are likely, thus increasing wellhead fluid temperatures and decreasing pumping lifts
- o Drill an additional well if the resource occurs at an economically shallow depth thereby reducing overall pumping lifts
- o Modify well construction to prevent water loss from a producing zone(s) into a "thief" zone resulting from different natural pressures in the zones, thus reducing the pumping lift or increasing the wellhead pressure
- o Reduce the scope of the application to permit use of the existing resource.

After the resource has been developed, characterized, and found to be suitable, the final design of the heating system can begin. The final design may differ considerably from the conceptual and preliminary designs if the completed geothermal supply differs significantly from estimates on which earlier designs were based. Construction follows the final

design/phase and, in most cases, will be preceded by competitive bidding and selection of a construction contractor. The last phase in Figure 1 is system operation and monitoring. This includes system modifications, system maintenance, and long-term monitoring of the well, the geothermal resource, and the system to utilize the resource.

1.4 Program Opportunity Notices

The source of information on geothermal development is the lessons learned and the experiences gained by project participants and by DOE in providing financial and technical support for 23 direct heat projects. Through the funding provided to participants in two Program Opportunity Notices (PONs), DOE obtained a variety of experience in conducting direct heat projects. Data are currently being obtained from actual operating conditions to provide evidence of economic feasibility. With a few exceptions, the 23 projects have essentially carried out the development process steps outlined in the previous section.

As a result, the PON projects will be referenced as examples throughout this document. The potential investor should use this experience, to avoid or mitigate potential difficulties. With this information, the investor can become familiar with the general procedure to develop a geothermal resource for a direct use application.

1.5 Report Overview

Chapter 2 of this report presents an overview of designing, drilling and constructing production wells, and, to a much lesser extent, injection wells. The importance of consultants to project success is addressed, as are the type of drilling contracts and the bidding process. The drilling plan is addressed in detail with regard to permitting; drilling; borehole geophysical logging; well construction, development, stimulation, and monitoring; and the special aspects of injection wells. Examples of PON project experiences are cited. Chapter 2 also addresses the characterization of the well and the geothermal reservoir from a hydrologic and thermal point-of-view using well discharging techniques.

Chapter 3 reviews the actual experience primarily with the DOE PON projects in the areas of well completion problems, the chemical logging of the drilling fluid, and borehole temperature logs.

Chapter 4 focuses on system design. It begins with a discussion of load matching, i.e., the process of matching potential energy uses with the geothermal energy supplies. The three key factors in load matching are described: retrofit vs. new applications, types and number of loads, and the adequacy of the geothermal resource.

The next section deals with energy supply system specifications. Six aspects of system specifications are considered: system configuration, energy use profile, energy supply profile, provisions to accommodate fluid quality, system administration features, and provisions for future growth. Project experience provides examples throughout the discussion.

Following the section on energy supply system specifications is a section on sub-system specifications. Design considerations are presented for each of the five major sub-systems: energy production, fluid transmission, heat exchangers, distribution system, and fluid disposal. Energy production design issues involve wellhead equipment, pumps, and geothermal fluid collection. Fluid transmission issues focus on the design of equipment used to transport the fluid from the wellhead to the heat exchangers. The various types of heat exchangers available and their advantages are presented. The fourth sub-system involves the distribution pipeline, which transports the geothermal fluid to the user. Sequential versus parallel distribution loops are discussed and space heating systems are described and compared. End-uses of the fluid are considered with respect to the different types of direct heat applications. Fluid disposal issues primarily require deciding between subsurface injection and surface disposal methods. Final comments are made on component selection and design for the geothermal system.

Chapter 5, System Construction, deals with the contracting procedure, construction management, and system operation. The discussion of the

contracting procedure examines the generation of bid packages, distribution and advertising, and contract selection and negotiation. The construction management section discusses two major responsibilities: scheduling and coordination of activities, and marketing procedures. Finally, system operation is briefly reviewed, with emphasis on design modification and system maintenance.

Chapter 6, System Operation, briefly discusses the operational experience of the DOE PON projects with emphasis on "lessons learned."

Chapter 7 is the Summary, and Chapter 8 lists references. Appendix A is a typical informal well flow test report. Appendix B is a list of DOE's direct use geothermal PON projects.

2. PRODUCTION AND INJECTION WELL DESIGN, DRILLING, AND CONSTRUCTION

2.1 Consultants

Specialists will be required for production and injection well design and drilling, and development of the well construction plan and specifications. These specialists must not only be familiar with regulations and permits applicable for geothermal well design and construction, but also the required materials, equipment, and procedures. A local driller familiar with the special requirements for drilling geothermal wells may be the most economic consultant in this regard, especially if the anticipated depth of the well is shallow. In the PON projects, a drilling consultant was usually hired to direct the driller. Whatever type of specialist(s) is chosen, the developer will require assistance by a qualified consultant to prepare an economically and technically feasible drilling plan that also ensures the safety of drilling site personnel. The drilling consultant, if employed, can be used to help select the driller via a bidding or other appropriate procedure. Either, the driller or the drilling consultant, but preferably both, should be familiar with geothermal well development techniques (including stimulation with acid or by hydraulic fracturing).

A specialist will be required for well testing and evaluation. A hydrogeologist or reservoir engineer can provide expertise in flow testing and evaluating the hydraulic characteristics of the well(s) and the geothermal reservoir. This consultant could also provide assistance in installing a monitor well or in designing a program to monitor existing wells and the performance of the production/injection well(s). The selection of specialists for well drilling and construction, and for well testing and evaluation is an important aspect of a project, one that can determine project success or failure.

2.2 The Drilling Plan

The drilling plan specifically describes how the well will be drilled based on information available before drilling. Drilling geothermal wells

often involves special procedures or equipment to deal with higher than normal temperatures and, hopefully, wellhead artesian pressures. The potential investor needs to plan the drilling process with great care since it represents a significant part of the overall investment.

Described in the plan are: expected geological formations and depths, bit sizes and expected drilling depths, the type and weight of drilling mud to be used, the type and size of casing to be installed, cement composition and its installation, and casing pressure test methods. Some features required of candidate drilling rigs such as depth capability of the rig, minimum length of drill pipe which can be vertically stacked (stored) on the rig, and number and type of mud pumps on the rig will be specified.

The drilling plan will give drillers background information on which they can base bids for the drilling contract. The plan represents information available prior to drilling. But, once drilling starts, unexpected drilling conditions often cause the plan to be revised as drilling progresses.

2.3 Types of Drilling Contracts

The cost of a well may depend on the contract between the drilling company and the project operator. The three basic types of contracts are:

- o Footage
- o Daywork
- o Turnkey.

Footage contracts are based on a rate per foot of well drilled. The rate per foot in the contract will reflect the expected drilling difficulty and the diameters of the boreholes. The costs of casing, logging, and testing services are assessed separately. For geothermal investors, such a contract is advantageous in that more of the risk is on the driller.

Daywork contracts are based on a daily rental charge for drilling and a slightly reduced charge for standby. The rig cost is based on the number of days in the drilling period. Where projects are limited to daytime drilling, by noise or environmental considerations, this type of contract may not be optimal. However, some geothermal project investors have found daywork contracts to be the most cost-efficient, especially for deeper wells.

With turnkey contracts, the investor is charged once for all of the services related to drilling the well.⁵ This essentially places all risk on the driller, as the cost to the operator (developer) will not change, regardless of what happens during the drilling. The driller can be expected to require a higher bid price for accepting the risks.

The drilling period can vary from a few days to a few months. Table 1 indicates the drilling period, well depth, and drilling costs for several of the DOE-supported projects. Rig costs account for a large portion of the total drilling costs. Sample rates include \$6,000/day at the Madison County project, \$10,000-\$12,000/day at Ore-Ida, and \$8,000-\$9,000/day at Utah Roses. As an example of the breakdown of drilling costs, Table 2 lists the intangible drilling costs of the Utah Roses project.^a In addition, the project's tangible costs were \$95,417 (1979 dollars), and \$86,000 more was spent in 1980 on working over the well in an attempt to improve production.^b

a. Telephone conversation with project administrator.

b. Tangible costs are the costs of items which physically remain as part of the completed well. They include the casing, cement and any wellhead equipment, such as valves. All other drilling costs are "intangible" and can be written off for tax purposes in the year incurred.

TABLE 1. WELL DEPTH, COST AND DRILLING TIME

<u>Project</u>	<u>Production Well Depth (feet)</u>	<u>Approximate Well Drilling Costs (nominal \$)</u>	<u>Drilling Period</u>
Elko Heat Company	868	135,000	12 days
Klamath County YMCA	1,410	65,500	N/A
Klamath Falls	795	64,000	N/A
Madison County	3,950	483,000	5 weeks
Ore-Ida	10,054 ^b	Approximately 2,000,000	12 weeks ^a
Haakon School	4,266	217,000	11 weeks
St. Mary's Hospital	2,176	320,000	N/A
Susanville	925	113,000 ^c	7 weeks
THS Hospital	3,885	172,000	12 weeks
Utah Roses	5,008	381,851	2 weeks
Warm Springs	1,498	300,000	7 weeks

Source: DOE, Geothermal Direct Heat Applications Program Summary Reports; Robinson, op. cit., p. 564; and, telephone conversations with project administrators.

a. Testing continued for a few months after drilling.

b. Inadequate production.

c. Includes well testing costs.

N/A: Not available.

TABLE 2. UTAH ROSES INTANGIBLE COSTS (1979 DOLLARS)

<u>Activities With Intangible Costs</u>	<u>Amount</u>
Rig Time	\$120,865
Engineering	32,669
Hauling	3,873
Fuel	18,397
Cementing	19,862
Excavating	3,159
Other	1,610
	<u>\$200,435</u>

2.4 Bidding Process

The bidding process for geothermal well drilling requires investor initiative. Normal notice releases requesting bids may produce little response and limited competition may result in higher-cost contracts. The problem of few responses may stem from geothermal projects being located far from oil producing areas, or misconceptions or lack of knowledge about geothermal well drilling.

Solutions to these problems include advertising for drillers in publications and sponsoring bidders conferences. An experienced drilling consultant should be able to help contact and attract qualified drillers to the bidding competition. In addition, the developer of the Klamath County YMCA suggests that the use of a standard bid specification package (such as the International Association of Drilling Contractors) increases the number of bids received and improves the competition for low contracts.⁶

Evaluation of the bids may be difficult for several reasons. The investor should be certain that equipment to be used is of sufficient capacity for the project and is in good condition. A low bid may not be the most economically attractive. The reputation and experience of the driller is an important, qualitative aspect of bid evaluation. The specialists can provide advice to the investor in selecting the best bid. Bid evaluation is an important aspect of the project and can have a significant impact on successfully completing the well at the lowest cost.

2.5 Regulations and Permits

Before drilling may begin, the potential investor must obtain the necessary permits (Reference 1). Long lead times (perhaps months) are prudent because these procedures can take longer than anticipated. Of the 23 DOE-supported projects reviewed, eleven reported problems or delays obtaining permits. Such problems can result in costly project delays and can be avoided if investors take two steps:

- o Locate appropriate regulatory bodies and learn their requirements for the initial stages of project development
- o Communicate with federal and state agencies, local governmental bodies and anyone who may exercise regulatory authority on the project.

Table 3 presents information regarding several regulatory organizations and examples of permit requirements; this should help potential investors with agency identification. Permits are required by federal, state, and/or local bodies for several project activities:

- o Drilling -- includes permission to drill at the site selected, measures against noise pollution, and disposal of drilling fluids.
- o Exploitation/development of the resource -- includes the water and mineral rights required to permit fluid withdrawals from the reservoir.
- o Building construction and pipeline installation.
- o Disposal of geothermal fluids when the project is in operation.

Federal agencies regulate a broad range of geothermal activities. The agencies require investors to obtain geothermal rights from the U.S. Forest Service or Bureau of Land Management when the land in question is federally-owned. In addition, requests for approval of geothermal disposal systems must be submitted to the U.S. Environmental Protection Agency (EPA) in the form of a National Pollution Discharge Elimination System (NPDES) request. The NPDES permitting procedure begins with a 180-day period of public notice. During that time, a temporary permit may be obtained, after which there will be a session for public comment. The NPDES is a discharge permit which must be renewed every five years.

TABLE 3. REGULATORY ORGANIZATIONS AND EXAMPLES OF PERMIT APPROVAL REQUIREMENTS

Project	Activity	Local		State		Federal	
		Organization	Requirements	Organization	Requirements	Organization	Requirements
<u>Idaho</u>							
Boise City	Disposal into river		Drilling permit	Idaho Dept. of Health & Welfare	Permit limits amount of fluid	U.S. EPA	NPDES ^a required.
	Other means of disposal			Idaho Dept. of Water Resources		U.S. Corps of Engineers	Land Ownership
Madison Co. ²	Water right drilling			Idaho Dept. of Water Resources	Water appropriation, Geothermal drilling application, permit to alter geothermal well		
<u>Utah</u>							
Utah State Prison	Disposal into Jordan River after cooling			Utah Bureau of Water Pollution Control	Cooling required before disposal into river.	U.S. EPA	NPDES required
Utah Roses ³	Well permit, heating system Construction	City of Sandy	Permits Required				
	Well permit, water rights, geothermal drilling permit			Utah Dept. of National Resources	Permits required		
	Permission to drill geothermal Well					U.S. DOE	Permission required
	Disposal into river					U.S. EPA	Temporary disposal permits with renewals during drilling.
				Utah Water Pollution Control Committee	Pre-EPA review and approval	U.S. EPA	NPDES required
Monroe City ¹	Disposal by injection			Utah Bureau of Water Pollution Control	Required to dispose by injection with monitoring program	U.S. DOE	Environmental Reports

TABLE 3. (continued)

Project	Activity	Local		State		Federal	
		Organization	Requirements	Organization	Requirements	Organization	Requirements
	Drilling permit, water appropriation		For Water Right	Utah State Division of Water Rights		U.S. BLM	Pipeline Construction
<u>Oregon</u>							
Klamath Falls	Disposal	City Ordinance ^b	Water must be pumped back into the same well.				
Ore-Ida ⁴	Well drilling, testing, geothermal drilling permit, conditional use permit for rezone	City of Ontario, Malheur Co.	Building permit				
	Geothermal well drilling permit			Oregon Dept. of Geol. and Mineral Res.		U.S. DOE	Environmental Assessment
<u>Colorado</u>							
Pagosa Springs	Disposal into river			State	Allowed to discharge into river.	U.S. EPA	NPDES ^a required
<u>Texas</u>							
THS Hospital	Disposal			Texas Railroad Commission	Permit required.	U.S. EPA	NPDES ^a required.
	Drilling			Texas Dept. of Health	Required health permit.	U.S. DOE	Environmental Impact Statement required; require to develop a quieter drilling technique.
<u>California</u>							
El Centro	Drilling	City of El Centro vote by the people	Submitted Environmental Impact Statement (EIS); voted against; required to select a new drill site, file new EIS, vote again.	California Division of Oil and Gas	Drilling Permit.		

TABLE 3. (continued)

Project	Activity	Local		State		Federal	
		Organization	Requirements	Organization	Requirements	Organization	Requirements
Kelly Hot Springs	Disposal into river, or if necessary, by reinjection.					U.S. EPA	NPDES ^a required.
Susanville	Using the resource				Mineral rights ownership requirements.		
<u>South Dakota</u>							
Haakon School	Disposal into river			South Dakota Office of Water Quality	Discharge permit.	U.S. EPA	NPDES ^a required; permit given with fluid treatment required before disposal.
	Using the resource			South Dakota Water Rights Commission	Water rights permit.		
<u>Nevada</u>							
Elko Heat Company	Using the resource			Nevada State Water Engineer	Water rights permit.		
Reno, Moana KGRA	Drilling	(Voluntary)	Limited to certain hours.				

a. National Pollution Discharge Elimination System.

b. An Injunction was implemented against this ordinance.

- References:
1. Direct Utilization of Geothermal Resources Field Experiments at Monroe Utah, Final Report July 14, 1978 - July 13, 1981, Terra Tek Inc., DOE/ET/27054-6.
 2. Industrial Food Processing and Space Heating with Geothermal Heat, Final Report, February 16, 1979 - August 31, 1982, Energy Services Inc., DOE/ET/27028-5.
 3. Floral Greenhouse Geothermal Heating Demonstration, Final Report, Jan. 24, 1979-Sept. 30, 1982, Oct. 1982, Energy Services Inc., DOE/ET/27056-5.
 4. Direct Utilization of Geothermal Energy Resources in Food Processing, Final Report, May 17, 1978 - May 31, 1982, CH2M Hill, DOE/ET/28424-6.

State regulations vary widely. Many states require environmental impact statements and disposal permits additional to those obtained from federal agencies. Geothermal production permits may be required, especially in the western U.S. where a developed system of water rights governs which resources may be exploited. In several states, whether geothermal production requires water rights or mineral rights remains a conflict.

Most permits for geothermal projects are obtained from the federal and state governments. Local government, however, may also regulate the development process. One example is regulation of the hours during which drilling is allowed. Several of the DOE-supported projects restricted drilling activity to daytime hours to avoid disturbing local residents. At the THS Hospital and St. Mary's Hospital projects, mufflers were used to quiet the drilling rig.^a

Utility regulation is another potential regulatory requirement required early prior to initial drilling. The Moana/Reno, and Elko Heat Co. projects found that Nevada laws might possibly classify their geothermal district heating systems as utilities. If so, they would be subject to heavy reporting requirements and regulated rates of return on investment. Also, their operations could infringe on existing utilities' rights within a service area. After some lobbying, the Nevada legislature passed a set of laws encouraging geothermal development. In many states, classification of geothermal projects as utilities remains unresolved. As in Nevada, legislation with clear procedural guidelines for geothermal development has been passed in Utah, Oregon, and recently in Colorado. As the use of geothermal energy spreads, more state legislatures will be prompted to enact geothermal legislation. The PON projects in Nevada and Colorado helped initiate favorable legislation to their respective state legislative bodies.

a. Remarks at the Department of Energy conference on Geothermal Direct Heat Applications, Boise, Idaho, September 1981.

2.6 Site Preparation

Drilling site preparation involves numerous items. Access to the site should be on an all-weather road suitable for heavy trucks. The drilling pad must be a large, leveled, all-weather, well-drained area with soil bearing properties capable of providing an adequate foundation for the drilling rig. This may require that a gravel base be placed on the site. The drilling pad area is also used to store drilling equipment, drilling fluid and additives, cementing operations equipment, sanitary facilities, etc., besides the drill rig. It may also be necessary to excavate a mud pit if a portable mud tank is not hauled to the site. A lined pond may be necessary for holding fluid prior to disposal when developing/flow-testing a well. Some means must be provided to dispose of fluid from a production well during flow testing. Provisions may also be necessary to dispose of drill cuttings. A blow-out-preventer is required when drilling into a pressurized reservoir, particularly if temperatures well above the boiling point are expected. The blow-out-preventer valve assembly essentially eliminates the possibility of an uncontrollable, geysering geothermal well. The blow-out-preventer such as that set at Madison County, Figure 2, which attaches to the wellhead must either be placed in an excavated cellar, or the drilling pad must be of sufficient height to provide the necessary clearance between the blow-out-preventer and the rotary table of the drill rig. An adequate electric power supply is also needed at the drilling site. A major potential problem with a conventional rotary drilling rig is that an adequate water supply is necessary to provide make-up water for the drilling fluid (drilling mud) and to provide make-up water if the production zone is drilled with water only. Lost circulation of the drilling fluid would require make-up water to be delivered at a significant rate. Surface water or water from a shallow well often serves as the supply of make-up water. The water is transported from the source to the drilling site via a temporary pipeline. Preparation problems must be resolved prior to moving the drill rig on site if the project is to be completed economically.

Figure 2. Well Head Drilling Configuration at Madison County, Idaho

In some cases, initial drilling of a deep well may be handled by a small, truck-mounted rig if judged cost-effective. The initial portion of the well has a relatively shallow, large diameter borehole lined with conductor pipe. The drilling consultant will also have this small rig drill a "rathole" immediately adjacent to the wellbore which is used to temporarily store a piece of drilling equipment called the Kelly.⁷

2.7 Well Design and Construction

Production wells are designed to extract water from the geothermal reservoir while providing the most economic tradeoff of well cost against fluid temperature, water quality, and production rate. For example, if the project requires a minimum wellhead temperature of 150°F, it may be necessary to case off zones that produce fluid at 130°F even though this may decrease the total production rate and/or increase the drawdown of the liquid level when pumping the well. Zones that produce geothermal fluid of undesirable quality may need to be cased off to simplify geothermal fluid disposal problems, perhaps by permitting discharge to surface waters rather than injection into ground waters and to avoid injection well cost and complexity. The well should also be designed to minimize drawdowns due to pumping, thereby minimizing pump costs and pump energy requirements and to permit pump installation at shallower depth. Above all, the production well must be designed and constructed to prevent the exchange of geothermal fluid with other aquifers that are or may be used as a source for domestic, municipal or irrigation water. The design and construction of the production well is an important aspect of the project.

Injection wells are used to inject spent geothermal fluid into a suitable reservoir. Injection wells are commonly used for injecting geothermal power plant waste.^{8,9} An injection well is somewhat similar in design and construction to a production well, but may be constructed with smaller diameter casing than a production well since downhole pumps are not installed. Pumps installed at the land surface may be required to force the fluid into the injection well. Major potential problems with an injection well are plugging of the receiving zone(s) and casing corrosion.

Chemical precipitates, and/or fine particulates produced by the production well, can rapidly plug an injection well. Casing corrosion rates are increased if aerated (exposed to atmosphere) water is injected. Only one of the PON projects Klamath County YMCA, Oregon, has used an injection well for disposal, since disposal of the raw or treated spent geothermal fluid to surface waters has usually been acceptable. An injection well is a potentially costly, high maintenance item that should be avoided whenever possible.

"As-built" well construction diagrams for several PON project production wells are presented in Figures 3 to 9. Construction characteristics of these wells are quite different in regard to casing depths, primarily as a result of the local geology and hydrology. The conductor pipe is installed to a shallow depth to convey the drilling fluid to the mud pit, to prevent washout around the base of the drilling rig, and to provide corrosion protection to subsequent casing strings.

The subsequent strings of casing are designed to protect the well against cave-ins, case off (seal off) lost circulation zones, and to isolate aquifers other than the target geothermal aquifer from the borehole. In addition, casing reductions (to smaller diameter) occur due to drilling problems related to geology and hydrology. For example, if a clay swells in contact with water and squeezes into the wellbore, if lost circulation occurs, or if excessive borehole wall caving occurs, a string of casing or a liner may be required to maintain an open borehole for deeper drilling or to permanently maintain the integrity of the well. To provide an effective seal, the casing must be grouted with cement in the annulus around the casing. The depth to the shallowest producing zones and other subsurface hydrogeologic characteristics will determine the casing and grouting schedule. Casing should also be placed to prevent cold water zone inflows to the well.

In the producing zone, a liner, slotted liner, or screen can be placed in the borehole if caving is expected to be a problem. Otherwise, the producing portion of the borehole should remain unlined or unscreened to

Figure 3. Completion and Casing Profile of Well PS-3, Pagosa Springs, Colorado

Figure 4. Completion and Casing Profile of Well PS-5, Pagosa Springs, Colorado

Figure 5. Completion, Utah State Prison Well, USP TH-1

Figure 6. Final Well Dimensions, Susan 1, Susanville, California

Pierre, South Dakota

INEL-A-19 372

Figure 7. Completion of St. Mary's Hospital, Pierre, South Dakota

Figure 8. Well Profile, Ore-Ida, No. 1, Ontario, Oregon

Figure 9. Well Completion for Holly Sugar/TRW Geothermal Project, California

minimize well costs and hydraulic well losses. It is not recommended that the liner be grouted in place and then perforated using casing perforation techniques as at St. Mary's Hospital, Figure 7. This should be avoided since the grout penetrates the fractures and pores near the borehole and prevents the productivity of the well from approaching that of an ungrouted producing zone. An extensive acidizing treatment can be performed to recover production somewhat, but this results in even greater expense.

While casing extends to the surface, a liner is a piece of pipe that is hung from an intermediate depth within a piece of casing extending to a deeper level. Liners are commonly made of steel, but if corrosion is a potential problem, more exotic materials such as stainless steel or fiberglass can be used provided these materials have the necessary strength at the maximum temperature occurring in the wellbore. Screens are commonly stainless steel or brass, depending on temperature conditions and corrosion problems. If the liner or perforated liner corrodes and falls down the borehole, well rehabilitation may be very expensive and time consuming.

Screens are more expensive, but they can be expected to result in greater well productivity than slotted liners since they have a much greater percentage of open area, resulting in lower hydraulic well losses. For example, the percentage of open area ranges from 1% to 18% for slotted liner; louvered screens range from 3% to 33%, while cage-type wire-wound screens range from 2% to 62%.¹⁰ Since most moderate to low temperature developments obtain geothermal fluid from fractured rocks, a properly developed well is unlikely to cave excessively when in production. Thus, screens, or slotted liners are unlikely to be required if the well is properly developed. A slotted liner with large holes e.g., one inch in diameter could be used if continual caving of large diameter rock fragments remains a problem. The use of a liner, slotted liner, screen, or open borehole should be largely decided by the drilling consultant and the driller based on actual field conditions encountered.

The number of production wells needed for a project is determined by four factors:

- o Estimated system load characteristics
- o Wellhead temperature
- o Well production rate and pumping water level relationship
- o Project economics.

Most PON projects have only one well, but the project of Boise City and Boise Warm Springs Water District has a total of six wells, and Aquafarms has seven. Only by drilling and testing wells upon completion can a final decision be made on the number and spacing of production wells.

For the PON geothermal projects reviewed, the wellhead temperature was in the expected range for about 70% of the wells drilled, but the discharge rate was less predictable. Geothermal drilling to date has resulted in a lower percentage of "dry" holes than oil and gas drilling.^a Nevertheless, geothermal wells with inadequate flow rates are not uncommon. Hence, the number of production wells which must be drilled is difficult for an investor to predict before drilling and testing each well (Reference 1).

2.8 Drilling Fluid

The drilling fluids or muds used when drilling with a rotary rig are formulated to perform the following tasks (Reference 10):

- o Remove cuttings formed by the drilling bit and convey them to the surface

a. For oil and gas wells, AAPG Bulletin, 65(10), 1981 reports a 54% success rate for geothermal wildcats in the U.S. for 1980.

- o Separate easily from the cuttings at the surface
- o Maintain hole stability
- o Cool the drilling bit
- o Prevent fluid entry into the borehole from aquifers with high artesian pressures
- o Reduce drilling fluid losses into aquifers
- o Lubricate and retard corrosion of drilling equipment.

Additives are available to adjust physical characteristics of the drilling fluid. Bentonite is a commercially available clay used for making drilling fluid more viscous and more dense. Heavier mud reduces artesian inflows and wellhead pressures during drilling. The drilling consultant and the driller should design the drilling fluid program.

Some problems have resulted when drilling moderate- to low-temperature geothermal wells because of mud invasion into the fractured producing zone. Deep invasion of mud into the producing zone will result in wellbore damage which will increase drawdown when pumping the well. To prevent this, the well should be drilled using mud until near the expected geothermal producing zone. At that time, water without additives, or water with biodegradable additives should be used as the drilling fluid. Drilling with water considerably increases risks associated with drilling (such as getting the drill pipe stuck and drilling with no drill cuttings being returned to the surface). Lost circulation materials such as mica and processed nut hulls should not be used since these materials cannot be readily removed from the lost circulation zone. Lignosulfonates, which are biodegradable, are used for high temperature drilling. Other techniques can be used to minimize the use of lost circulation materials: reducing the weight of the biodegradable drilling mud, increasing the discharge rate at the wellhead by allowing the well to artesian flow by air lifting while

drilling, temporarily casing off the lost circulation zone, or drilling without having returns to the surface which will tend to plug the lost circulation zone with natural drill cuttings. The benefits are generally worth the risk of drilling with water or a biodegradable mud with no lost circulation materials added as opposed to drilling with a bentonite based mud plus lost circulation materials added as needed. Drilling with water also avoids excessive costs for making up more mud to replace mud lost downhole. If the producing zone is exposed to drilling mud, the well development program must remove the residual mud or production from the well will be reduced.

2.8.1 General Mud Logging

Formation samples are obtained by examining the cuttings in the drilling return fluids for a direct-circulation-rotary-tool drilling rig. These samples are usually collected at regular intervals of 5 to 10 feet.¹⁰ The samples may contain some material which caves from the uncased section of the borehole, and fine material recirculated by the mud pump. Because of the differential settling velocities of the various sized cuttings and of the time lag between drilling through the material, borehole geophysical logs are often run to confirm the depths of formation tops and bottoms. Cylindrical cores may be cut with special drilling tools. Although they are expensive and rarely obtained, they can be used to accurately define lithology. The drill-cutting lithologic log can be interpreted by the driller or a commercial mud logging firm representative. Good lithologic logs are necessary for the satisfactory completion of a viable production/injection well with properly set casings and an efficiently completed production/injection zone(s).

The temperatures of the mud circulated to the bit and of the returns from the well are also recorded while drilling. This log provides qualitative data on the temperature regime being penetrated. The actual wellhead temperatures are less than the bottom hole temperatures, but it is still a useful log for estimating the resource temperature.

2.8.2 Chemical Mud Logging

Chemical logging of a geothermal well while drilling can, under suitable conditions, be used to detect hot water zones prior to drill bit penetration.¹¹ The technique is based on determining changes in selected chemical constituents in the drilling fluid returning from the hole as the well is drilled. It does not interfere with drilling operations. Changes in the drilling fluid chemical composition due to nearby geothermal aquifers can result from dilution of the drilling fluid by water in the geothermal aquifer and/or by having the drill bit penetrate materials altered by geothermal fluid seeping from an aquifer. The most useful ratio of chemical concentrations at the DOE Raft River Geothermal Test Site in southcentral Idaho and at the Idaho National Engineering Laboratory site in eastern Idaho was calcium/alkalinity. The constituents used for geochemical logging, in decreasing order of cost-effectiveness, as observed in the wells chemically logged to date are: hardness, alkalinity, silica, specific conductance (conductivity), and fluoride.¹² When drilling an expensive geothermal well, chemical logging of the drilling fluid can provide some warning when approaching geothermal producing zones prior to actually penetrating the zones.

2.9 Borehole Geophysical Logs

Borehole geophysical logs should be used to define the aquifer(s) that produce/receive water. The preferential ranking for the 3 borehole logs of greatest general value are temperature, caliper, and fullbore-spinner flowmeter, Table 4. The temperature log provides information not only on temperature; but by using fluid temperature differences, where fluid is entering or leaving the borehole. Where combined with a spinner and caliper log, the temperature of the fluid in the producing zone(s) can be calculated. Since heat is generated when cement cures behind casing, the borehole fluid temperature is increased and can be used to delineate cement tops and bottoms. The temperature log can also indicate aquifers cased off from the wellbore. The temperature log is very useful for delineating the geothermal ground-water flow system and in

TABLE 4. SELECTED BOREHOLE GEOPHYSICAL LOGS FOR LOW-TEMPERATURE WELLS^a

General Tool Category	End-Use	Applicability Low-Temperature Geothermal
Temperature	Maximum borehole temperature, differential temperature for production zones, determining where casing is cemented, cased-off aquifer delineation.	Very high
Caliper	Volume of required cement grout for casing, other borehole geophysical log interpretations, delineating faulted or fracture caving zones.	Very high
Fullbore-Spinner Flow-meter	Borehole fluid movement well discharging/shutin, location of producing/receiving zones, location of casing leaks.	High
Borehole Fluid Resistivity	Water quality and aquifer identification.	High
Resistivity/SP (Spontaneous Potential)	Lithology differences, water quality, and hydrostratigraphic differences.	High in sediments; low in metamorphic and igneous material

a. Modified after Goldman 1982, Reference 17.

most cases is the most valuable and economical geophysical log. Because of the wellbore cooling by mud circulation during drilling, the temperature logs run during and shortly after drilling will not necessarily indicate true aquifer fluid temperatures under producing conditions, but can be used to determine setting depths for casing, and the final borehole depth, especially if colder water occurs below a geothermal aquifer.

The caliper log is often run to determine the volume of cement grout required to cement the casing, and the cross-sectional area for borehole fluid flow rate determinations. When combined with the spinner log, the caliper log can be used to determine where a caving broken rock zone is penetrated by the borehole. The caliper log also permits the interpretation of other borehole geophysical logs.

The fullbore-spinner flowmeter is a propeller (mounted on a vertical shaft) which can be inserted into the borehole to measure vertical fluid velocity. Fluid velocities can be determined with the well discharging at the wellhead or shut-in. Major casing leaks can be located with the well shut-in under suitable hydrogeologic conditions. The vertical groundwater flow direction can, under suitable circumstances, also be determined with a spinner log on a shut-in well. Since most geothermal wells will flow using artesian pressure, this log can usually be run without having to install a downhole pump. The fullbore-spinner flowmeter, when combined with the caliper log, can be used to determine the inflow/outflow rates of various producing/receiving zones in a production/injection well.

Another borehole log which, although useful but rarely used, is the borehole fluid resistivity log. This log can be used to determine the specific conductance of the fluid in the borehole. This is an excellent parameter to provide an estimate of the total dissolved solids of the fluid entering a wellbore from an aquifer. If wellhead water quality is a problem, this log could provide some insight into possible remedial action such as casing off a poor-water-quality aquifer.

There are numerous other borehole geophysical logs. The resistivity-spontaneous potential (SP) log is used to determine lithology and water quality in uncased boreholes.¹⁰ These data can be used for selecting depths for casing setting. A gamma log can provide information on lithologic units behind casing and in the open borehole via radiation measurements. The following are some of the borehole geophysical logs commercially available:

- o Cement bond log
- o High resolution thermometer
- o Fluid sampler
- o Neutron log (measures porosity of formation)
- o Casing-collar locator (depth reference)
- o Pipe analysis log (determines casing corrosion)
- o Microlog (indicates permeable zones)
- o Compensated formation density log
- o Borehole compensated sonic log
- o Dipmeter (indicates dips of formations, borehole drift).

Borehole directional surveys, downhole television logs and acoustic televiewer logs are also used.

On most low-temperature projects, only the temperature and perhaps the caliper logs are run. For higher-temperature resources, and for low-temperature wells with special problems, additional logs are run to increase knowledge of subsurface conditions; thus, problems can be solved quickly and economically.

2.10 Casing Cementing Program

Casing used for well construction must be cemented in place. The space between the casing and the borehole wall must be cemented to prevent leakage of fluids in the annulus between the casing and the borehole wall, to physically support the casing, and to reduce external corrosion of the casing. State, Federal, and other governmental body legal regulations regarding well casing cementing should be satisfied. The volume grout can be estimated by running a borehole caliper log on the section of open borehole to be cased and calculating the volume between the casing and the borehole wall. This volume can also be estimated based on bit size and experience. Usually 25% to 100% of excess cement grout is planned to account for formation losses, etc. Companies that specialize in providing cement grout are usually subcontracted to provide the grout via bulk cement handling facilities. These companies provide excellent service and advice. Several types of American Petroleum Institute (API) cements are available. Class G cement was generally used for the PON projects. Many additives (Table 5) are available to change the density, the quantity of water required, the viscosity, the thickening time, the setting time, the early strength, the late strength, the durability, and the water loss. The make-up of the cement grout, the method of emplacement and other details of the cementing operation should be determined by the expert consultants available.

2.11 Well Development

Well development is one aspect of low- to moderate-temperature geothermal production wells which has generally been neglected. Well development is the process of removing the finer grained material (fines) in an aquifer in the immediate vicinity of the wellbore, thereby increasing the formation porosity and permeability, allowing for more water to freely enter the well.¹³ Any residual drilling mud must also be cleaned out immediately upon completion of the well.¹⁰ These benefits of well development apply to wells in both unconsolidated and consolidated formations. An additional benefit for aquifers in unconsolidated formations is that the sand formation around the well can be stabilized,

TABLE 5 SOME ADDITIVES COMMONLY USED WITH CEMENT

EFFECTS OF SOME ADDITIVES ON THE PHYSICAL PROPERTIES OF CEMENT		BENTONITE	PERLITE	DIATOMACEOUS EARTH	POZZOLAN	SAND	BARITE	ARSENOFERRITE	CALCIUM CHLORIDE	SODIUM CHLORIDE *	LIGNOSULFONATES	CMHEC†	DIESEL OIL	LOW-WATER-LOSS MATERIALS	LOST-CIRCULATION MATERIALS	ACTIVATED CHARCOAL
DENSITY	DECREASE	⊗	⊗	⊗	x											
	INCREASE					⊗	⊗	⊗	x	x	x					
WATER REQUIRED	LESS										⊗					
	MORE	⊗	x	⊗	x	x	x	x							x	x
VISCOSITY	DECREASE								x		⊗					
	INCREASE	x	x	x	x	x	x	x							x	x
THICKENING TIME	ACCELERATED	x					x	x	⊗	⊗						
	RETARDED			x						x	⊗	⊗	x	⊗		
SETTING TIME	ACCELERATED						x	x	⊗	⊗						
	RETARDED	x	x	x	x						⊗	⊗		x		
EARLY STRENGTH	DECREASED	x	x	x	x		x	x			⊗	⊗		x	x	x
	INCREASED								⊗	⊗						
FINAL STRENGTH	DECREASED	x	x	⊗	x		x					⊗		x	x	x
	INCREASED										x					
DURABILITY	DECREASED	x	x	x									x		x	
	INCREASED				⊗											x
WATER LOSS	DECREASED	⊗									x	⊗	x	⊗	x	
	INCREASED		x	x												

x DENOTES MINOR EFFECT.

⊗ DENOTES MAJOR EFFECT AND/OR PRINCIPAL PURPOSE FOR WHICH USED.

* SMALL PERCENTAGES OF SODIUM CHLORIDE ACCELERATE THICKENING.
LARGE PERCENTAGES MAY RETARD API CLASS A CEMENT.

† CARBOXYMETHYL HYDROXYETHYL CELLULOSE.

thus resulting in a well producing sand-free water. Sediment-free water is desirable to minimize pump wear, maximize well efficiency, and to minimize possible adverse effects in the geothermal utilization of the fluid.¹⁴

The basic purpose of the numerous well development techniques is to break down the bridging of small clay particles between larger particles such as sand, and to remove fine particles from fractures. This is accomplished by surging or by hydraulic jetting. When surging, the initial backflow of water from the well into the formation breaks down the bridging, while the return flow into the well from the formation moves the fine material through the screen or slots into the wellbore. Surging can also be used to develop wells in consolidated rock. Hydraulic jetting disturbs the material surrounding the well screen or borehole wall by high pressure water jets. A return flow of the loosened fines occurs above and below the jets. The fines that enter the screen, slotted casing, or open wellbore, must be removed from the well bottom.

Several well-surfing techniques have been developed.¹⁴ By forcing a surge plunger or a heavy bailer up and down inside the casing, a surging action of the water in the wellbore will result. If an aquifer contains many thin clay beds, care must be exercised when using a surge plunger not to collapse or smear clay on the screen. The use of a surge plunger is a common method of well development.

Surging can also be accomplished using air.¹⁴ Using the two-pipe system, air is introduced into an eductor or pumping pipe via an air line inside the eductor pipe, Figure 10. The air line is initially above the bottom of the eductor pipe and the well is air lifted until the water is clear of sand grains. The air line is shut in and then lowered below the bottom of the eductor pipe. Air is introduced until the water between the eductor pipe and casing reaches the surface. The air is then turned off permitting the lifted water to fall back down the annulus. The air line is then pulled up into the eductor pipe and the well pumped via air lift. This procedure is repeated until the water is clear of sand beginning at

Figure 10. Well Development Using Air Surging

the bottom of the well screen or open wellbore, and progressing toward the top. For best results, approximately 60% of the total length of air line should be below the water level when pumping.¹³ The static water level must also be deeper than 10 ft to permit effective backwashing.¹⁰

Several variations of this basic method have been used: single-pipe system open to the atmosphere, single-pipe system closed to atmosphere,¹⁵ and the double-packer air-lift developing tool.¹⁰ The air development methods can result in satisfactory well development provided the driller has adequate practical experience.

Surging can be accomplished using several backwashing procedures.¹³ One method is to pump water to the surface, allow fines to settle, turn the pump off, and discharge the water back into the well, thus producing a surging effect. Another method, rawhiding, is to pump water to the surface and then turn off the pump, allowing the water to drain back into the well. This procedure is repeated as rapidly as possible. In most cases, rawhiding does not provide surging sufficiently vigorous for optimum well development. Backwashing can also be accomplished, if the static water level is high, by pumping water from the well using a portable pump at the surface while circulating the water back into the well via pipe extending to the section of well to be cleaned. The resulting turbulence helps develop the well. There are undoubtedly other backwashing techniques with varying potential for developing a well. If a backwashing technique is used for well development, it should be one that results in a vigorous surging effect.

Swabbing¹³ is somewhat similar to the surge-plunging technique except the swab is lowered onto the casing and pulled upwards with no attempt to reverse the flow through the screen or borehole wall. This technique is commonly used for developing wells in consolidated rock.

Jetting is one of the best techniques used for well development.¹³ A high-velocity horizontal jet of water is used to agitate and rearrange the grains outside of a screen or slotted liner, thus developing the well. Jet velocities of 150 to 300 fps are used. The jetting tool is placed in

the zone to be developed; high pressure water is pumped down a pipe to the jets which then slowly rotate at successive levels. The well is pumped at a rate of 5 to 15% more than the jetting flow rate in order to create a net flow towards the wellbore.¹⁴ Jetting is simple and not likely to cause difficulties by over-application; it can be used for selectively developing portions of the borehole or screen.¹³

Overpumping is also a technique used to develop a well. Pumping can be either continuous or interrupted.¹⁴ The well is pumped at discharge rates up to twice those expected in normal service. Overpumping does not produce a surging action, so there is less break down of fine-grained bridges.¹³ If the sand is discharged through the permanent system pump, pump damage may result in an inefficient long-term operation. It may not be possible to significantly overpump large capacity wells due to inadequate equipment capacity. In general, overpumping does not result in optimal well development.

Well development can often be enhanced by using chemicals to disperse clays when developing the well (using techniques previously discussed).¹³ These polyphosphates are particularly useful in dispersing clays used in the drilling mud. Acids can also be used for washing limestone aquifers.¹⁴ Commercial drilling fluid service companies, especially in the oil field industry, can provide advice and field service on chemicals suitable for mud removal, clay fixation, acidizing, etc. Well development may be less expensive if dispersants are used to promote the well development.

2.12 Well Stimulation

Well stimulation, as referred to in this report, will be limited to well treatments using acidization, hydraulic fracturing, and explosives. Well stimulation is probably more widely used in the oil well industry than in the water well industry. Acidization is the most commonly used of the stimulation technique for geothermal wells. The acid is primarily intended to dissolve rock.¹⁵ The two treatments used are acid fracturing and

interstitial or matrix acidizing. With acid fracturing, the acid is injected at a pressure sufficient to fracture the rock and create passageways for the acid. With matrix acidizing, the acid is injected at low pressures permitting flow through the open pore spaces. Hydrochloric acid is most commonly used for treating carbonate formations, and acetic and formic acid are frequently used if formation temperatures exceed 250°F. Hydrofluoric acid is used to treat sandstone. Additives are used along with acids to inhibit metal corrosion (corrosion inhibitors), to prevent the reprecipitation of iron (suspending agents), to reduce the surface tension of raw and spent acid solutions (surfactants), to reduce friction losses and fluid losses, and to retard the acid-rock reaction rate. Acidizing a well to increase the potential production rate requires an experienced driller and consultant to ensure that the treatment is as cost-effective as possible, and is performed in a physically and environmentally safe manner.

Hydraulic fracturing is another technique which, although expensive, can be used to stimulate a well.¹⁵ The basic principal is to build up sufficient hydraulic pressure in the wellbore to physically fracture the reservoir rock. The pressure required for fracturing varies from 600 to over 1000 psi for each 1000 ft of well depth. Once the fracture has been formed, it can be held open by a propping agent such as sand suspended in the fracturing fluid. The fracturing fluid often contains additives to reduce the fluid friction losses both in the fracture and within the wellbore, to minimize fluid losses through the walls of the fracture, and to minimize transportation problems of propping agents. Because of the considerable expense involved and the specialized knowledge and experience required, an expert oil field consultant should be utilized should this stimulation technique be applied to a geothermal well.

Explosives can also be used to stimulate a well. Certain kinds of formations respond better to stimulation by explosives than stimulation by hydraulic fracturing or acidization.¹⁵ Modern explosives and new techniques being developed for oil wells result in safer and more effective

well stimulation. This is an untried technique to date for stimulation of a low- to moderate-temperature well with a production rate too low for economic development.

2.13 Long-Term Monitoring

A long-term monitoring program that is properly designed and executed can be a valuable asset to a geothermal development in which the resource is shared with many users. The monitoring program may result from:

- o Permitting conditions by regulatory agencies
- o The desire to protect the developer from unjustified legal suits from nearby well owners
- o The need for additional knowledge of the geothermal resource to permit a more cost-effective development strategy.

The basic purposes of the monitoring program are to quantify the three dimensional groundwater potentiometric head, water quality, thermal regime, and hydraulic transmissivity distributions that existed before the investor's project started, the expected impacts as a result of the project, as well as the actual impacts that occur. Establishing "baseline" conditions prior to starting the investor's project can prevent litigation later. Land surface elevation surveys should be undertaken if subsidence is a potential problem.

Ideally, it is desirable to monitor several parameters at all the monitor wells, production and injection wells, unused production/injection wells, local irrigation and domestic wells, and natural springs. Realistically, some selectivity is required. For monitor wells, it is desirable to have continuous monitoring of the potentiometric head, at least initially, to determine the effects of the project. Temperature logs and water quality determinations should be undertaken for "baseline" data after well completion, and occasionally thereafter or whenever a change is suspected. Permeability determinations (i.e., slug tests, pump tests)

would probably be performed only once, but may change with time if the well is improperly developed or if aquifer fines are induced to migrate as a result of hydraulic effects and possible rock-water interactions, especially in high-pressure, high-flow-rate injection wells.

One of the major problems in designing a monitoring well network is in selecting the location and the depth of the wells, especially where little subsurface data are available and the geothermal flow system is fracture controlled. The spatial distribution and type of construction¹⁶ will depend on the advice of the project consultants, legally and environmentally sensitive aspects and areas, etc. As additional monitoring data become available, more technically sound monitor well siting can be undertaken if necessary.

2.14 Characterization of the Well and the Geothermal Reservoir

The best method to quantify the hydraulic characteristics of the well, as well as the hydraulic, thermal and water quality characteristics of the geothermal reservoir, is to discharge water from the well and evaluate the hydraulic effects, the thermal effects, and the water quality variations primarily at the wellhead and to a lesser degree within the wellbore. The characteristics of particular concern are the hydraulic well losses that remain following proper development, the discharge rate-pumping head/water level relationship, determining the size and ability of the reservoir to transmit and store fluids, the temperature of the fluid at the wellhead at the anticipated production rate, the water quality of the discharged fluid, and the probability of having temperature and water quality changes when the well is in production. Legal considerations are important in regard to water rights, permits, interference effects, and possible legal proceedings.

Often the well test will not fully define all these parameters because of field test conditions and economic constraints. The guidance of a qualified hydrogeologist or reservoir engineer is necessary to obtain the best possible quantification of the most sensitive parameters effecting the economic feasibility of the project.

A possible testing strategy is outlined in Figure 11 (modified from Goldman 1982).¹⁷ This strategy is a combination of groundwater and petroleum technology. For test preparation, the first major step in the strategy, legal requirements must be satisfied for production and disposal of the geothermal fluids during testing. Next, it is necessary to determine if there are wells or springs within a 1-3 mile radius that can be monitored for possible hydraulic interference effects during testing. The necessary permits should be obtained, the reservoir categorized as to whether it is intergranular or fracture permeability controlled (or perhaps a combination). This is done because of potential problems in evaluating the hydrologic data. It should then be determined if the flow rate of the monitor well(s) and spring(s) can be regulated or monitored. This concludes the test preparation.

For the next major step in the testing strategy, the test must be designed, Figure 11. Wellhead pressure changes caused by wellbore fluid density changes induced by initial wellbore fluid temperature transients are a significant problem when testing geothermal wells. Downhole fluid pressure-temperature instrumentation could help to avoid this effect, but it is expensive and not widely used. The test design should attempt to minimize the initial transient temperature change in the wellbore. A small pre-test flow may be enough to minimize the temperature transient by preheating the wellbore.

The first tests to be conducted are a series of pulse tests each of which is a short-duration (1-8 h) constant discharge flow rate, variable-head test with wellhead pressure allowed to recover between each successive test. If possible, the initial pulse test should be undertaken with the drill rig still set up at the wellhead. The initial pulse test, which is often an artesian flow test or an air-lift test, can be used to obtain preliminary estimates of the resource characteristics. If well workover or additional development is required, this can be accomplished with the aid of the drill rig and the equipment necessary for more vigorous

Figure 11. (1 of 2) Recommended Testing Strategy for Low-Temperature Convective Hydrothermal Systems

Figure 11. (2 of 2) Recommended Testing Strategy for Low-Temperature Convective Hydrothermal Systems

pulse and long-term testing. If the resource appears promising, the expensive drill rig may be dismissed. More extensive pulse tests can be conducted once the rig has been removed.

Test design for the more rigorously controlled pulse tests must be able to accommodate a wide range of discharge rates that should be used to aid in determining hydraulic well losses and, if possible, to determine the reservoir hydraulic characteristics. These pulse tests provide the preliminary data necessary for determining the maximum, long-term discharge rate that the well can sustain. The long-term test should last from 10-30 days and should be a constant-discharge, variable-head test. The test design should also specify pretest and posttest procedures and data requirements to be certain data are accurately collected. The technical aspects of fluid disposal, such as the pond size required or the thermal and water quality impacts on surface water bodies, need to be addressed. To minimize costs, artesian flow should be used for as much of the pulse testing and long-term testing as possible. If adequate artesian flow rates are not possible, a pump will be required. An internal combustion engine direct-drive test pump can provide the flexibility in discharge rates that may be required while sparing a permanently installed pump from damage that may result if the well produces sand during early pumping. Instrumentation must be selected to measure the discharge rate, the temperature of the discharged fluid, and the pressure or water level drawdown in the wellbore that results from flowing the well. If the well has a positive shut-in wellhead pressure, this needs to be monitored. If the pumping water level falls below the wellhead at any time, a bubbler tube using compressed air or nitrogen can be used to determine the subsurface drawdown. Table 6 lists the resolution and accuracy recommended for the instrumentation to monitor the various parameters.¹⁷ Duplicate or backup instrumentation should be used for wellhead data. Interference effects with springs and other wells must be considered in designing the test. Following the procurement of instrumentation and the required services, the test design phase is completed.

TABLE 6. TEST DATA REQUIREMENTS^a

<u>Test Parameters</u>	<u>Resolution</u>		<u>Accuracy</u>	
	<u>Desirable</u>	<u>Minimum Acceptable</u>	<u>Desirable</u>	<u>Minimum Acceptable</u>
Pressure	0.1 psi	1.0 psi	±0.1% F.S. ^b	±1% F.S.
Depth to fluid	0.01 ft	0.05 ft	0.01 ft	0.05 ft
Temperature	±0.1°C	±0.05°C	±0.1°C	±1°C
Flow				
gage	±0.1% F.S.	±0.5% F.S.	±0.1% F.S.	±1% F.S.
other	±1% T.F. ^c	±2.5% T.F.	±1% T.F.	±5% T.F.

a. Goldman 1982.

b. Full scale.

c. Total flow.

Field preparation for the test is the next phase of testing, Figure 11. Site and testing preparation involves items such as installing power lines (if needed), providing shelters for instruments, installing instruments and necessary lighting, and installing the necessary piping, valves, etc. for testing and conveying the geothermal fluid to the disposal sink. Baseline data on parameters such as spring discharge rates, water quality and temperature; monitor well wellhead pressures/water levels, temperatures, and possible discharge rates; and a borehole temperature log of the test well should be collected. The pump and production well instrumentation can then be installed.

After being certain that sufficiently trained personnel are available, wellbore preheat is initiated. Preheating should be at 10-20% of the intended discharge rate and should continue until the wellhead temperature stabilizes.¹⁸ If artesian flow is not available to preheat the well, wellbore preheating may have to be omitted since most pumps cannot be operated at 20% or less of their nominal discharge rates. This step concludes the field preparation for the test.

The pulse test is the next phase of testing. The well is discharged at a constant rate and data are collected to define the pressure drawdown that occurs in the wellbore, the temporal changes in wellhead temperature, and the water quality and any temporal changes that may occur during the test. Data are also collected at monitored springs and other wells. After it has been decided to end the test, the discharge rate is reduced to the preheat discharge rate, if possible, and recovery data collected. If the well will not artesian flow, post heating of the wellbore may not be possible. Water quality data may not be representative of the producing zone(s) since flushing of residual drilling fluid may still be occurring. An analysis of the data should be made to determine if another pulse test is necessary, or if the long-term test should be the next step. The pulse tests provide data for deciding on the discharge rate to be used for the long-term test. If the resource does not meet requirements, the feasibility of undertaking remedial action must be investigated, Figure 11.

For brevity, it will be presumed that the long-term test is the next testing phase, the test data collected for the long-term test are basically the same as for the pulse test(s). However, the long-term test will provide more information on possible reservoir hydrologic boundaries, possible temporal water quality variations, corrosion testing, hydrologic interference effects with wells and springs, and wellhead temperatures that can be expected under end-use conditions. Reservoirs that have fracture-controlled permeability should be discharged for a longer period of time than reservoirs dominated by intergranular permeability because of potentially greater heterogeneity in the fracture system. Recovery data should be collected for the long-term test, followed by continued base-line data collection on a reduced schedule until the well becomes operational. These base-line data are helpful in defining naturally occurring trends or those occurring as a result of surrounding utilization of the resource. The data analysis and the projections made from extrapolation of the monitored parameters conclude the long-term test phase.

During corrosion and scaling testing, applicable results can only be obtained if the fluid tested is representative of that which will occur under long-term production. Thus, drilling fluids should be flushed from the producing zones and water quality parameters stabilized as much as is practical. Corrosion and scaling test coupons can be inserted into the geothermal fluid and temporally dependent weight losses, pitting, and scaling for different materials determined as was undertaken at nearly all of the PON projects. A small heat exchanger was even tested at the Elko, Nevada project. Corrosion and scaling rates can also be estimated from water quality data, but fluid corrosion coupon tests are recommended. Selection of suitable materials depends on properly determining the corrosion and scaling characteristics of specific materials in the specific geothermal fluid.

A three-month corrosion coupon test program with flowing geothermal fluid is recommended. At the start of the test, three sets of material coupons are exposed to the fluid. At the end of the first month, one set is removed. At the end of the second month, the second set is removed and

another (fourth set) is installed. At the end of the test (third month), the remaining two sets are removed. This procedure allows the evaluation of time-dependent factors so extended corrosion and scaling rates can be predicted.

3. RESOURCE DEVELOPMENT PROJECT EXPERIENCE

Considerable experience has been gained while carrying out the PON projects and a few other projects. Such experience can serve as "lessons learned" for the potential investor in that it suggests pitfalls that could have been avoided if the investor had been forewarned. These examples are not intended to "second guess" the projects, but are cited to permit the new investor to benefit from the experience.

3.1 General Well Completion Problems

Problems with well completion occurred at Elko, Nevada, Figure 12. The 12-3/4 in. grouted casing, which extended to 259 ft, did not case off shallower aquifers used for domestic and municipal water supply. The spinner borehole geophysical log indicated large flows up the open borehole from the producing zone near the bottom of the well, through the liner and out the space between the casing hangers at 242 ft and the 12-3/4 in. casing. Squeezing of plastic silty clay into the borehole below the liner almost plugged the borehole. A drill rig was set up and an unsuccessful attempt was made to remove the 8-5/8 in. diameter liner. The borehole was deepened to 868 ft to create some potential nonproductive borehole below the producing zone to catch rubble in case of future caving. A second 6-5/8 in. diameter liner extending to a depth of 820 ft (which was in very hard non-caving rock, possibly basalt) was then hung inside the 8-5/8 in. liner. The overlap of the 8-5/8 in. and the 6-5/8 in. casings was cemented. The remedial drilling cost \$69,000 in 1982 for a well which originally had a drilling cost of \$96,000 in 1981.¹⁹ This remedial work resulted in higher wellhead pressures when shut in and flowing, has eliminated sediment from the geothermal fluid, and has eliminated leakage of geothermal fluid from the borehole into the shallow domestic and municipal aquifer.

The Klamath County Oregon YMCA had a well with inadequate casing. The first well was drilled to a depth of 2016 ft with 512 ft of casing which was inadequate to case off shallow cold water aquifers. When pumped, the

***Changes made during rework**

S3 9455

Figure 12. Elko Heat Company Well EHC GP-1 After Rework
(June 1982)

wellhead temperature was only 110°F. This well is now used as the injection well. A new production well drilled to a depth of 1410 ft is cased to 968 ft with the main production zones at depths of 1150 ft and 1350 ft. These zones are producing fluids with temperatures of 135°F and 165°F, respectively. The wellhead temperature is 147°F which is adequate for the project.

Madison County experienced considerable problems in well construction,¹⁷ Figure 13. Drilling from depths of 3150 ft to 3940 ft proceeded without drill cutting returns to the surface (lost circulation). These cuttings were presumably lost to very permeable zones in basalt. Prior to setting the 5-1/2 in. diameter liner, borehole spinner logs indicated downward flow from 2400 ft to 2800 ft where the borehole was bridged or blocked. To case off the cold production zone near 2400 ft and to permit production from a suspected producing zone at 3600 ft, a 5-1/2 in. diameter liner was hung with a liner hanger and packer from 2208 ft to 3540 ft. Cement was spotted around the casing bottom and the borehole was cleaned and drilled to 3950 ft. However, the packer ports at the top of the liner failed to close because of defective shear pins. Unsuccessful attempts were made to seal the failed packer with mechanical devices to eliminate the cold water flow originating at 2400 ft. These well construction problems were finally solved, but inadequate temperatures led to abandonment of the well and the project.

The Monroe, Utah project¹⁷ also had well construction shortcomings, Figures 14 and 15. The heavy weight drilling mud used to reduce wellhead pressures and stabilize the wellbore could have created sufficient pressures at the bottom of the borehole to force mud deep into any fractures or permeable pore space. In addition, a slotted liner was used where definitive information does not indicate that it was necessary. Swabbing and surging the well did improve the production rate to 600 gpm, but a low temperature and a drastically higher system construction cost estimate forced the termination of the project.

All Levels Referenced to Ground Level

Figure 13. Madison County Well Profile, Well MCG-1

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Figure 14. Final Construction and Lithology of Production Well MC-3 at Monroe, Utah

Note: Mc-2 was drilled to 825' but caved in and could only be redrilled and cased to 620'.

Figure 15. Lithology of Well MC-3, Monroe, Utah

The Warm Springs State Hospital Project in Montana also had some shortcomings in well construction, Figure 16. The drilling mud was heavier than necessary and probably resulted in mud invasion of the production zone(s).¹⁷ A slotted liner was used because of loosely consolidated material in the slotted liner section. Acidizing was used to treat the well. During drilling, a spot check of the cuttings indicated that a few samples were carbonaceous. Later it was determined that only a natural carbonate cement was present. The acidizing probably had minimal effect in decreasing well water level drawdowns when pumping. The effects of acidizing this well were probably negligible or detrimental. No well development was attempted. Well damage or improper construction is suggested by the 100 ft of well loss estimated to occur when the well is discharged at 50 gpm. Borehole television camera logs indicated that, even after swabbing, some of the slots were partially restricted and packed with soil.²⁰ The drawdown in the well could probably be reduced by additional hydraulic development and well construction modifications.

Another geothermal project with well construction problems was in the User-Coupled Program, Honey Lake Geothermal Project in Lassen County, CA. This 5823 ft deep well was cased to 5054 ft, Figure 17. Sediment was produced from the well during pulse testing. With the wellhead shut in, a borehole temperature log indicated that the well was almost isothermal (constant temperature) from 230 ft to the bottom of the open borehole. This was interpreted as indicating a casing break at 230 ft; the break was confirmed with a borehole spinner log and a downhole television log. A continuous break apparently existed between 211 and 251 ft. A bridge plug was set in the casing at 850 ft and the well was repaired with a cemented casing liner overlapping the damaged casing. The well is now operational.

3.2 Drilling Fluid Chemical Logging

Chemical logging of the drilling fluid was undertaken at Utah Roses, Sandy, Utah, Figure 18. At Utah Roses, the chemical log implies a geothermal aquifer was penetrated between 4400 and 4500 ft. This was indicated by the increased hardness, silica, fluoride, and conductivity.

S3 9460

Figure 16. Warm Springs State Hospital Production Well

Figure 17. Honey Lake, California, Well Construction Profile

Figure 18. Drilling Water Chemistry Analysis, Utah Roses, Sandy, Utah

Geothermal fluids are normally high in these constituents. The drilling log indicates that lost circulation occurred near the 4366 ft depth, but circulation was restored by adding mica and processed nut hulls to the drilling fluid. Chemical logging can forewarn the driller that a geothermal aquifer is being approached by the drill bit. The Utah Roses well chemical log also indicates when the bit has passed a geothermal aquifer and can provide information that can be used to help decide when to stop drilling and which portions of the well should be more intensively developed or stimulated.

3.3 Borehole Temperature Logs

Borehole geophysical logs consist mainly of temperature logs for the PON projects. The temperature logs at the PON sites indicate that significantly different geothermal gradients and vertical temperature regimes exist at the various projects. The temperature logs for Elko, Warm Springs State Hospital, and Utah Roses, Figures 19, 20, and 21 respectively, indicate somewhat uniform temperature gradients. The temperature generally increases continuously with increasing depth as is generally assumed to occur in the upper part of the earth's crust.

Temperature logs at some other sites do not indicate a uniform thermal gradient. At Monroe, Utah, Figure 22, the test wells MC-1 and MC-2, as well as thermal gradient holes RH-2 and RH-4, are very close to or actually on natural tufa mounds deposited by spring water, Figure 23. These wells have very high thermal gradients near the land surface probably as a result of surface heating due to discharged water. At depth, the thermal gradient decreases significantly and, for MC-2, becomes almost isothermal (temperature does not change with depth). This isothermal condition is probably due to: the upward flow of water from the fault zone, Figure 15, into the alluvium, the proximity of the boreholes to the subsurface conduit conveying geothermal fluid to the land surface, and the subsurface leakage of geothermal fluid from this conduit or other open permeable fractures. As the distance from the spring increases, the temperatures and the temperature gradients decrease, especially upstream (eastward and south) in

Figure 19. Temperature Gradient Profiles of Elko, Nevada Test Wells

Figure 20. Temperature Gradient, Warm Springs State Hospital Well No. 1

Figure 21. Temperature Gradients, Utah Roses Production Well and Nearby County Well

Figure 22. Temperature Profiles of the Production Well, Test Wells and Thermal Gradient Holes at Monroe, Utah

Figure 23. Location Map of the Monroe-Red Hill Production Well, Test Wells, and Thermal Gradient Holes

the shallow ground-water flow system near the land surface. A plume of geothermally heated fluid can be expected to exist in the ground-water flow system down-gradient from the natural geothermal fluid discharge area. This type of geothermal subsurface temperature data can help locate subsurface geothermal discharge areas. However, it is not always definitive, because of the effects of groundwater flow in the overlying, shallow water table aquifer.

Other hydrothermal systems do not have relatively constant temperature gradients. Pagosa Springs, Colorado wells, Figures 24 and 25, exhibit high thermal gradients from the surface to approximately 40 m (130 ft) for all wells except PS-4. The temperature declines with increasing depth for 0-2, PS-3, and P-1 below a depth of approximately 38 m (125 ft). The temperature for P-1, which was to be a test production well, encountered a fault at 250 ft which free flowed at least 1500 gpm at 140°F. The elevated temperature near 76 m (250 ft) is probably due to the active flow of geothermal fluid in the fault zone. This well was cased off to 156 m (511 ft) because of hydraulic interference effects with a nearby spring. The temperature declines in P-1 below approximately 76 m (250 ft). These temperature logs, combined with hydrologic data, indicate that the geothermal fluid is flowing through distinct fractures. The temperature does not necessarily increase with depth. If a well does not encounter a highly-permeable fault, the temperature is relatively low, e.g., PS-4. Well PS-4 was plugged and abandoned because of the low 228 gpm flow rate and low 118°F wellhead temperature. Temperature log data, such as were collected at Pagosa Springs, can aid in defining the geothermal resource and providing some insight into the groundwater flow system(s) being exploited.

The Madison County, project at Rexburg, Idaho, also has some enlightening temperature data. Figure 26 is a map indicating the estimated subsurface temperature at an elevation of 4200 ft, 665 ft below the Snake River Aquifer. The map is based on well temperature data and on a thermal gradient of 1.5°F/100 ft. Figure 26 suggests an elevated temperature near the production well drilled south of Rexburg, Figure 27.

Figure 24. Temperature Gradients for Wells at Pagosa Springs, Colorado

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Figure 25. Location Map of Pagosa Springs Production Wells, Test Wells and Private Hot Wells

Figure 26. Rexburg Area Subsurface Temperatures

Figure 27. Location Map of Madison County Test and Production Wells

Temperature logs were also run in two test wells HTW-1 and HTW-2,¹⁷ Figure 28. Test well HTW-2 had a noticeable thermal reversal at approximately 1000 ft, but was still a cold well. Test well HTW-1, near the production well, was even colder than HTW-2, but indicated an increasing thermal gradient near the bottom of the well. The production well log is cold and is somewhat isothermal throughout the borehole. The temperature reversals in HTW-2 could be due to hot water discharging into a basalt aquifer at some distance from HTW-2 and then migrating laterally in response to the regional groundwater flow system. The large quantity of groundwater flowing through the Snake Plain Aquifer is an effective mechanism for removing subsurface heat and diluting thermal discharges. Drilling in this type of hydrogeologic environment is risky unless a thick and areally extensive hydrologic confining bed exists at depth to locally reduce groundwater flow rates.

White Sulphur Springs, Montana also has a noticeable thermal reversal in the First National Bank production well when it is shut in, Figure 29. This well is located in a 20-acre geothermal spring area associated with a steeply-dipping fault which probably penetrates through bedrock to an underlying low-angle thrust fault. The geothermal fluid also flows through conduits (faults or fissures or other permeable zones) in the 150-250 ft thick alluvium overlying bedrock. Although the well is 875 ft deep, the geothermal fluid appears to be originating in the 95 to 340 ft zone which has an uncemented slotted liner hung in this section, Figure 30. This well, which was drilled too deep, might have an increased wellhead temperature if the borehole below 360 ft were grouted or plugged off. This is a successful well since the drawdown in the well when pumping at 50 gpm is only 1.22 ft, with a wellhead temperature of 117-119°F and a pump setting depth of 15 ft. Since geologic data suggest that the borehole below 360 ft is not producing significant quantities of water, well workover (plugging below 360 ft) is probably not worth the additional expense.

Utah Roses, Utah, has a suite of informative temperature logs. The well construction and lithology are indicated in Figure 31. Figure 32 is a

Figure 28. Temperature Gradients for Madison County Test and Production Wells

Figure 29. Temperature Logs of First National Bank Production Well, White Sulphur Springs, Montana

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(Not drawn to scale)

Figure 30. Final Construction Diagram and Lithology of the First National Bank Production Well, White Sulphur Springs, Montana

(All depths referenced to Kelly Bushing)

INEL-A-18 622

Figure 31. Well Profile and Lithology for Utah Roses, Sandy, Utah

Figure 32. Temperature Log, December 2, 1979, Utah Roses, Sandy, Utah

temperature log run after cement grouting of the 8-5/8 in. casing. When cement is curing (hardening), the reaction produces heat which results in elevated temperatures in the borehole opposite portions of the casing surrounded with a large proportion of cement. Channels of water that cannot necessarily be detected with a temperature log can be present through the grout. The temperature log in Figure 32 suggests cement grout from a depth of 2230 ft to at least 100 ft. Cement returns were reported to occur at the surface for all casing grouting operations. The low temperature between the surface and 100 ft is apparently the result of an active, cold, shallow ground-water flow system conveying heat away from the well. Several temperature logs would need to be run while the cement is hardening to determine where temperature changes are occurring rather than just determining absolute temperatures. This would of course, result in additional expenses. Temperature log data can be used to provide estimates on portions of the casing that are at least partially grouted.

Temperature logs obtained during drilling are not necessarily representative of formation temperatures. Figure 33 contains a typical series of logs made during the drilling of a well. At shallow depths in the geothermal reservoir, the temperatures are significantly suppressed because of the cold drilling fluid, make-up water, and heat losses that occur near the land surface (e.g., Dec. 4, and 5 logs). As the well is drilled deeper, the temperatures for the entire borehole generally increase and bottomhole temperature increases (e.g. Dec. 11 log, two days after termination of drilling on Dec. 9, 1979). A subsequent temperature log, on March 7, 1980, indicates that ultimate temperatures can be expected to increase by several degrees compared to logs run immediately after well completion.

Another sequence of borehole fluid temperature logs at Utah Roses, Sandy, Utah, indicates the fluid temperature changes that occurred in the well after hanging the liner, but before it was perforated. Figure 34 contains temperature logs run on Mar. 7, 1980, (1 day after liner installation), Mar. 16, and Mar. 22. During the period after liner installation, the borehole fluid temperature below the liner continually

Figure 33. Summary of Temperature Logs, Utah Roses, Sandy, Utah

Figure 34. Temperature logs after liner installation, Utah Roses, Sandy, Utah

increased. When the well was discharged, the March 16 temperature log within the lower section of the liner indicated a temperature decline comparable to that on March. 7. This is a result of the downward flow of colder water in the lower portion of the annulus between the unperforated liner and the well borehole wall. The casing was perforated in July 1980 to reduce head losses by letting the fluid flow inward through the liner rather than downward behind the liner before traveling up to discharge at the surface.

The most unusual aspect of this series of temperature logs is that the temperature increases in the depth interval from 1780 to 2230 ft in the grouted and cased portion of the well. One possible explanation is that the lower portion of the 8-5/8 in. casing was not properly grouted. However, the temperature log in Figure 32 suggests the casing was properly grouted. A more likely explanation is that the lower 450 ft of the 8-5/8 in. casing is located in a permeable aquifer described as dark brown clay and sandstone. If the fluid potentiometric head is lower in this geologic unit than the average in the borehole below 2330 ft, hot fluid will flow from the lower part of the open borehole, up the borehole, and into the dark brown clay sandstone unit. This will result in a gradually increasing temperature behind the grouted casing until the hydraulic gradient is reversed due to fluid withdrawals from the well. The withdrawal of fluid should result in a slight wellhead temperature decline during the heating season as the temporarily stored heat is lost due to the migration of colder native fluid from the dark brown clay and sandstone unit towards the well. This temperature decline has not been observed, although the resultant temperature changes may be too small to be detected with the temperature monitoring equipment. This sequence of temperature logs illustrates the use of temperature data in delineating the groundwater flow that results in the vicinity of a well when the well penetrates aquifers that have a tendency for groundwater flow from deeper to shallower aquifers.

3.4 Well Flow Testing

Evaluation of the resource by well discharge tests often resulted in incomplete data because of a lack of planning and understanding of the requirements for testing procedures, instrumentation, etc.

Monroe, Utah, difficulties resulted from inadequate instrumentation and a lack of hydrologic experience.¹⁷ Specifically, problems resulted from poor discharge rate control, inadequate measurements of the discharge temperature, and the short duration of the individual step-test and the long-term tests. Based on these test results, the well was developed by air surging which increased the artesian flow rate from 150 to 253 gpm. This additional development, between the initial 70 hr test at 330 gpm and the second 30 hr 618 gpm test, rendered the earlier test data invalid since producing zones were certainly developed by the removal of residual drilling mud. Serious and expensive testing should only be undertaken after the well has been thoroughly developed since well productivity is likely to change if development is not complete prior to extensive pump testing. The test data did indicate that the Monroe Hot Springs would dry up and the Red Hill Hot Springs would have a reduced flow rate over a period of time. The large 400 ft drawdown in the production well during peak pumping rates provides conditions conducive for cold groundwater to invade the production well fault zone. The leakage could occur in the monitor wells which are completed in both the production well fault and the alluvium. The monitor wells are of little use since they are open borehole completions in two aquifers. The reservoir evaluation pump testing at Monroe, Utah, did not adequately define the well productivity and reservoir size.¹⁷

At Pagosa Springs, Colorado, interference problems were encountered when monitoring privately owned wells while testing the project wells.¹⁷ Only limited construction data were available on the private wells. This complicated data interpretation since the monitor well could be responding to the pressure in any of several different aquifers. In addition, since they were used for space heating, it was not possible to control the discharge from many of the private wells which further complicated well

the interpretation of the interference test. Some of the private wells could not be individually monitored because of common discharge through a storm sewer and old, fragile well head hardware which could not be disturbed.

Complex fracture controlled hydrology at Pagosa Springs, Colorado, is suggested by the 18°F difference in discharge water temperature for wells that are only 141 ft apart, but are hydraulically connected with each other. The hydrology consultant projected that one well could artesian flow at 400 gpm for 100 yrs while the other well could free flow at 700 gpm for 25 years. The problems of varying temperatures and flows encountered at Pagosa Springs are typical of those at a site where the resource occurs in a complex hydrologic system. Current development is further complicated by complex interference conditions with previously established private users.

Utah Roses, Sandy, Utah, also experienced some problems in well testing.¹⁷ Following release of the drilling rig, a temperature log suggested that the borehole was bridged at the 2840 ft depth. A pump was set. Extrapolation from a 6 hr pump test suggested a sustained, heating season discharge of 90 to 100 gpm was possible. The pump was pulled, the well was "mudded up", a liner was hung, Figure 31, and the pump reset. Two four-hour pump tests and another of unspecified duration were run which suggested high hydraulic head losses near the wellbore. The pump was pulled and the well air lifted from the 2000 ft depth in an attempt to increase well development. The well production did not appear to be improved as evidenced by artesian flow rates. The liner was then shot perforated (explosively punctured) with 400 shots. The pump was reset and 3 pulse tests were run. The well produced sand which indicated that the well was still developing during the test. This resulted in questionable drawdown data for predicting future pumping water levels or for determining well losses. A 24 hr test was run with questionable flow rate control beyond 300 min. The well was allowed to recover for 400 min and another test was run for 1200 min. The modifications to the well, well development and sand pumping during testing resulted in much of the pump test data being of little value in predicting pumping water levels in the well.

Other problems include inadequate instrumentation, testing periods that were too short (24 hr) and unreliable discharge control.

As an example of a suitable well flow test, Appendix A contains a report on the St. Mary's Hospital well in Pierre, South Dakota. The problems encountered are typical of geothermal testing. This test report outlines the basic methods used to predict production wellhead pressures and well losses.

4. SYSTEM DESIGN

The key factor in designing a geothermal direct heat application system is to take into account both the characteristics of the energy supply, and the characteristics of the demand energy load. In contrast to conventional heat-supply systems, where the fuel and fuel conversion equipment is designed to meet a specified peak load of unlimited duration, the peak demand load which can be satisfied by the geothermal resource is dependent upon the previous load history and the duration of the peak load. This load profile must be matched to the resource capacity in designing a geothermal heating system. Moreover, because the characteristics of geothermal fluids can vary significantly more than those of conventional fuels, the selection of materials in contact with the geothermal fluid and the method of disposal may be affected. Still, the design of a geothermal direct use system generally involves straightforward engineering practices concerning the movement of hot fluids and heat transfer.

System design is usually a continuing process throughout the resource assessment, and production well drilling development and stimulation stages (Figure 35). The conceptual design begins at the earliest stages of a project. During the resource assessment stage, the potential loads and their requirements (i.e., temperature, average and peak loads, flow rates) will influence the decision whether to proceed with the project. Once the resource has been quantified by a completed production well, material corrosion tests and the final design can begin. However, design modifications may continue throughout the construction stages and even into the early stages of operation if unanticipated problems arise.

This chapter focuses on the main design efforts. As illustrated in Figure 35, these include:

- o Integration of information regarding potential system loads, the geothermal resource, and an alternative conventional fuels back-up system, if used

Figure 35. Stages of Geothermal Project Design Phase

- o Overall specification of the energy supply system
- o Development of detailed subsystem specifications.

Each of these design steps is discussed in detail below.

4.1 Load Specification and Matching

Some load-matching takes place during resource assessment, but the final matching of energy uses with geothermal energy supplies cannot occur until the resource has been confirmed after production well drilling, development and flow testing. After the long-term flow test of the well, and it is in its final form, critical resource parameters such as fluid temperature, flow rate, shut-in water level or wellhead pressure, chemical composition, and corrosion characteristics are finally known.

Key factors in matching load to the geothermal resource include:

- o Whether the application will use geothermal energy to displace conventional energy in existing applications (retrofit) or to provide energy to new end-uses
- o Whether the geothermal energy will be used for a single application, for multiple applications with similar temperature requirements (parallel use), or for multiple applications with different temperature requirements (cascaded use)
- o Whether the geothermal resource is adequate for the provision of the necessary load, or whether supplemental fossil fuels, additional production wells, or additional resource development is necessary.

4.1.1 Retrofit/New Applications

Among the twenty-three DOE PON demonstration projects, most applications have been retrofits as shown in Table 7. Of the retrofit

TABLE 7. RETROFIT VERSUS NEW LOAD APPLICATION

Retrofit	New Load
Boise City and Boise Warm Springs Water Dist.	Aquafarms
Diamond Ring Ranch	Kelley Hot Springs
Douglas High School	St. Mary's Hospital ^a
El Centro	
Haakon School	
Elko Heat Company	
Holly Sugar	
Klamath Falls	
Klamath YMCA	
Madison County	
Monroe City	
Navarro College	
Ore-Ida Foods	
Pagosa Springs	
Reno, Moana KGRA	
St. Mary's Hospital	
Susanville	
THS Hospital	
Utah Roses	
Utah State Prison	
Warm Springs State Hospital	

a. St. Mary's Hospital uses geothermal energy to heat both a pre-existing and a new hospital wing.

applications on which construction has been completed, only Diamond Ring Ranch in South Dakota; Boise, Idaho; Utah Roses in Utah, and Elko, Nevada use some or all geothermal fluid directly. Direct use of the fluid may require replacing the existing system's piping if the fluid composition causes scaling or corrosion. Because of this problem, most retrofits involve the indirect application of the geothermal fluid; that is, the heat is extracted from the geothermal fluid by an isolation heat exchanger or occasionally, heat pumps from which the fluid is disposed directly. Heat is then transferred to a closed, recirculating loop of treated water which distributes the system's heat. A "new load" design case allows the designer the added flexibility of revising the planned load in response to the actual resource characteristics.

4.1.2 Types and Number of Loads

There are three major types of end-uses, each of which can have different load characteristics:

- o Space and water heating
- o Agriculture/aquaculture
- o Industrial processing.

Commercial, institutional, and residential heating can involve both space and water heating. Such geothermal heat applications include systems designed for one building, whether multi-unit or one unit, or for a number of buildings. The latter refers to district heating systems in which hot water is usually piped from a central source to a number of buildings. Usually these systems will provide space heating as well as domestic and/or process water heating. Space heating is seasonal on an annual basis, but is also affected by a daily cycle. Water heating is usually non-seasonal, but also has a daily cycle. Some process water heating is seasonal per the processing season.

Agricultural and aquacultural uses of geothermal energy for heating would include space heating for greenhouses and animal husbandry, air heating for crop drying, and warm water supplies for fish farming. Industrial applications could involve the need for hot water in food preparation processes, including the pasteurization of milk, beer, or other consumable liquids; pulp, paper, and wood processing; and space heating for kiln drying of lumber.¹

In general, industrial applications require higher temperatures and flows than other applications, while agricultural and aquacultural applications best utilize lower temperature and flow resources. Table 8 lists the projects reviewed by their type of application.

Designers should consider cascading potential loads in a project, especially when applications with a wide range of temperature are available. In industrial processing, this may involve using the cascading principle within one plant. For example, the Ore-Ida project in Ontario, Oregon proposed applying geothermal energy to the processing of potatoes, corn, and onions into frozen food products. The 300°F fluid would supply energy for blanching; this would drop the temperature to approximately 200°F. Pealers would further extract energy from the fluid to approximately 170°F. At this point, the fluid would be used to provide space heating, domestic hot water, and process makeup water to the plant.²¹ Cascading may also be used in district heating systems. Lower temperature applications, such as swimming pool heating or aquaculture, could be found for the system discharge. Or several houses in series could each receive lower temperature geothermal fluid, but this can create billing and user satisfaction problems. Table 9 lists projects reviewed which use a cascading design.

4.1.3 Adequacy of Geothermal Resource

A major factor in assessing the adequacy of geothermal resources is matching potential loads to the resource. If the resource is inadequate,

TABLE 8. CLASSIFICATION OF PROJECTS BY APPLICATION

<u>Industrial Processing</u>	<u>Agriculture/Aquaculture</u>	<u>Space/Water Heating</u>
Holly Sugar	Aquafarms	Boise City and Dist.
Madison County	Diamond Ring Ranch	Diamond Ring Ranch
Ore-Ida Foods	Kelley Hot Springs	Douglas High School
	Utah Roses	El Centro
		Elko Heat Company
		Haakon School
		Klamath YMCA
		Klamath Falls
		Madison County
		Monroe City
		Navarro College
		Pagosa Springs
		Reno, Moana KGRA
		St. Mary's Hospital
		Susanville
		THS Hospital
		Utah State Prison
		Warm Springs Hosp.

TABLE 9. PROJECTS WITH CASCADING DESIGN

Project	Application	Project Description
Aquafarms	Prawn Ponds	Geothermal fluid is supplied to ponds where shrimp are grown. The pond overflow is collected and recycled.
Diamond Ring Ranch	Water/Space Heating	The system provides hot air for grain drying in a conventional grain dryer and provides space heating for four homes, a shop, and a hospital barn.
Haakon School	Water/Space Heat	The project's primary service is heat for the Haakon School District buildings. Cascaded use includes heat for eight commercial buildings and the fire station in the City of Haakon.
Holly Sugar	Industrial Processing	The project would have employed cascading for industrial processing of sugar beets.
Madison County	Industrial Processing/District Heating	The original project design included utilizing discharged fluid from a potato plant to provide or supplement space and water heating for nine public buildings, and various apartments and residences.
Ore-Ida	Industrial Processing	The project would have employed the cascading principle within the plant, using different temperatures for different processing stages of frozen food processing.
Susanville	District Heating/Industrial Processing	Space heating and hot water is provided for 14 municipal buildings. Plans exist for cascading the residual energy through an industrial park.

system designers--most likely in conjunction with other technical staff--would consider several types of remedial measures.

Table 10 draws on the experience gained from the DOE-supported projects and illustrates solutions to an inadequate resource. When actual resource temperature is lower than expected, higher temperatures can sometimes be obtained by drilling deeper. This measure involves economic and technical risks, and should not be considered unless the resource assessment suggests the presence of hotter fluid at greater depths. A second remedial measure for inadequate resource temperature involves the use of supplementary energy supplies.

In peaking, conventional fuels are used, as needed, to supplement the geothermal energy to meet peak loads. In retrofit loads, this peaking configuration may be economically advantageous due in part to the capital already invested in boilers for the conventional fuels. The investor, however, must note that the portions of the heating systems which use both conventional fuel and geothermal energy in normal operation are not eligible for the geothermal energy tax credit under current tax regulations. An emergency backup system using conventional fluid does not harm the geothermal tax credit.

Several techniques can be used to increase the available well discharge rate. One technique is to pump the fluid rather than to rely on artesian flow. The deeper installation of a high-lift pump, as compared to a low-lift pump, will permit additional water level drawdown and thus increase the long-term well production rate. Additional techniques include drilling the production well deeper or drilling additional wells. The majority of the projects with inadequate flow, however, used well stimulation techniques such as hydrofracturing and acidizing as previously mentioned.

Attempting to improve an inadequate resource involves the risk that it may not be successful. However, stimulation of wells and/or the use of supplemental energy sources by some projects have demonstrated that abandonment of a project can be avoided in some cases.

TABLE 10. SOLUTIONS TO AN INADEQUATE RESOURCE

Resource Inadequacy	Potential Solutions	Projects Where Used	Outcome/Project Status
Low temperature	Drill deeper	Utah Roses (Part 1)	A 3,000 ft well was planned. The well was drilled to 5,088 ft in search of hotter water. Although this was not completely successful, the project is in operation.
Low temperature	Fossil fuel supplement	Utah Roses (Part 2)	Although this project anticipated supplementing the geothermal energy with conventional fuel heat, a low temperature resource requires a greater percentage of supplemental fuel. Project is operational.
Low temperature	Drill deeper	Navarro College	The "injection" well was extended to 4,760 ft in search of water hotter than that found by the "production" well. There was no water production below 4,500 ft, so the hole was plugged back to 4,100 ft, where the temperature is 23°F higher than the "production" well fluid. Therefore, the uses of the wells will be switched by reversing the original flow direction, and the project continued at reduced scope.
Insufficient well discharge	Use pump	Warm Springs State Hospital	With pumping, the project is in operation at reduced scope.
Insufficient discharge	Use natural CO ₂ -lift	Utah State Prison	With natural CO ₂ -lift system, pressure and flow are adequate and project is under construction. Backup to design would add conventional pump if needed.
Insufficient well discharge and wellhead pressure	Used pumps and drilled additional wells	Boise City	A total of four pumped wells had inadequate discharge; but pumps were added. Project is in operation.
Insufficient well discharge	Drill additional well	Pagosa Springs	Discharge of second well inadequate; so another drilled. The project is in operation.
Low temperature	Drill additional well	Klamath Co. YMCA	The first well drilled had inadequate temperature and is used as their injection well. Project is operational.

TABLE 10. (continued)

<u>Resource Inadequacy</u>	<u>Potential Solutions</u>	<u>Projects Where Used</u>	<u>Outcome/Project Status</u>
Inadequate flow	Develop well	Klamath Co. YMCA	Airlift used to develop well. Project is in operation.
Insufficient well discharge	Develop well	Monroe City	This project was only partially successful at further deloping the well with airlift. The project was halted.
Insufficient well discharge	Hydrofracture	Ore-Ida	Fluid was injected to fracture the production zone, but the attempt was unsuccessful. The project was halted due to the "dry hole".
Insufficient well discharge	Acidize	St. Mary's Hospital	Hydrochloric acid solution was injected to open the production zone. Flow was increased from 250 to 375 gpm and the project is in operation on artesian flow.
Insufficient well discharge	Acidize	Warm Springs State Hospital	Hydrochloric acid solution was injected and partially succeeded in improving flow. Project is in operation at reduced flow.

4.2 Energy Supply System Specifications

Once the designers have identified the end-uses to be served by the new energy supply system, the process of developing the design specifications can proceed. As for the design in general, specification development takes place both before and after this particular point in the system development process. The system design must consider several technical and economic aspects. These aspects include:

- o System configuration**
- o Energy use profile**
- o Energy supply profile**
- o Provisions to handle fluid chemistry**
- o System administration features**
- o Provisions for system growth.**

4.2.1 System Configuration

Three basic variables determine system configuration:

- o Type of application of the geothermal fluid**
- o Type of service to loads**
- o Fluid disposal method.**

The projects reviewed for the application of the geothermal fluid are listed in Table 11 with their respective configurations. As mentioned, the three methods of applying geothermal fluid to loads were: physical contact, direct heat exchanger(s) or isolation heat exchanger(s). With physical contact, the geothermal fluid is used in the application

TABLE 11. SYSTEM CONFIGURATIONS OF PROJECTS REVIEWED

Project	Application	Application ^a of Geothermal Fluid	Number of Loops	Fluid Disposal Method
Aquafarms	Aquaculture	Physical use	0	Evaporation/seepage
Boise City	Water/space heating	Direct HE	1	Into Boise River
Boise Warm Springs Water District	Water/space heating	Direct HE	1	Into Boise River
Diamond Ring Ranch	Space heating and grain drying drinking	Isolation HE	2	Surface disposal
		Physical use	1	
Elko	Water/space heating laundry	Direct HE	1	Surface disposal
		Physical use		
Haakon School	Water/space heating	Isolation HE	2	Into river
Klamath County YMCA	Water/space heating	Isolation HE	1	Injection
Klamath Falls	Water/space heating	Isolation HE	1	Injection or dis- charge into city sewer system
Pagosa Springs	Water/space heating	Isolation HE	2	Into San Juan River
St. Mary's Hospital	Water/space heating	Isolation HE	1	Into Missouri River
Susanville	Water/space heating	Direct HE	1	Injection
THS Hospital	Water/space heating	Isolation HE	1	Into storm sewer system to Bean Branch River
Utah Roses	Agriculture	Direct HE	1	Into Jordan River

a. Isolation HE = Closed loop of fresh water fed to individuals heat exchanger(s). Geothermal fluid kept out of distribution system by isolation heat exchanger(s).

Direct HE = Geothermal fluid in individual users heat exchanger(s).

Physical use = Geothermal fluid used in process.

process/and is in direct contact with the warmed product. Examples are prawns at Aquafarms and laundry at Elko, Nevada. When the geothermal fluid is not particularly corrosive, it is piped through the distribution system to the individual users heat exchangers. This is termed direct heat exchanger use.

When the geothermal water quality is not good, one or more isolation heat exchangers are usually used near the wellhead to extract the heat from the geothermal fluid; the fluid is then disposed of immediately, minimizing contact with the other portions of the system. The secondary side of the isolation heat exchanger carries treated, domestic water in a closed-loop through the distribution system. The treated water carries the heat to the individual users heat exchangers. The treatment is usually a fungicide/biocide additive.

The system at Diamond Ring Ranch contains two of these types of applications. Both the grain dryer and the space heating system for the homes and barns use closed loops of treated water on the secondary side of an isolation heat exchanger (top, left-center of Figure 36). The geothermal fluid is also used for watering cattle and for domestic drinking.

The second variable in determining system configuration concerns the service to loads, which falls into two categories: cascading (sequential), and parallel feed. Figure 36, a schematic of the Diamond Ring Ranch project, illustrates both categories. At Diamond Ring Ranch, the grain dryer and all space heating areas are fed from two isolation heat exchangers in parallel. The space-heating closed loop, is then broken into two parallel sub-loops, each of which feeds three users in parallel. Meanwhile, the geothermal discharge from the space-heating heat exchanger (top of figure) has been partially cooled and used as domestic hot water. These two applications are cascaded (in series).

Parallel service, a configuration where each user taps the same distribution line and disposes of the fluid into the same return line of the loop, is illustrated in Figure 37, a schematic diagram of the Pagosa Springs' geothermal heating system. The number of independent loops service loads is another important configuration. Pagosa Springs is

Figure 36. Schematic of Diamond Ring Ranch Geothermal System

Figure 37. Schematic of Pagosa Springs Geothermal System

usually discussed as a two-loop secondary system (east and west loops) because of the physical layout, but actually it is one loop with all users in parallel. Table 11 lists the number of independent loops at the projects reviewed.

Fluid disposal is the third variable in determining system configuration. Disposal into a nearby river, pond, or swamp is usually the most economical method; surface disposal, however, is often infeasible due to environmental regulations on the federal, state, and local levels. Alternative methods include injection of the fluid into either the production aquifer or another aquifer. Injection of the fluid into the production aquifer introduces the possibility of cold water break through into the production well and thus, has some risk. Drilling injection wells may not be necessary if existing wells, previously designated for exploration or production, are used. When an injection well is drilled, however, site selection requires a compromise between minimizing the length of the disposal pipeline and assuring that the injected fluid does not thermally break through to feed back to the production well.

4.2.2 Energy Use Profile

The energy use profile, another aspect of system definition, aids the designer in specific load matching in a system. Peak energy use, average energy use, and the required temperature at each point of use are important in deciding how much supplemental energy may be necessary. For institutions such as hospitals or prisons where interruptions in energy supply would pose severe problems, system designers should retain the existing space and water heating systems as back-up. Other projects may require no back-up supply.

Experience at the Diamond Ring Ranch indicates how dependency on geothermal energy at projects in remote locations may call for special precautions to prevent damage to the system. Specifically, winter power

failures at the ranch allowed the fluid in the pipelines of the closed-loops to freeze. The following summer anti-freeze was added to the recirculation loops.²²

Table 12 illustrates typical heat loads for several of the projects reviewed and indicates whether or not they have back-up supplies.

The energy use profile which will be served must be selected such that it results in a geothermal flow demand which the resource can accommodate. The characteristics of the users system(s) must also result in economic benefits to both the user and to the operator of the energy supply system if the project is to be successful.

Examination of an equation for energy transfer for water going through a heat exchanger can be used to illustrate several factors:

$$Q = 500 \times V \times \Delta T = 500 \times V \times (T_s - T_d)$$

where

Q = rate of energy transfer, Btu/hr

V = volumetric flow rate of water, gal/min (gpm)

ΔT = temperature drop of the hot, energy-supply water going through the heat exchanger

T_s = temperature of supply water

T_d = temperature of the same water as it is discharged from the heat exchanger.

The energy supply system is sized on the basis of the peak heating rate. For this peak heating rate, Q_{pk} , doubling the ΔT in the user's heat exchanger will cut the peak flow rate of the fluid supplying the energy in half. This conserves the resource (lower geothermal fluid flow for the

TABLE 12. ENERGY USE PROFILE

Project	Application	Heat Load (design) (Btu/hr.)	Yearly Utilization (Btu/yr.)	Back-Up Supply
Aquafarms	Prawn growing	N/A	170×10^9	None
Boise City & Boise Warm Springs Water District	District heating	74×10^6	149×10^9	Pre-retrofit fossil fuel systems for most users
Diamond Ring Ranch	Space, water heating and grain drying	2.3×10^6	4.7×10^9	Pre-retrofit fossil fuel systems in the residential buildings
Haakon School	Institutional heating	5.5×10^6	9.5×10^9	Pre-retrofit fossil fuel system
Klamath County YMCA	Space and water heating	4.4×10^6	7.8×10^9	Pre-retrofit fossil fuel system
Klamath Falls	District heating	15.3×10^6	40.0×10^9	Pre-retrofit fossil fuel systems plus two buildings with geo- thermal wells.
Pagosa Springs	District heating	11.3×10^6	24.7×10^9	Pre-retrofit fossil fuel systems
St. Mary's Hospital	Institutional heating	5.6×10^6	11.5×10^9	Pre-retrofit fossil fuel system
Susanville	District heating	14.0×10^6	18.7×10^9	Pre-retrofit fossil fuel systems
THS Hospital	Institutional heating	3.4×10^6	9.6×10^9	Pre-retrofit fossil fuel system
Utah Roses	Agriculture	2.8×10^6	16×10^9	Pre-retrofit fossil fuel system

N/A: Not available.

Sources: DOE, Geothermal Direct Heat Applications Program Summary Reports and Robinson, op. cit., p. 564.

given load) and cuts system capital and operating costs since smaller system hardware can be installed. Both of these factors would improve the economic return to the operator of a geothermal energy supply system.

The system user faces an economic tradeoff if he is billed on the basis of total water flow. If he buys a larger, more expensive, heat exchanger (high ΔT), he will have a higher capital cost and a lower operating cost (billed on total flow). Conversely, a small heat exchanger (low ΔT) would result in a low capital cost to the user, but a higher operating cost (more supply water consumed each month). Often, users are unrealistically tempted to minimize capital costs. The energy supply system operator may protect his and the user's interests by requiring that exchangers be designed for a some minimum ΔT value. The Pagosa Springs district heating system requires users to design to a minimum ΔT of 25°F.

The ΔT available for use is bound by the maximum temperature at which water can be supplied to the user, and by the minimum driving temperature the user's application can accept, T_d . The temperature is usually about 5°F above the users minimum driving temperature. Typically for space heating, T_d would be about 100°F. Therefore, the minimum economic supply temperature, T_s , would be about 120-125°F. The useful T_s can be lowered by lowering T_d . St. Mary's Hospital used direct space heating in one building and a heat pump in another in an economical application where $\Delta T = (105-80) = 25^\circ\text{F}$. Adding the heat pump does increase overall capital costs.

4.2.3 Energy Supply Profile

The energy supply profile and the geothermal fluid flow profile are determined by taking the aggregate user energy load demand, and the total temperature drop of the geothermal fluid (ΔT) which reflects the average of user system characteristics plus the energy losses between the wellhead and the user. This fluid flow or energy supply profile must match the available resource.

Individual energy user's ΔT 's were discussed previously. If a group of energy users have temperature requirements that are higher or lower than other users, it may be possible to add their ΔT 's by going to a cascaded system design. That is, group "A" from 150 to 125°F followed by group "B" from 125 to 100°F for a total ΔT of 50°F. The overall system ΔT is a measure of the economic use of the resource. Again, the higher the resource temperature, the more ΔT is available for use. Geothermal fluid delivery temperatures and design ΔT 's are listed for several projects in Table 13.

With many users, such as in a district heating system, adding all the individual user peaks will be more conservative than necessary. The oversized system could be built for growth after operating experience shows how much excess capacity the sum of peak loads provided. To size the system for the actual load, a detailed time-phased analysis of individual loads is often impractical. Usually, the total of the individual peak loads (connected load) is reduced by multiplying it by a diversity factor (ratio of actual peak load to total connected load). The value of the diversity factor should be determined from experience with similar systems. A 70% diversity value has been used in some geothermal district heating models.

Energy losses between the wellhead and the user are usually small ($<5^\circ\text{F}$). This is partially due to proximity of the wells to users since long pipelines are too expensive. Also, insulated supply pipelines are used in most of the systems.

Some of the systems use conventional fuels to supplement the geothermal energy, Table 13. Supplementary fuel may be used steadily if the application load is considerably larger than the geothermal resource. If the geothermal resource is able to handle most of the peak load, then supplementary fuel may be used for peaking. Peaking is the occasional use of an alternate energy source to handle loads greater than the primary energy source can supply. Systems with no supplemental fuel requirement may have room for growth in load served particularly if conventional backup systems are available for peaking during larger loads.

TABLE 13. ENERGY SUPPLY PROFILE

Project	Fluid Temperature at Delivery (°F)	Geothermal Design ΔT (°F)	Supplemental Fuel Requirements
Aquafarms	82	N/A	None
Boise City	168	50	None to Peak
Diamond Ring Ranch	150	20	None
Haakon School: Schools	155	20	None
Business District	130	20	Peak
Klamath County YMCA	132	40	None
Klamath Falls	219	43	Peak
Pagosa Springs	140	25	None
St. Mary's Hospital	105	25	Steady
Susanville	170	35	Peak
THS Hospital	150	45	None
Utah Roses	123	31	Peak to Steady

4.2.4 Water Quality Considerations

Provisions to mitigate potential problems resulting from water quality are important because of corrosion and scaling caused by many geothermal fluids. Specifications related to water quality include fluid treatment, material constraints, and monitoring and testing plans.

Most of the project's systems were designed to retain the geothermal fluid in a closed system until after heat extraction and delivery to the discharge point. Generally, no water treatment was needed. Navarro College designed their aquaculture system to include an isolation heat exchanger and a closed-loop because of the low-level radioactivity of the geothermal fluid.¹⁸ Fluid treatment at the Haakon School Project posed a greater problem. The U.S. Environmental Protection Agency refused to grant a discharge permit unless most of the Radium 226 in the geothermal fluid was removed. A process using a barium chloride solution was selected to precipitate the radium. The preliminary design for a simple discharge line into the river was modified to include a treatment plant where solid sulfates containing Radium 226 are precipitated and settled in a holding pond. From there, the fluid flows into the river.²²

Although fluid treatment may be avoided by keeping the geothermal fluid in closed systems and by choosing injection instead of surface disposal, constraints on material selection cannot be avoided. Determining appropriate pipeline, valve, and heat exchanger materials, in the projects reviewed, required long-term testing of candidate materials in the specific geothermal fluid. The next best approach was to select the materials based on key chemical constituents in the geothermal fluid using guidelines from a DOE materials project.²³

Poor water quality could require that the pipe be corrosion resistant. The first choice would be PVC (poly vinyl chloride) or other plastic pipe, but this would be limited to projects with fluid temperatures less than 150°F.²⁴ When higher temperatures and pressures are involved,

an epoxy lined asbestos concrete pipe is an economical solution. Such pipe must be carefully inspected for proper joining and bedding during installation. The latter requirement is to avoid brittle beam fractures.

Steel pipes could be used either with a liner material or a heavier wall thickness which would allow for corrosion losses without failure. The pipe material selection depends on the specifics of each individual project. Four pipe materials used at projects reviewed are black iron (Klamath County YMCA), filament wound fiberglass (Haakon School and St. Mary's Hospital), PVC (Utah Roses) and epoxy-lined asbestos concrete pipe (Boise and Pagosa Springs).

Plate heat exchangers (PHX), common at projects reviewed, are also made of corrosion resistant material. Of the 11 projects reviewed, 9 use plate heat exchangers, and of those, 8 selected stainless steel as the most desirable material (5 of the projects used 316 stainless steel in particular). No corrosion of the stainless steel plate heat exchangers has been reported.

Not only is the material important in selecting components for the system, but ease of system maintenance must also be included in the provisions for mitigating potential adverse effects due to water quality. For instance, valves and pipes should be accessible and heat exchangers that can be easily dismantled are preferred.

Water quality should be monitored throughout the life of a project. The Haakon School project which had excessive levels of Radium 226, takes samples monthly. Other projects should take samples annually to monitor the presence of certain chemical constituents, especially if surface disposal or human consumption of the geothermal water is part of the system design. Under severe corrosion conditions, coupons of construction materials might be kept in the system for real-life corrosion monitoring.

4.2.5 System Administrative Features

Although many geothermal projects do not sell energy commercially, others do charge each user. District heating projects, in particular, require metering and billing systems. When determining the billing schedule for the geothermal energy, numerous methods may be employed. These include metering systems which assess the user according to the volume of water, or the quantity of heat used. Charges may be based on the size of the building serviced. Metering systems, which are based on the quantity of heat used, require either measurement of the temperature differential at fixed flow rates for each customer or installation of Btu meters in the distribution line to individual users (integrates the product of flow and ΔT). The Btu meter system provides the most accurate billing method, but is more costly than others. For example, at the Pagosa Springs project, it was determined that since the cost of Btu meters was so high (\$300 to \$500 per meter), each user would be assessed for a maximum flow. (The cost of a flow-limiting valve is about \$200.)²⁵ Later, the project decided to use the more practical method of volume of supply water used.

Billing based on total volume of hot supply water used has two advantages. It only requires an integrating flow meter, which is cheaper than a Btu meter since it has no temperature measurements, and it encourages the user to maximize the ΔT at his heat exchanger. As discussed previously, a high user ΔT conserves the geothermal resource and reduces system costs.

Other alternative billing methods include setting uniform rates based on past load demand for the system, or assessing the user according to his previous cost of alternative fuels. Non-metered billing, such as that based on the number of cubic feet or floor area in the building serviced, is a less costly billing method, but is difficult to apply equitably to buildings of dissimilar insulation, materials and design.

4.2.6 Provisions of Growth

The use of geothermal energy is still in the development stages with respect to large-scale applications. As a result, many investors hesitate to launch large district heating projects all at once, but prefer to design small systems which may be expanded at a later date. Such provisions for system growth may take several forms. The most frequently used provision, which allows such flexibility, involves over-sizing the transmission and distribution lines for greater flows. Another provision allows for development of new lines or extensions of the original lines, while a third allows for new service along existing distribution lines.

Boise City has provided for growth by using pipelines which will be able to carry larger loads than those anticipated for servicing the system as initially designed. This project proposes to service from 500 to 1,000 customers with two transmission lines, one carrying 2,000 gpm and the other 3,000 gpm. The first line, however, is sized to carry 4,000 gpm in anticipation of expanding service to more residences.²² Pagosa Springs' system is designed for a flow of 1,800 gpm, although anticipated flow is less than half of that for the initial loads.

Other projects, in providing for expansion of the system, designed their pipeline layout so that additional heat loads could easily be accepted. The Haakon School project initially involved space and water heating for municipal buildings, but eight commercial buildings were connected. Cascading the discharged fluid from the school complex, these customers have replaced ~90% of their energy needs with geothermal energy. Klamath Falls installed 50% of their primary transmission pipeline in concrete conduits which are designed for several pipes, and sized their distribution pipeline to service all the buildings along the route, although the project will only serve 14 public buildings initially.²²

In addition to these provisions for flexibility in system growth, a less obvious provision has been to place extra user-taps in the distribution pipes to facilitate connecting new hook-ups to the pipes.

4.3 Subsystem Specification

When the overall system has been designed, each subsystem must be specified in detail for bidding, construction, and operation. For each subsystem, specific items of equipment, piping, and other material must be chosen. In most cases, off-the-shelf components can be used; in other cases, items must be custom designed and built using standard components. It is beyond the scope of this document to discuss the design considerations that must go into the selection of each component. In fact, the selection of specific components may be left to the construction contractor who will agree to meet the system performance specifications. Nevertheless, a few issues which have been discussed above are worth highlighting.

Component selection is determined primarily by: (1) system pressures; (2) ability to withstand the system temperatures or thermal shock; (3) resistance to scaling and corrosion; and (4) component cost and availability. Additional factors are system administrative features and provisions for system growth as discussed in the preceding section.

Most geothermal direct heating application systems can be divided into five major subsystems:

- o Energy production
- o Fluid transmission
- o Heat exchange/storage
- o Distribution/end-use
- o Disposal.

Each of the five subsystems is discussed in detail below.

4.3.1 Energy Production

The geothermal energy production subsystem consists of the wellhead, the well pump production system, if needed, and a geothermal fluid collection system if more than one geothermal source is used. Design decisions are influenced by the time-dependent fluid production rate(s) and water quality, as reflected by the need for multiple wells and downhole pump(s) to prevent gas separation from the fluid and to provide increased well fluid production. In addition, the energy production design must consider monitoring needs such as well pressure, valves to permit water quality samples to be obtained at the wellhead, plus temperature and flow rate monitoring at the wellhead, and the fluid pressure in the well whether shut in or producing.

Chapter 2 discussed the decision-making process for determining the necessary number of production wells. Production pumps are an important consideration at all stages of the project. Pumps are necessary for non-artesian wells and may also be desirable to increase the discharge rate of some artesian wells. A pump may also be needed to maintain adequate pressures on the fluid in the system to prevent CO₂ or other gases from coming out of solution and causing scaling. There are two types of pumps in general use:

- o Line shaft pumps
- o Submersible pumps.

Table 14 lists examples of production pumps at the projects reviewed. Submersible pumps are advantageous because high speed pumps at deep pump settings (up to 1200 ft.) can be used to increase well production rates above those possible with line shaft pumps. Line shaft pumps are seldom set deeper than 900 ft. and are expensive for deep installation. Another consideration, when selecting production pumps, is their resistance to high temperature and corrosion. In addition, some of the projects reviewed encouraged the use of variable speed drive (VSD) pumps because of their flexibility in response to load changes.²⁴

TABLE 14. TYPE OF PRODUCTION PUMP FOR PROJECTS REVIEWED

<u>Project</u>	<u>Type of Pump on Well</u>
Aquafarms	7.5 and 15 h.p. wellhead centrifugal
El Centro	Submersible
Elko Heat Co.	15 H.P. line shaft (when artesian insufficient)
Klamath Falls	75 h.p. line shaft (one for each well variable speed)
Navarro College	Submersible
Pagosa Springs	Line shaft as backup
THS Hospital	10 h.p. submersible
Utah State Prison	Line shaft as possible backup
Warm Springs	30 h.p. submersible

The conventional fuel supplementary energy needs, if any, must be specified. The supplementary energy design includes selection of the fuel to be used and estimation of fuel storage requirements. These design decisions are a function of conventional fuel availability, costs, and ease of adaptability in the system configuration envisioned. In addition, designers must consider the location of the supplemental source in the system. Most of the projects involved retrofits of existing facilities where the pre-retrofit energy source was kept for emergency backup or for normal peaking or continuous supplementary heating.

Designing for the integration of geothermal and conventional energy supplies requires deciding the extent to which such systems will be common and separated. If the investor is not tax-exempt, the decision is important, at present, for tax reasons. Heating system components which normally use both conventional fuel and geothermal heated fluid are not eligible for the geothermal energy tax credits. As a result, supplying the supplementary energy at end-use location(s), rather than from a central facility, it would be necessary to maintain two separate systems for distributing the two types of energy. This decision on location of the supplemental source requires economic and technical comparisons between receiving the tax break in return for constructing and maintaining an entire secondary supply system, or using a common system without the geothermal tax credit. For specific applications the tax code and/or a tax lawyer should be consulted.

As discussed above, conventional fuel may supplement the geothermal energy by producing heat continuously or intermittently (e.g., peaking), and may serve as a full-load back-up energy supply system. At the THS Hospital in Marlin, Texas, for instance, the source of energy for the space and water heating systems was originally steam provided by a low-pressure, natural-gas-fired boiler. This boiler system has remained in place both for back-up and for any emergency peaking requirements needed because of particularly severe weather. The geothermal supply, however, is anticipated to cover the hospital's space and water heating needs.²⁵

4.3.2 Fluid Transmission

The transmission line is defined as the piping from the wellhead to the first user, or to the point at which the supply pipe splits into branch lines for distribution to a local area. If an isolation heat exchanger is used, it is usually at the wellhead and part of energy production system. The thermal and economic importance of this simple subsystem is largely a function of the distance between the geothermal resource and end-use(s). Longer transmission lines can be expected to result in greater heat losses from the fluid, and hence decrease system efficiency. These heat losses can be reduced by insulating the pipeline. Pressure losses can also increase with pipeline length, thus requiring additional pumping costs. However, the initial cost of the transmission pipelines is usually the factor which restricts long distance uses.

For the projects reviewed, the length of the transmission line varies from less than 50 ft. to over a mile (See Table 15). In considering pipeline length, designers must decide not only where the heat exchangers should be located with respect to the production well and the end-use, but also the topographic and right-of-way factors that may affect the location of the pipeline. Topographic factors include obstacles such as rivers or changes in elevation, and right-of-way factors refer to regulations which require a permit for laying pipelines across roads, etc. Ease of excavation and surface restoration costs are also important considerations in laying the pipelines.

In addition to the length of the pipeline, other design issues are pipeline size and material. Pipeline capacity increases as a function of the pipe diameter and the fluid velocity in the pipe. The increased fluid velocity results in increased pressure losses due to friction which causes greater pumping costs. Pipe cost increases with pipe diameter. The selection of an appropriate pipe diameter for the project depends on many variables and is best determined by a designer.

TABLE 15. TRANSMISSION LINE CHARACTERISTICS^a

Project	Length (ft)	Diameter (in.)	Material	Insulation	Capacity (gpm)	Above/Below Ground
Boise City	5,280-7,920	N/A ^b	A/C + Epoxy ^c	N/A	4,000	Below
Boise Warm Springs Water District	N/A	N/A	A/C + Epoxy	N/A	3,000	Below
Diamond Ring Ranch	4,000	6		Fiberglass		Above
Haakon School			Filament wound fiberglass epoxy resin		250	Below
Klamath County YMCA	540	5	Black iron	Yes--type unknown		Below
Klamath Falls	4,100	8	Steel	2 in. of foam w/polyurethane wrap		Below
Pagosa Springs			A/C + Epoxy			Below
St. Mary's Hospital	450	N/A	Filament wound fiberglass	1/2 in. PF ^d & PVC jacket	N/A	Below
Susanville	5,000	6-8	A/C + Epoxy	Yes--2 in. foam	2,000	Below
THS Hospital				Yes--type unknown	N/A	Below
Utah Roses	1,312	6	Asbestos cement	Epoxy-lined	300	Below

a. Source: DOE, Geothermal Direct Heat Applications Program Summary Reports.

b. N/A: Not available.

c. A/C + Epoxy: Asbestos concrete pipe with epoxy lining.

d. PF: Polyurethane foam insulation.

Selection of pipeline material requires consideration of the advantages and disadvantages of plastic asbestos-cement, fiberglass reinforced plastic and metal with respect to friction factors, corrosion, fluid temperature and pressure. Metal pipelines have higher friction factors and are less corrosion resistant, but are suitable for higher temperature fluids at greater pressure than pipes constructed from the other materials.

Other pipeline considerations are whether it will be placed above or below ground, the allowances that are needed for thermal expansion and whether or not the pipe will be insulated. The need for insulation is a function of fluid and ambient temperatures, pipeline lengths, and the minimum acceptable temperature at the use point. The type of insulation selected is a function of cost and pipe diameter. Insulation may be necessary only for supply lines and not return lines, but the designer should consider insulation not only as protection from heat loss but also as protection from exterior corrosion. Polyurethane foam loses its effectiveness as an insulation unless it is protected from moisture by a waterproof outer jacket.

4.3.3 Heat Exchange/Storage

Major heat exchanger issues include the need for an exchanger, and if needed, its location in the system, its size, material and type. This discussion focuses on isolation heat exchangers used with the geothermal fluid and a closed-loop, treated water circuit, e.g., water-to-water units, and does not address end-use heat exchangers, such as water-to-air units for space heat.

The prevalence of isolation heat exchangers in geothermal space and water heating systems reflects the numerous advantages of isolating the geothermal fluid as close to the geothermal supply source as possible. The cost of purchasing and maintaining pipes exposed to any corrosion or scaling caused by geothermal fluid can be reduced if the length of pipes exposed is minimized. In retrofit situations, where old systems would have to be entirely replaced, an isolation exchanger and a fresh-water closed loop can

avoid substantial retrofits costs. If the geothermal fluid will result in acceptable corrosion or scaling, no secondary fluid need be used.

There are also non-technical issues associated with heat exchanger decisions. Because of unjustified concerns with a good quality resource, potential users may refuse to participate if geothermal fluids are used directly without a secondary medium. Since geothermal energy is not a common heat source, the public's knowledge of this technology is minimal and occasionally erroneous. Such misconceptions can make marketing of geothermal resources difficult, if the developer does not provide adequate education to the public before such concerns are too well set.

Several design decisions are associated with heat exchangers used for isolation of the geothermal fluid. They may be used individually or in parallel. They may be located downhole, at the wellhead, or along the transmission line, depending on the type of heat exchanger and other system design factors. The major types of heat exchangers used in direct heat systems are flat plate, and shell-and-tube. Shell-and-tube heat exchangers are used in both surface installations and downhole installations in a well.

Table 16 summarizes the advantages of the different types of heat exchangers. Plate heat exchangers (PHX) are the most common type used at geothermal direct heat application projects. They have geothermal and treated secondary water passing between alternate plates, allowing heat transfer with a relatively low temperature differential in a compact unit.

Shell-and-tube heat exchangers have a series of tubes which usually carry geothermal fluid and are surrounded by clean secondary water enclosed in a shell. For corrosive or questionable fluids, however, PHXs are preferred to shell-and-tube exchangers because they are easier to disassemble for cleaning, inspection, and, if needed, replacement of individual plates. When materials other than steel are required, they are more economical. In addition, PHXs are smaller than shell-and-tube exchangers and may also be readily expanded for additional loads by adding plates.

TABLE 16. ADVANTAGES OF DIFFERENT TYPES OF HEAT EXCHANGERS

<u>Heat Exchanger Type</u>	<u>Advantages</u>	<u>Projects Where Used</u>
Plate Heat	Economical Easily expanded Relatively small Lower approach temperature Easily cleaned Efficient Off-the-shelf	Diamond Ring Ranch Haakon School Klamath County YMCA Klamath Falls Pagosa Springs St. Mary's Hospital Susanville THS Hospital
Shell-and-Tube (surface installation)	Off-the-shelf Well-developed technology Good temperature range	Kelley Hot Springs Susanville
Shell-and-Tube (downhole installation)	Fluid disposal unnecessary if well not flowed Economical	Klamath Falls residential

The downhole version of the shell-and-tube heat exchanger is usually a very simple system of pipes or tubes which can be suspended in the well at the production zone. Clean secondary water flows through the tubes, extracting heat from the geothermal fluid. The downhole heat exchanger's major advantage is that provisions do not have to be made for extracting and injecting the geothermal fluid. Problems with scaling are minimal when the fluid is contained in the wellbore. The diameter of the wellbore, the depth, permeability and thickness of the production formation, the casing size, and the length of the heat exchanger are parameters affecting the efficiency of this type of exchanger. Generally, these exchangers are limited by natural convection heat transfer coefficients to low heat rate applications such as one or two family homes per well.

Two other types of heat exchangers are available but not currently in use in direct heat geothermal systems. One is the direct-contact heat exchanger. This system physically mixes the geothermal fluid with the clean secondary fluid, providing one of the most efficient means of heat transfer. The fluids can be separated later because of being immiscible and having different boiling points. This system only works if the secondary fluid has been carefully selected for those chemical and thermal characteristics which will lead to complete separation of the fluids.

The fluidized-bed heat exchanger is a shell-and-tube design which uses a granulated material on the geothermal fluid side of the exchanger. Since the abrasive action of granulated material minimizes scaling, it is particularly advantageous for use with geothermal fluids that can be expected to result in scaling.

Key factors in selection of the type of heat exchanger are the geothermal fluid chemistry and temperature. Experience has shown that plate heat exchangers best serve the needs of direct heat application projects, but PHX performance over the very long-term remains to be evaluated. Experience of over two years has shown no degradation of seals or corrosion of plates. Typically the once through geothermal side of each plate is cleaner than the closed-loop fresh water side (Haakon School, St. Mary's Hospital and Idaho Agriculture Laboratory).

An assessment of the costs and risks associated with each type of heat exchanger is appropriate before the designer proceeds to specifications for the distribution system. Table 17 lists some representative heat exchanger costs. The exchanger cost is not only a function of flow rate, material and type of construction, but is also very sensitive to pressure, approach temperature and the temperature difference between the fluids. Table 17 should be used with discretion since factors not considered in the table may influence costs substantially.

Designers should also consider thermal storage in the system. Some geothermal projects store either the geothermal fluid or the secondary fluid. Those projects which have a storage tank have usually used a central tank for the entire system. At the St. Mary's Hospital, an insulated 4,000 gallon hot water (secondary fluid) storage tank in the well house and heat exchanger building makes domestic water available at peak rates in excess of that which can be supplied by the heat exchanger.²¹ This flexibility in the system is particularly important for institutions such as hospitals. In addition, thermal reserves can provide a system with a more economic alternative to conventional fuel for meeting peaking requirements, and may eliminate the need for maintaining a conventional fuel back-up system. In systems with a large closed-loop secondary circuit, such as a district heating system, the large volume of the secondary fluid in the distribution and return pipelines can provide two hours or more of operation if the geothermal input failed completely.

4.3.4 Distribution/End-Use

Distribution systems can vary from a single loop serving several points in one large building to a complex district heating network with multiple loops each serving tens of buildings. Most district heating projects use parallel service rather than sequential (cascaded).

Once the basic distribution network layout has been developed, the designers must address several specific parameters regarding the equipment involved. As with the transmission pipeline, specification of pipe size is based on current load plus any planned load expansions. Expansion of the

TABLE 17. REPRESENTATIVE HEAT EXCHANGER COST^a

Type/Materials	Working Fluid Flow Rate (gpm)	Cost (\$)
Tube-Shell/Cast I. Shell, Copper Tubes	10	460
	150	7,000
	250	12,000
Tube-Shell/Cast I. Shell, SS Type 304 Spiral Tube	10-15	1,100
	300	7,500
Plate/Type 316 SS	10	2,500
	250	6,000
Simple U-Tube/Steel	10	500

a. Source: I. A. Engen, "Residential Space Heating Cost: Geothermal vs. Conventional Systems," EG&G Idaho, Inc., p. 34.

system can occur with increased load per user; with new hook-ups at intermediate points along the distribution lines; or at points requiring system extension.

A second issue that must be resolved is the number of pumps, their location, and their capacity and discharge head characteristics. These parameters are a function of flow rate requirements, pipe size and friction, and topography where the distribution line is laid.

Physical design elements requiring attention include pipe material, as well as corrosion (both internal and external) and scale prevention measures. In addition, designers must consider the various pipe joining and laying techniques and tapping devices. The valving and connections to customers systems also require design attention. Experience with the several types of pipe have indicated that each can give satisfactory service if an inspector is present during installation, and the contractor is required to perform a high-pressure leak test prior to acceptance of the work.

The design goal for end-use heat exchangers should be to achieve as great a decrease in supply fluid temperature as possible while maximizing the economic return. The type of end-use equipment also determined by the type of direct heat application.

Space and water heating system designers can choose from several kinds of end-use heating equipment, whether the load is new or retrofit. The four types of equipment most often used for space and water heating are:

- o Central, forced air coil systems
- o Baseboard convectors
- o Fan coils--unit heaters and cabinet heaters
- o Radiant wall panels and floor or ceiling pipe.

A central, forced air heating system warms cool air by passing it through a matrix of hot water filled coils. The source of the heat is usually the secondary fluid heated by the geothermal energy. The central forced-air system is particularly advantageous for geothermal projects because of its adaptability in changing the coil assembly in retrofit systems. Hydronic circulation systems distribute hot water to heat-distributing units (radiators, baseboard grids, etc.) from which radiant and convective heat is transferred to the air. Convector units, hot finned tubes which use natural convection of air, are usually mounted as baseboard strips. Thermostatic valves control the hot water flow to the units to regulate the room temperature. Convector heaters transfer less heat per unit area of tube than fan coil units.

Fan coil units are similar to the convector units except, in addition to finned-tubes or plain tubes, a fan blows air across the tube coil so that the higher forced-convection heat transfer rates are obtained. Fan coil units may be in cabinet heaters installed on lower walls, often under windows in places like classrooms. In larger, less formal areas, such as factories, gyms, and commercial garages, large fan coil units are mounted below the ceiling to blow warm air down on relatively large areas.

The third system used for space conditioning is the heat pump. The water-to-air heat pump is convenient because it is available off-the-shelf, it can economically use low temperature fluid, and it may be used for cooling. Water-to-water heat pumps can also be used to boost temperature when the temperature of the geothermal resource is inadequate. In determining which system is most economical and technically preferable, the designers must weigh the system's advantages with respect to equipment costs, ease of installation and general heat transfer efficiency.

Geothermal direct use heating can service numerous end-uses in industrial processing:

- o Preheating for boiler or other process feeds
- o Washing

- o Cooking, blanching, and peeling
- o Evaporating
- o Sterilizing
- o Distilling and separating
- o Drying
- o Refrigerating.²⁴

These tasks are required in food processing, slaughter operations, forest industries, and others. The most common industrial use for lower temperature resources is food processing, which requires temperatures from about 100°F to 250°F (38° to 121°C). Particularly, when relatively high temperature energy is delivered, designers should consider cascading the spent geothermal fluids through lower temperature applications to make more effective use of the thermal resource. The Holly Sugar project planned to use such a design for the processing of sugar beets. The plans specified that if the resource temperature was 370°F (188°C), steam at 366°F (186°C) would provide hot water for cleaning the beet slicers' blades, 350°F (177°C) fluid would provide heated air for pulp drying, and steam at 293°F (145°C) would provide heat for the evaporators. Pulp drying represents approximately 44 percent of the factory's total fuel demand.²¹

The potential for using geothermal fluid in industrial applications is great, but to date, only limited use has been made of geothermal energy. The risks associated with finding a resource for industrial applications are higher than with other applications because they usually require higher temperatures and greater well production rates. Examples of these higher risks are the Holly Sugar, Madison County, and Ore-Ida Foods DOE-supported projects, all of which are abandoned. Table 18 compares expected and actual resource characteristics at the three projects and shows how much greater resource expectations and needs were compared to those at the other projects reviewed. Madison County's well was obstructed by well

TABLE 18. EXPECTED AND ACTUAL RESOURCE CHARACTERISTICS AT INDUSTRIAL AND OTHER PROJECTS

<u>Project</u>	<u>Temperature (°F)</u>		<u>Flow (gpm)</u>	
	<u>Expected</u>	<u>Actual</u>	<u>Expected</u>	<u>Actual</u>
<u>Industrial</u>				
Holly Sugar	350	>303	1,000	3
Madison County	350-450	72	N/A	600-700 with pumping
Ore-Ida	300	380	800	~1
<u>Other</u>				
Klamath Falls		220		
Others	Under 175	Under 180	300-500	N/A
<hr/>				
N/A: Not available.				
<hr/>				

construction problems, but it was the low resource temperature that led investors to halt the project. Both the Ore-Ida Foods and the Holly Sugar projects were suspended because of an inadequate well discharge rate. Both projects encountered adequate bottomhole temperatures but the reservoir rocks did not have adequate water yielding characteristics to permit economic project development. It is interesting to note that, for the 16 non-industrial application projects that drilled production wells, the average well depth is 2,000 feet; whereas, for the three industrial projects, the average is 7,600 feet. Higher temperatures generally require deeper wells which generally have a lower probability of encountering high water yielding reservoirs as the depth increases.

Outside the DOE program, some geothermal direct heat application projects in industry have succeeded, however. Food processing applications include vegetable and fruit dehydration and slaughter operations. Crop drying applications include alfalfa dehydration, grain drying, and barley malting. Forest industry applications include kiln drying of lumber, material drying in plywood mills, and pulp and paper processing.²⁴

A subset of industrial process uses that can effectively utilize low temperature geothermal resources are agricultural and aquacultural applications. These projects are likely to be new loads at sites requiring low cost energy, although some are retrofit applications.

Agricultural uses include:

1. Space and soil heating for greenhouses (soil warming may also be applied outdoors)
2. Space and water heating for environmentally controlled livestock growth
3. Forced air heating for grain drying
4. Biogas generation.

Aquacultural uses include heating freshwater ponds with pipes through the ponds, or the direct use of the geothermal fluid in raceways.

4.3.5 Disposal

The major design issue regarding geothermal fluid disposal is usually whether surface disposal may be used or if injection is required. Factors influencing the decision are fluid composition and regulatory constraints. Then, the distance to candidate disposal sites, and costs will determine the final selection.

Surface disposal is almost always more economical and simpler than injection where there are nearby rivers, ponds, swamps, or marsh land areas. When an existing well can be used for fluid disposal, especially without additional pumping, the added cost would be less severe. In many cases, however, legal constraints by local, state, and federal environmental regulatory bodies, often dictate the means of disposal. Laws and permitting systems based on the composition and temperature of the fluid often forbid or limit surface disposal or limit the subsurface aquifers that are acceptable for injection.

When determining the chemical composition of the geothermal fluid, the total dissolved solids (TDS in ppm or mg/l), selected individual chemical constituent concentrations, and types and activity levels of radioactive constituents should be ascertained. Often the state in which the resource is located has a state-operated analytical laboratory. If it does not, the regulatory agency for the state probably has a list of approved analytical laboratories. Just be sure to use a laboratory with a quality control program which is approved by the regulatory agency to which the permitting application is being made.

Fluid with a TDS below 2000 mg/l appears to be more likely to be acceptable for surface disposal. However, no matter how low the TDS, the EPA requires determination of the following constituents: arsenic, barium,

cadmium, chromium, lead, mercury, nitrate as (N), selenium, silver, and fluoride. An excess of just one of these elements will prevent surface disposal.

Initially, radiation levels are most conveniently checked by determining the combined radium-226 and radium-228 activity, and by determining the gross alpha activity. If both of these activity levels are low enough, then more expensive analysis will not be required.

For disposal into bodies of water, the project may be able to take advantage of dilution effects to meet the disposal concentration criteria. In rivers, the minimum ratio of geothermal flow to river flow will be the critical point of minimum dilution (usually occurs in the winter).

Other issues which should be considered are those mentioned in the discussion on transmission pipelines: pipeline size, material, and layout design. Surface mounted pumps may be required for injection or to provide the pressure to force the fluid to distant surface disposal site(s).

Table 19 lists the various disposal systems used at the projects reviewed.

When the final design and related cost estimates have been completed and found to be economically acceptable, the project can proceed with the construction stage which is addressed in the next chapter.

TABLE 19. DISPOSAL SYSTEMS AT PROJECTS REVIEWED

Project	Description of Disposal System
Aquafarms	Evaporation, percolation and a drop box drainage system.
Boise City	Discharge into the Boise River from a diffuser.
Diamond Ring Ranch	Discharge into cattle watering reservoir.
Haakon School	Discharge into the Bad River after treatment to remove Radium 226; pipeline is an 8-in. PVC sewer line.
Klamath County YMCA	Injection into a new well 90 ft away.
Klamath Falls	Injection into existing well at county museum.
Pagosa Springs	Discharge into the San Juan River.
St. Mary's Hospital	Dispersed from submerged diffuser into the Missouri River through a 6-in. PVC pipe which 1,100 ft long.
Susanville	Injection into new well, but expect surface disposal approval for 1983-84 heating season.
THS Hospital	Discharge into the city storm sewer system to a storm water basin, and then into the Bean Branch River.
Utah Roses	Discharge into the Jordan River.
Utah State Prison	Discharge into the Jordan River.

5. SYSTEM CONSTRUCTION

Once the final system design has been completed and all environmental and institutional issues have been resolved, the developer can proceed with the system construction phase of the project.

The preceding chapter, System Design, addressed most construction issues, such as material selection and pipeline laying, leaving primarily administrative issues for this chapter. Administrative issues include the contracting procedure (from generating the bid package to contract negotiation), construction management, and marketing efforts. Design modification and maintenance during system operation are discussed at the end of this chapter.

5.1 The Contracting Procedure

The competitive contracting process, from completing the system design to signing a construction contract, generally encompasses the following activities:

1. Generation of the bid package
2. Reproduction and distribution of the package
3. Advertising
4. Responding to enquiries
5. Investigation of contractors
6. Evaluation of bids
7. Negotiation
8. Contract award.

5.1.1 Generation of Bid Packages

Generating bid packages requires adapting system design specifications into a standard package which can be issued to construction companies. Packages should be both detailed, to minimize misunderstandings, and standardized to save contract management time. Several projects split system construction into more than one contract which allowed for cost reductions and more efficient management. The splits depended on the type of specialty contractors available locally. Local contractors were solicited since they were likely to be conscientious knowing they would have "to live with" the system owners and users. Typically, all pipeline trenching and installation work was grouped into one contract to maximize response for that portion of the work. All pipefitting, construction and controls work was grouped in another contract. If the users were from organizations independent from that of the system owner, then the users were responsible for their own retrofit or new, end-use construction. If the system's owner was also the user, the end-use construction might be combined with the system pipefitting, construction and controls contract. Additional reductions in construction costs occurred where the project management team assumed responsibilities such as the purchasing and furnishing of equipment.

5.1.2 Distribution and Advertising

To obtain the least costly system, most administrators rely on competitive bidding. As discussed in Chapter 3, driller selection, pre-construction conferences and seminars on geothermal direct heat applications encourage contractors and lead to more bids. Other advertising methods for drawing bids include those used at the Susanville project: "extensive use of Building Exchanges... and the Daily Pacific Builder (a California contractor's daily newspaper), plus normal advertising in local newspapers and information dissemination to major pipeline, pump, heat exchanger manufacturers and to the construction industry..." Susanville project administrators also reported that contracts under \$400,000 failed to attract significant response and therefore limited competition.²⁶

5.1.3 Selection and Negotiation

After the call for bids has been made, a designated response period allows potential contractors to obtain responses to enquiries concerning system specifications and to prepare and submit their bids. The project administrators then evaluate the bids received and thoroughly investigate the potential contractors. Selection of the contractor depends not only on the amount of the bid, but also on his reputation, reliability, and previous experience with related heating applications. The selection criteria should be clearly stated in the bid package. Contract negotiation can lower bids, as at the Haakon School project where the bid was reduced by negotiation from \$490,700 to \$436,700. When bids are significantly higher than budgeted, however, design modifications may be necessary.

5.2 Construction Management

Project management in the pre-operational stage involves not only negotiation of contracts, but also scheduling and coordination of activities.

Scheduling and management follow-up are important aspects of project management, which can determine the economic success or failure of the venture. Many projects faced delays in the earlier activities, especially in the permitting process, but had little trouble keeping on schedule during system design and construction. It was these early delays, however, that postponed the more expensive project activities and resulted in some significant cost overruns caused by inflation during intervening period.

In order to minimize schedule slippages, project administrators are responsible for professionally coordinating and supervising the project activities. Because the project team can include representatives from many different companies, Table 20, coordination can be particularly challenging. The Susanville project found that by setting up a Construction Management Team, problems were more readily defined and

TABLE 20. PROJECT TEAMS AT PROJECTS REVIEWED

Aquafarms	Aquafarms International Inc. (AII) Meidav Associates (geothermal consultant) Kreiger Inc. (accounting)
Diamond Ring Ranch	South Dakota School of Mines and Technology RE/SPEC, Inc. (design and construction supervision) Gerlack and Egert Plumbing and Heating (construction) Gene Armstrong, Diamond Ring Ranch (owner)
Haakon School	Haakon School District 27-1 Hengel, Berg and Associates (architects--engineers) Mintech, Inc. (corrosion tests) Francis-Meador-Gellhaus, Co. (well design) Wolff's Plumbing and Heating (construction) WYO-DAK Plumbing and Heating (construction)
Klamath County YMCA	Klamath County YMCA James K. Balzhiser (engineering) E. E. Storey and Son (drilling contractor) Patterson Plumbing (retrofit contractor) East Side Electric (electrical contractor) Valley Pump (pump supplier) Nelson Drive (pump components) Alan M. Lee (legal) OIT Geothermal Heat; Lawrence Berkeley Laboratories (well testing) OIT Department of Natural Sciences (environmental reporting)
Klamath Falls	City of Klamath Falls Balzhiser/Hubbard and Associates (design engineers) LLC Geothermal Consultants (conceptual design and master planning) GeothermEx, Inc. (reservoir engineering) Lawrence Berkeley Laboratory (reservoir engineering) Bruun and Sorensen (engineering and pipeline design) Eliot Allen and Associates (land use planning)
Pagosa Springs	Town of Pagosa Springs Archuleta County School District #50-Joint Coury and Associates, Inc. (overall engineering) Hydrosciences, Inc. (hydrological test and analysis) Chaffee Geothermal, Ltd (geology) Hydro-Triad Ltd. (piping design) Roseberry Plumbing and Heating (construction)

TABLE 20. (continued)

St. Mary's Hospital	Hospital Management and Maintenance Personnel Kirkham, Michael and Associates (engineers) Sherwin Artus (reservoir consultant) Dr. J. P. Fries (geologist) Kinning and Reil, Inc. (construction) Mintech, Inc. (Radium-226 removal consultants)
Susanville	City of Susanville Lahontan, Inc. (construction management/technical assistance) Koepf and Lange, Inc. (engineering) Aeroproject Energy Conversion Company (design and engineering review) GeothermEx, Inc. (resource assessment/geologists) Energy Technology Engineering Center (engineering review)
THS Hospital	THS Memorial Hospital Radian Corporation (geothermal consulting engineers) Spencer Associates (architects) Ham-Mer Consulting Engineers (HVAC consulting engineers) Layne Texas Company (drilling and completion) Lockridge-Priest, Inc. (constructors) City of Marlin (surface disposal) Marlin Chamber of Commerce (community coordination) J. Welch (legal) W. M. Parish and Co. (accounting)
Utah Roses	Utah Roses, Inc. Energy Services, Inc.

decisions were made and executed quickly. In any case, a central administrator should be accessible to the contractors and subcontractors for project development to proceed smoothly.

5.3 Marketing Geothermal Energy

Marketing the geothermal energy involves three steps:

1. Assessing the market characteristics
2. Disseminating information to the community
3. Obtaining a firm commitment from prospective customers.

Each of these steps is discussed below.

5.3.1 Assessing Market Characteristics

The major factors controlling the viability of marketing geothermal energy are: the resource characteristics, the potential application's development and retrofit costs, competing alternative energy costs, and institutional and environmental considerations. As discussed in Chapter 4, the resource characteristics (discharge rate-pumping relationship, wellhead temperature, and water quality) must be such that potential applications are economically viable. Institutional and environmental (disposal) considerations might prevent the development of the geothermal resource or increase development costs beyond the limit of economic feasibility. Another consideration with respect to potential applications is regional land use (e.g., industry, lumber, agriculture). Comparison of the cost of geothermal energy with the cost of alternative or existing energy supplies will show whether the geothermal energy is competitive. The price of the geothermal energy must be low enough for the user to amortize his retrofit costs in an attractively short time with the savings obtained by displacing the conventional energy source. The availability and cost of retrofit funds can significantly influence the rate of market penetration.

5.3.2 Community Acceptance

Community acceptance plays an important role early in the project and can determine project success in the long run. Because of the novelty of geothermal energy in many areas of the U.S., sociological issues can hamper the development of geothermal markets. Public hearings and public presentations to civic organizations are two methods employed at the projects reviewed in order to promote community acceptance and to minimize erroneous information. Experience at the Pagosa Springs project led the project participants to advise avoiding interviews with media reporters, and instead to designate a public relations person to submit written news releases to the media.²⁴ Generally, this may be impractical.

The problems at Klamath Falls, Oregon, present another facet of project community relations. Some of Klamath Falls' existing geothermal users, feeling threatened by the new district heating project, sought community support of their opposition to the project. A city ordinance was passed which required that fluid be returned to the well from which it was withdrawn. Somehow, a rumor sprang up that existing wells would be condemned. The project sponsors attempted to counter this opposition by publishing and distributing to existing well owners a newsletter which provided information about ongoing monitoring programs, production testing, and other pertinent reservoir data.²⁴ Meetings were held with well owners, but the project is still being delayed.

The Susanville administrators sought community support of their district heating project from the start. The project gained strong political support. A municipal law was passed stating that the city should utilize geothermal energy, and continuous interaction was maintained between the project developers and the community.

Community relations may also be important for project investors who are not seeking to market geothermal energy, but for whom public attitudes are nevertheless important. Institutions such as schools, hospitals, or prisons must confront the public's uncertainties with regard to direct use of geothermal fluid in public buildings. The THS Hospital project, for

instance, changed their system design from direct to indirect use of the fluid at the request of hospital administrators who expressed concern about geothermal fluid being piped across the hospital roof.

Other relevant issues that involve project/community communication are drilling noise, potential domestic and municipal water supply contamination, and environmental protection. Participants at the projects stress the importance of interaction with the community and government organizations during all stages of geothermal development and into the operational period.

6. SYSTEM OPERATION

System operation concerns the potential investor primarily in the areas of operation, maintenance, and equipment replacement. System operation experience thus far is brief for the projects reviewed, but valuable lessons can be learned from those design modifications which have occurred.

6.1 Design Modifications

As discussed earlier, design modifications occur throughout system construction and into the early stages of system operation. The following modifications at projects reviewed illustrate some possible reasons for such changes:

1. **Aquafarms:** In an effort to reduce the high levels of heat loss from the shrimp-growing ponds, the surface area was cut in half by changing the design of later ponds to longer, deeper, and narrower ponds which retained the geothermal heat better.²⁷
2. **Boise City:** The sequencing of three pumps in the Boise City district heating system was designed to provide a continuous range of flows from 400 to 4000 gpm. The sequencing tests of the 500 gpm, 1500 gpm and 2000 gpm rated pumps showed that butterfly valves would be needed on the discharge lines from the larger pumps to suppress water hammer pressure spikes.
3. **Diamond Ring Ranch:** The Diamond Ring Ranch project had trouble with gas pockets forming at three high spots in the pipeline. To remedy the situation the project engineers installed a degasser at the wellhead. This measure proved insufficient, but they eventually solved the problem by installing simple PVC air vent valves at the first two pipeline high spots. In addition, problems with freezing the fluid in the recirculating loops during winter power outages required the use of anti-freeze.²⁷

4. Elko Heat Company: Despite drinking water standards quality (606 TDS),²⁷ leaks at two or three mild-steel threaded connections enlarged rapidly. The system was shutdown briefly each time to install welded or gasket-sealed couplings.²⁸
5. Haakon School: The stainless steel, high-shear static mixer at the Radium-226 removal plant required excessive maintenance to remove a solid barium sulfate precipitate which adhered to piping immediately after injection of the triggering barium chloride solution. The system was ultimately modified to inject the barium chloride solution at the head of an open, baffled trough which empties directly into a settling pond. This minimizes adherence of the precipitate to system hardware while removing the Radium-226 from the fluid.²⁷
6. Pagosa Springs: A smaller pump was added to the original set of sequencing pumps for the recirculating loop. The system can now meet low-flow loads at reduced pump electrical costs.
7. St. Mary's Hospital: The 120 ft of 6 in. diameter pipe from the wellhead pressure reducing valve to the heat exchangers was specified as polyvinyl chloride (PVC) when the construction specification was reviewed; but, somehow, steel pipe was installed. Within a year, the system was shut down to replace the corroded steel pipe with fiberglass reinforced plastic (FRP) pipe.^{27,28}
8. Susanville: The Susanville project planned to use an existing water well as an injection well. When tested, it leaked badly because the well casing was not cemented at depth and could not be used. Subsequent permitting problems delayed access to adequate injection sites.
9. Utah Roses: A pressure relief valve was added on the pump discharge to reduce water hammer pressure spikes when the pump was started. The valve discharge drops a small quantity of water back into the well bore during each start of the pump.

As mentioned above, the designs for the THS Hospital and Pagosa Springs projects were modified to include the use of heat exchangers and a secondary fluid.

6.2 System Maintenance

System maintenance is no different from a standard hydronic system for the hardware which the geothermal fluid does not touch. For the geothermal fluid components, it is best to keep the system fully filled (no air in system) to keep the system clean of scale and minimize corrosion. Material selection, discussed above, plays an important role in determining the effort which will be required for system maintenance. Valves, heat exchangers, and the pipes themselves need to be inspected regularly. The Diamond Ring Ranch system, for instance, requires flushing every few months to remove an iron pyrite precipitate. However, when heat exchangers were inspected at Haakon School, and St. Mary's Hospital, the geothermal side was clean and uncorroded. But in each case, some rust film or "slime" had accumulated on the closed-loop treated water side.

Some project specific items follow:

The Haakon School project requires batch mixing of the barium chloride solution at the Radium-226 removal plant. The Radium-226 removal plant is the most maintenance intensive part of the system.²⁷

The St. Mary's Hospital fluid discharge is through perforated pipe laid on the bottom of Missouri River. When shut down for several months to replace of corroded pipe, silt covered the pipe and a scuba diver had to dive down to clear the silt layer off of the pipe before restarting the system.²⁷

7. SUMMARY

This report discusses resource development which includes well drilling, development, and flow testing. These activities are followed by designing and building the geothermal direct use system. Initial start up and operation to complete the system development project.

One of the major lessons from the project experience to date is the importance of contracting capable drillers and consultants for drilling and well flow testing, since well drilling is a major cost component of a geothermal energy supply system. Project experience also reveals the complexity of legal systems and the process of obtaining the required permits for exploiting the geothermal resource.

System design and construction issues which were covered demonstrate the need for well-organized management of the project management team and the system contractors. Projects reviewed showed the variety of designs possible for subsystem specifications. Significant points which emerged include the importance of matching the geothermal resource with potential loads and performing corrosion tests to select system components which resist corrosion and scaling.

The experience reviewed indicates that once a productive well has been completed, system design and construction proceed relatively smoothly. A final point is made regarding the importance of a project maintaining strong community relations to assure project acceptance.

A list of the DOE direct-use geothermal PON projects and related data are given in Appendix B.

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APPENDIX A

INTEROFFICE CORRESPONDENCE

date August 2, 1979
to J. A. Strawn
from W. L. Niemi *W. L. Niemi*
subject PIERRE WATER WELL #1 AQUIFER TEST, JUNE 5-7, 1979 - WLN-32-79

An aquifer test was conducted June 5-7, 1979, by Niemi and Strawn (EG&G Idaho, Inc.) at Pierre water well #1 (St. Mary's Hospital), Pierre, South Dakota. The objectives of the test included:

1. Preliminary estimate of borehole flow characteristics including specific capacity and well losses.
2. Preliminary determination of aquifer boundaries in the immediate vicinity of the well.
3. Preliminary estimation of the artesian flow rate which can be sustained while maintaining a wellhead pressure of 5 psig.
4. Estimate of the transmissivity of the aquifer (Madison Limestone) penetrated.
5. Preliminary determination of the thermal characteristics of the aquifer penetrated.
6. Obtain water samples.

Summary of Results

- 1.. Pierre water well #1 will not sustain an artesian flow rate of 400 gallons per minute (gpm) and maintain the wellhead pressure of 5 pounds per square inch gauge (psig) needed to operate the heat exchangers.
2. The wellhead pressure apparently stabilized at 27 psig, while artesian flowing at 375 gpm, after 270 minutes of flow.
3. The specific capacity of the well ranged from 0.887 gpm/psig to 1.144 gpm/psig after 10 minutes of artesian flow at rates ranging

from 420 gpm to 215 gpm and from 0.847 gpm/psig to 0.960 gpm/psig after 60 minutes of flow at the same rates.

4. The Q/s_{10} of the aquifer penetrated (Madison Limestone) does not appear to be dependent on discharge rate. This indicates that draw-downs at different production rates may be predicted at higher degrees of certainty than usually occurring in geothermal wells penetrating aquifers in which groundwater flow is fracture controlled.
5. The well losses in Pierre water well #1 are approximately 20-25 psig, not as great as preceding acidizing.
6. It is recommended that a long-duration artesian flow test, 10 to 14 days, be conducted at Pierre water well #1. The recommended flow rate is 375 gpm.
7. If it is decided that the hospital heating system requires greater than 375 gpm, a pump should be rented and constant rate pulse and production tests conducted at the rates required by the heating system.
8. Water quality samples were analyzed by Drs. Howard and Canda of Mintech Inc., Rapid City, South Dakota. The water does not meet primary drinking water standards in that TDS is too high (Howard and Canda, 1979).

Test Procedure

The Pierre aquifer test consisted of two segments: pulse testing conducted on June 5 and production testing conducted on June 6-7 (see Appendix A for testing hardware and instrumentation). The pulse testing consisted of allowing Pierre water well #1 to artesian flow at various constant rates and recording wellhead temperature and pressure. The well was shut-in after sufficient data were produced and allowed to recover, again recording wellhead temperature and pressure. The recovery portion of each test lasted until the wellhead pressure had stabilized; the time required for recovery was in every case longer than the time of constant artesian flow. Data from the pulse tests are included in Appendix B. Four pulse tests were conducted at rates of 26.5 liters per second (lps) [420 gallons per minute (gpm)], 17.7 lps (280 gpm), 13.6 lps (215 gpm), and 24.0 lps (380 gpm). The 26.5-lps (420-gpm) test did not supply quantitative data as a constant discharge could not be maintained. Pertinent wellhead pressures are listed in Table I. The temperature of discharge water, measured at the wellhead, stabilized at approximately 41 degrees Centigrade ($^{\circ}\text{C}$) [106 degrees Fahrenheit ($^{\circ}\text{F}$)]. Graphs of the wellhead pressure during the pulse tests versus the logarithm of production time are presented in Figure 1.

TABLE I
INITIAL AND SHUT-IN PRESSURE JUNE 5-7, 1979

<u>Discharge Rate</u>	<u>Initial Pressure</u>	<u>Shut-in Pressure</u>	<u>Test Length</u>	<u>Variation in Discharge Rate</u>
420 gpm 26.5 lps	475 psig 3275 kPa	0.2 psig 1.4 kPa	60 min.	15%
280 gpm 17.7 lps	471 psig 3247 kPa	160 psig 1103 kPa	61 min.	7.5%
215 gpm 13.6 lps	473 psig 3261 kPa	249 psig 1717 kPa	60 min.	9.3%
380 gpm 24.0 lps	472 psig 3254 kPa	55 psig 379 kPa	32 min.	4.5%
400 gpm 25.2 lps	^a 436 psig 3006 kPa	1.3 psig 9.0 kPa	219 min.	3.5%
375 gpm 23.7 lps	474 psig 3268 kPa	^b 29 psig 200 kPa	824 min.	4.3%

^a Well was allowed to artesian flow at 40+ gpm for 615 minutes preceding 400 gpm production test.

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

Two production tests were conducted. Artesian flow was maintained constant and wellhead pressure and temperature were monitored. The well was allowed to artesian flow at approximately 2.52 lps (=40 gpm) for 615 minutes preceding the production testing to minimize fluid density effects. The well was then flowed at 25.2 lps (400 gpm) during the initial production test. The test was shut-in after 219 minutes due to failure to maintain the desired 5 psig (34 kPa) wellhead pressure. The valve used to control discharge was fully open prior to shutting-in the well. A water sample was collected after 30 minutes of production. The second production test was conducted at 23.7 lps/ (375 gpm). The well was allowed to flow for 824 minutes. A water sample was collected immediately preceding shut-in. Recovery data were collected for 25 minutes following shut-in, at which time the wellhead pressure was 447 psig (3082 kPa).

The initial and shut-in wellhead pressures for the production tests are listed in Table I. Production test data are included in Appendix C. Graphs of the wellhead pressure during the production tests versus the logarithm of production time are presented in Figure 2. The wellhead temperature of discharge water stabilized at 41.1°C (106°F) during the production tests.

Data Evaluation

Aquifer Inhomogeneities: The wellhead pressure during the 23.7-lps (375-gpm) production test appeared to have stabilized (Figure 2) after 270 minutes of production. Stabilization of pressure decline in an intergranular porous material is indicative of an aquifer inhomogeneity having constant hydraulic potential, a recharge boundary. If a recharge boundary does occur, the well may be able to supply 23.7 lps (375 gpm) and maintain the required wellhead pressure for the life of the project. The facts that quartzite, the basement rock, was penetrated beneath the Madison Limestone and the formation thins to a zero thickness line "in the western Great Plains areas" (Peterson, 1978, p. 3) suggests the possibility of the well's cone of influence reaching a barrier boundary, an aquifer inhomogeneity having a zero hydraulic conductivity. A barrier boundary would decrease the artesian capabilities of the well. The recovery data, graphically analyzed by two methods, Figures 3, 4, and 5, did not indicate the presence of a recharge or barrier boundary. A 10-to-14 day constant rate aquifer test should be conducted to confirm the presence of a boundary. The well should be produced by artesian flow at a rate of 23.7 lps (375 gpm). A longer-duration production would increase the probability of accurately predicting the artesian capabilities of the well.

Aquifer Coefficients: A linear regression was used to find the drawdown occurring per log cycle of production time (s_{10}) in Table II. The 25.2 lps (400 gpm) production test was analyzed as a 22.7 lps (360 gpm) test due to the approximate 2.52 lps ($\approx$ 40 gpm) pretest discharged to minimize density effects.

The s_{10} value has been used in conjunction with the modified nonequilibrium method in the calculation of aquifer transmissivity (T). Transmissivity calculations may be inappropriate in many geothermal aquifer tests (Allman et al., 1979), resulting in the use of Q/s_{10} (discharge rate divided by drawdown per log cycle of production time). The principal reasons for calculating Q/s_{10} are fracture-controlled groundwater flow within the aquifer, an unknown thickness of the aquifer penetrated, and the possibility that a boundary may occur before the test discharge rate could be maintained constant. The Q/s_{10} for the test ranged from 9.27 gpm/psig/log cycle (0.086 lps/kPa/log cycle) to 20.2 gpm/psig/log cycle (0.185 lps/kPa/log cycle) with a logarithmic mean of 11.73 gpm/psig/log cycle (0.107 lps/kPa/log cycle). The Q/s_{10} values

TABLE II

Q^a	$(r^2)^b$	s_{10}^c	t^d	Q/s_{10}
280 gpm 17.7 lps	0.9587	29.8 psig/log cycle 205 kPa/log cycle	1-60 min.	9.40 gpm/psig/log cycle 0.086 lps/kPa/log cycle
215 gpm 13.6 lps	0.9806	21.3 psig/log cycle 147 kPa/log cycle	1-60 min.	10.1 gpm/psig/log cycle 0.092 lps/kPa/log cycle
380 gpm 24.0 lps	0.9587	41.0 psig/log cycle 283 kPa/log cycle	1-32 min.	9.27 gpm/psig/log cycle 0.085 lps/kPa/log cycle
360 gpm 22.7 lps	0.9627	17.8 psig/log cycle 123 kPa/log cycle	5.5-219 min.	20.2 gpm/psig/log cycle 0.185 lps/kPa/log cycle
375 gpm 23.7 lps	0.9618	30.0 psig/log cycle 207 kPa/log cycle	1.3-90 min.	12.5 gpm/psig/log cycle 0.114 lps/kPa/log cycle

^aDischarge rate.

^bCoefficient of determination.

^cDrawdown per log cycle.

^dData used in regression analysis.

calculated from the various tests are presented in Table II. The high Q/s_{10} calculated from the 22.7 lps (360 gpm) data may be anomalous due to the pretest flow.

The recovery data from the pulse tests (Figure 3) and the production tests (Figure 4), when analyzed by use of the Theis ratio method, do not yield a readily apparent linear portion, which is required for quantitative analysis. The data does indicate that well losses are slight and that acidizing of the well increased its efficiency.

The calculated recoveries are graphed versus the logarithm of time since shut-in (Figure 5). The 25.2-lps (400-gpm) production test and the 26.5-lps (420-gpm) pulse test were not used in the analysis because the discharge rates were not maintained constant and these rates overstressed the artesian capabilities of the well. The 23.7-lps (375-gpm) production test data graph in the same region as the 24.0-lps (380-gpm) pulse test and are omitted for clarity. A s_{10} and Q/s_{10} were derived from the linear regressions of the calculated recovery (Table III).

TABLE III

Q	s_{10}	t'	r^2	Q/s_{10}
280 gpm 17.7 lps	29.4 psig/log cycle 203 kPa/log cycle	1-99 min	0.9695	9.51 gpm/psig/log cycle 8.72×10^{-2} lps/kPa/log cycle
215 gpm 13.6 lps	19.9 psig/log cycle 137 kPa/log cycle	2-60 min	0.9889	10.8 gpm/psig/log cycle 9.91×10^{-2} lps/kPa/log cycle
380 gpm 24.0 lps	44.1 psig/log cycle 304 kPa/log cycle	3-16 min	0.9924	8.62 gpm/psig/log cycle 7.89×10^{-2} lps/kPa/log cycle
375 gpm 23.7 lps	37.5 psig/log cycle 259 kPa/log cycle	3-25 min	0.9747	9.99 gpm/psig/log cycle 9.17×10^{-2} lps/kPa/log cycle

Q = discharge rate
 s_{10} = drawdown per log cycle
 t' = time since shut-in
 r^2 = coefficient of determination
 Q/s_{10} = discharge rate divided by drawdown per log cycle

Comparison of Tables II and III show a close resemblance between Q/s_{10} values for the various tests. The differences are most likely related to density effects. The close similarity between drawdown and recovery Q/s_{10} values indicates that no boundaries occurred in the portion of the aquifer affected by producing the well.

The calculated Q/s_{10} values were graphed versus Q (Figure 6) to determine if Q/s_{10} was dependent on the discharge rate. The Q/s_{10} values are apparently independent, indicating that the well performed as a theoretically "ideal" well. This indicates that drawdowns occurring at one artesian flow rate may be extrapolated to other artesian flow rates. The validity of extrapolating drawdowns which would occur during pumping from artesian flow data should still be questioned, due to results observed in testing at the Raft River KGRA. No data are available from tests prior to acidizing the well for comparison to determine if the well characteristics have changed.

The specific capacity (Q/s), production rate divided by drawdown, was calculated after 10 and 60 minutes of production. The Q/s values are 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. The logarithmic means were 0.994 gpm/psig and 0.891 gpm/psig for 10 and 60 minutes, respectively (Table IV).

TABLE IV
SPECIFIC CAPACITY OF PIERRE WATER WELL #1

Q (lps)	10 Minutes		60 Minutes	
	s (kPa)	Q/s (lps/kPa)	s (kPa)	Q/s (lps/kPa)
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}

Q (gpm)	10 Minutes		60 Minutes	
	s (psig)	Q/s (gpm/psig)	s (psig)	Q/s (gpm/psig)
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

The specific capacity data is graphed versus discharge rate in Figure 7. The close spacing of data points does not allow a reliable productivity curve to be established.

A transmissivity was not estimated from the specific capacity due to violation of aquifer testing assumptions, as discussed previously. The T estimated from specific capacity is 2.7 times lower than that calculated from the Q/s_{10} . The difference is perhaps related to well losses caused by inefficiencies of the well and/or boundaries occurring before stabilization of discharge rate.

Well Losses: Well losses do not occur during recovery, allowing a comparison of drawdown and calculated recovery to give an estimate of well losses. The drawdown and calculated recovery data of three pulse tests are graphed in Figure 5. Figure 5 indicates the well losses are approximately 138 to 172 kPa (20 to 25 psig). Recovery data show that the well requires a longer length of time to recover than the length of production. This indicates that well losses are slight and that acidizing of the well increased its efficiency.

Water Quality: Water samples obtained during the production tests were analyzed by Drs. Howard and Canda of MinTech, Inc., Rapid City, South Dakota. Table V is their presentation of the data. Howard and Canda's conclusions included:

1. The total dissolved solids (TDS) are too high for primary drinking water standards, and
2. The probability of calcium carbonate scaling is remote, provided the water is not aerated.

TABLE V
 WATER ANALYSIS

Specie	PPM
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	

Conclusions

1. Pierre water well #1 can apparently be artesian flowed at 23.7 lps (375 gpm) and maintain sufficient wellhead pressure to operate the St. Mary's Hospital heating system.

2. The well will not sustain a rate of 25.2 lps (400 gpm) for longer than 120 minutes while maintaining a wellhead pressure of 34 kPa (5 psig).
3. No phenomena apparent in the data indicate a hydrologic boundary occurring before 270 minutes, at which time an ideal recharge boundary apparently occurs.
4. A long-duration production test, 10-14 days in length, should be conducted to evaluate Pierre water well #1. The test should be of constant rate, 23.7 lps (375 gpm), with wellhead pressure and temperature being monitored.
5. A longer-duration test would provide information concerning the possibility of obtaining higher temperature water from the well than the maximum 41.1°C (106°F) seen during the test, i.e., will the temperature increase as more water is discharged?
6. It is recommended that a pump test be conducted to determine draw-downs in water level which would occur should rates greater than 23.7 lps (375 gpm) be required from the well.

References

1. Allman, D. W., D. Goldman, and W. L. Niemi, "Evaluation of Testing and Resource Parameters in Geothermal Wells at Raft River and Boise, Idaho," to be presented at the 9th Annual Rocky Mountain Ground-Water Conference, October 1979.
2. Peterson, James A., "Subsurface Geology and Porosity Distribution, Madison Limestone and Underlying Formations, Powder River Basin, Northeastern Wyoming and Southeastern Montana and Adjacent Areas," U. S. Geological Survey Open-File Report 78-783, 1978.

SW

Attachments:
As stated

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S. G. Spencer
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Central File

Time Since Artesian Flow Began (min)

Pierre Water Well #1 Pulse Tests June 5, 1979

Wellhead Pressure (psig)
A-10

Wellhead Pressure (psig)
A-11

Time Since Artesian F. Began (min)

Pierre Water Well #1 Production Test June 6-7, 1979

1. Well was allowed to artesian flow at 40+ gpm for 615 minutes preceding 400-gpm production test.
2. Artesian flow had decreased, allowing wellhead pressure to increase from 27 to 29 psig.

Figure 3. Pierre Water Well #1 Recovery, June 1979 Pulse Tests

Figure 5 Comparison of drawdown and calculated recovery, Pierre Water Well #1, June 5-7, 1979.

Figure 6. Q/s_{10} vs Q , Pierre Water Well #1, June 1979

Note: Poor control of Q was maintained during the 360 gpm production test.

Figure 7. Pierre Water Well #1, Specific Capacity, June 5-7, 1979

- Specific capacity after 10 minutes of production.
- Specific capacity after 60 minutes of production.

APPENDIX A

PIERRE WATER WELL NO. 1 TESTING HARDWARE AND INSTRUMENTATION

Pierre water well #1 was allowed to artesian flow at controlled rates. Water was discharged through a 15.2-centimeter (cm) [6-inch (in)] in diameter, 18-meters (m) [60-feet (ft)] length aluminum irrigation pipe coupled to the 20.3-cm (8-in) wellhead tree. A 15.2-cm (6-in) steel discharge pipe, 9.1 m (30 ft) in length with a 10.2-cm (4-in) beveled orifice at discharge end was coupled to the aluminum pipe. Discharge rate was measured by the height of the water column behind the free discharge orifice. Clear plastic tubing and two 91.4-cm (36-in) measuring sticks, giving a total height of 183 cm (72 in), were used in constructing the manometer. The steel discharge line and the manometer were level and perpendicular, respectively. The discharge rate, as measured by the manometer, was not checked in any other way. A 20.3-cm (8-in) gate valve on the wellhead tree was utilized to adjust the discharge rate. This valve was not considered an optimal method of controlling discharge because of the number of turns required to make a discharge adjustment. The valve performance was considered adequate (see variation in discharge, Table 1). A Heise gauge, 0-1000 psi, with 1-psi increments, was used to monitor wellhead pressure changes. A digital thermometer with a type G thermocouple was used to monitor the temperature of discharged water at the wellhead.

APPENDIX B

Pierre Water Well #1 Pulse Test Data June 5, 1979

t = time in minutes since start of test
t' = time in minutes since shut-in
WHP = wellhead pressure in psig
Temp = temperature of discharged water in °F
man = manometer reading in inches of water
Q = discharge rate in gallons per minute

<u>Time</u>	<u>t</u>	<u>t'</u>	<u>WHP</u>	<u>Temp</u>	<u>Man</u>	<u>Q</u>
1444:30			475			
1445:00	V a l v e O p e n					
1445:10	.17		396			
1445:15	.25		344			
1445:25	.42		308			
1445:30	.5		285			
1445:40	.67		248			
1445:50	.83		220			
1446:00	1		189	70		
1446:10	1.17		125			
1446:20	1.33		110			
1446:30	1.5		99	70		
1446:45	1.75		92			
1447	2		86	71		
1447:15	2.25		83	72		
1447:30	2.5		60	73		
1447:45	2.75		12	73		
1448	3		3.5	73		
1448:30	3.5		2.5	75		
1448:45	3.75		2.5			
1450	5		2.25	75	55	469
1450:30	5.5		2	76		
1451	6		2	76	54	465
1451:30	6.5		2	77		
1452	7		1.8	80	51	453
1452:30	7.5		1.8	83		
1453	8		1.5	84		
1453:30	8.5		1.8	87		
1454	9		1.5	88	50	448
1454:30	9.5		1.5	90		
1455	10		1.5	91	40	444
1457	12		1.5	97	48	440
1459	14		1.0	101	44	420
1502	17		1.2	103	44	420
1505	20		1.0	104	44	420
1508	23		0.8	104	43	415
1510	25		0.8	104		
1513	28		0.8	104		

Time	t	t'	WHP	Temp	Man	Q
1515	30		0.5	104	42.5	413
1518	33		0.5	105		
1521	36		0.5	105	42	411
1525	40		0.5	105	42	411
1529	44		0.5	105	41.5	408
1533	48		0.3	105		
1535	50		0.3	105	41	406
1540	55		0.2	105	41	406
1544:30	59.5		0.2	106		
1545	S h u t - i n					
1545:10	60.17	0.17	0.2			
1545:20	60.33	0.33	90			
1545:30	60.5	0.5	184			
1545:40	60.67	0.67	215	105		
1545:50	60.83	0.83	256	105		
1546	61	1	280			
1546:10	61.17	1.17	300			
1546	61.33	1.33	310			
1546:30	61.5	1.5	322			
1546:40	61.67	1.67	328			
1546:50	61.83	1.83	336			
1547	62	2	344			
1547:15	62.25	2.25	354			
1547:30	62.5	2.5	360			
1547:45	62.75	2.75	365	106		
1548	63	3	373			
1548:15	63.25	3.25	377	106		
1548:30	63.5	3.5	382			
1548:45	63.75	3.75	385			
1549	64	4	389	106		
1549:30	64.5	4.5	396			
1550	65	5	401	106		
1551	66	6	410	106		
1552	67	7	418			
1554	69	9	428	107		

Note: Increasing temperature caused by sun heating discharge pipe.

1555	70	10	432			
1558	72	11	440	108		
1601:15	76.25	16.25	447			
1605	80	20	452	109		
1610	85	25	457	109		
1615	90	30	460	112		
1620	95	35	463			
1625:30	100.5	40.5	465			
1630	105	45	466	110		
1635	110	50	467	112		
1645	120	60	469	113		
1700	130	70	471	111		
1704:45			471			
1705	V a l v e O p e n					
1705:10	0.17		418			
1705:15	0.25		378			
1705:20	0.33		344			
1705:30	0.5		308			

<u>Time</u>	<u>t</u>	<u>t'</u>	<u>WHP</u>	<u>Temp</u>	<u>Man</u>	<u>Q</u>
1705:40	0.67		286			
1705:50	0.83		300			
1706	1					
1706:10	1.17		302			
1706:20	1.33		276			
1706:30	1.5		275			
1706:40	1.67		266			
1706:50	1.83		258			
1707	2		257		21	292
1707:15	2.25		251			
1707:30	2.5		244			
1707:45	2.75		243			
1708	3		243			
1708:15	3.25		241			
1708:30	3.5		240			
1708:45	3.75		236			
1709	4		232		19	278
1709:15	4.25		233			
1709:30	4.5		232	99		
1709:45	4.75		230	99		
1710	5		228	99	19	278
1710:30	5.5		228	99		
1711	6		227	100		
1711:30	6.5					
1712	7		223	99	18	271
1712:30	7.5		223			
1713	8		221		17.5	268
1713:30	8.5		218	98		
1714	9		218			
1716:30	11.5		192	99	20.5	289
1719	14		186	101		
1722	17		182	102	19.5	282
1725	20		182	104	19.5	282
1728	23		179	104		
1731	26		178	105	19.5	282
1735	30		177	105	19	278
1738	33		176	105	19	278
1742	37		176			
1745	40		177		19	278
1750	45		175	105	19	278
1755	50		174		19	278
1800	55		162	105	20.25	287
1804:30	59.5		160	105		
1805:30	60.5		160	105		
1806	S h u t - i n					
1806:05	61.08	0.08	240			
1806:10	61.17	0.17	265			
1806:15	61.25	0.25	270			
1806:20	61.33	0.33	308			
1806:25	61.42	0.42	320			
1806:30	61.5	0.5	328			
1806:35	61.58	0.58	336			
1806:40	61.67	0.67	345			
1806:45	61.75	0.75	350			
1806:50	61.83	0.83	355			

<u>Time</u>	<u>t</u>	<u>t'</u>	<u>WHP</u>	<u>Temp</u>	<u>Man</u>	<u>Q</u>
1807	62	1	362			
1807:10	62.17	1.17	370			
1807:15	62.25	1.25	373			
1807:20	62.33	1.33	376			
1807:30	62.5	1.5	382			
1807:40	62.67	1.67	385			
1807:50	62.83	1.83	390			
1808	63	2	393			
1808:15	63.25	2.25	398			
1808:30	63.5	2.5	402			
1808:45	63.75	2.75	405			
1809	64	3	409			
1809:15	64.25	3.25	413			
1809:30	64.5	3.5	415			
1809:45	64.75	3.75	417			
1810	65	4	419			
1810:15	65.25	4.25	422			
1810:30	65.5	4.5	423			
1810:45	65.75	4.75	425	105		
1811	66	5	426			
1811:30	66.5	5.5	429			
1812	67	6	431			
1812:30	67.5	6.5	434			
1813	68	7	436			
1814	69	8	439			
1815	70	9	442	105		
1816	71	10	445			
1817	72	11	447			
1818	73	12	449			
1820	75	14	452	104		
1822	77	16	454	103		
1825	80	19	457	103		
1830	85	24	461			
1835	90	29	463			
1945	160	99	473	93		
1948:30			473	92		
1949:45			473	92		
2000	V a l v e O p e n					
2000:20	0.33		448			
2000:30	0.5		392			
2000:40	0.67		368			
2000:50	0.83		355			
2001	1		344		12	225
2001:10	1.17		337			
2001:20	1.33		322			
2001:30	1.5		329			
2001:40	1.67		323			
2001:50	1.83		322			
2002	2		321		11.5	220
2002:10	2.17		317			
2002:20	2.33		315			
2002:30	2.5		313			
2002:40	2.67		311			
2002:50	2.83		310			
2003	3		308		11.3	218

<u>Time</u>	<u>t</u>	<u>t'</u>	<u>WHP</u>	<u>Temp</u>	<u>Man</u>	<u>Q</u>
2003:15	3.25		306			
2003:30	3.5		305			
2003:45	3.75		303			
2004	4		302	99		
2004:30	4.5		299			
2005	5		296	99	11	215
2005:30	5.5		295			
2006	6		293	99		
2006:30	6.5		292			
2007	7		290	99	10.5	210
2007:30	7.5		290			
2008	8		288	99		
2008:30	8.5		288			
2009	9		286			
2009:30	9.5		286			
2010	10		285	99	10	205
2013	13		282			
2016	16		279	99	10	205
2020	20		277	101	10	205
2023	23		277	102	9.5	200
2026	26		270	103	9.5	200
2030	30		270	104	9.5	200
2034	34		270	104	11.8	222
2037	37		254	105		
2040	40		253	105	11.5	220
2043	43		251	105	11	215
2046	46		251	105	11	215
2050	50		250	105		
2054	54		249	105		
2058	58		250	105		
2059:30	59.5		249			
2100	S h u t - i n					
2100:05	60.08	0.08	300			
2100:10	60.17	0.17	328			
2100:15	60.25	0.25	343			
2100:20	60.33	0.33	352			
2100:30	60.5	0.5	367			
2100:40	60.67	0.67	377			
2100:50	60.83	0.83	386			
2101	61	1	393			
2101:10	61.17	1.17	397			
2101:20	61.33	1.33	403			
2101:30	61.5	1.5	406			
2101:40	61.67	1.67	410			
2101:50	61.83	1.83	413			
2102	62	2	416			
2102:10	62.17	2.17	418			
2102:20	62.33	2.33	420			
2102:30	62.5	2.5	424			
2102:50	62.83	2.83	426			
2103	63	3	427			
2103:15	63.25	3.25	429	103		
2103:30	63.5	3.5	432			
2103:45			433			
2104	64	4	435			

<u>Time</u>	<u>t</u>	<u>t'</u>	<u>WHP</u>	<u>Temp</u>	<u>Man</u>	<u>Q</u>
2104:15			436			
2104:30			437			
2104:45			438			
2105	65	5	440	101		
2105:15			440			
2105:30			441			
2105:45			442			
2106	66	6	443	101		
2107	67	7	446	100		
2108	68	8	449	100		
2109	69	9	451	99		
2110	70	10	453	99		
2111	71	11	454	99		
2112	72	12	456	99		
2113	73	13	457	98		
2114	74	14	458	98		
2116	76	16	459	96		
2118	78	18	460	95		
2120	80	20	462			
2125	85	25	465	93		
2131	91	31	469	92		
2140	100	40	469	90		
2150	110	50	471	88		
2200	120	60	472	86		
2206:30	126.5	66.5	472			
2207	V a l v e O p e n					
2207:10	0.17		364	100		
2207:20	0.33		240	101		
2207:30	0.5		180			
2207:40	0.67		160			
2207:50	0.83		180	101		
2208	1		178			
2208:10	1.17		174			
2208:20	1.33		168	101		
2208:30	1.5		168			
2208:40	1.67		164			
2208:50	1.83		160			
2209	2		156			
2209:15	2.15		152	101		
2209:30	2.5		152			
2209:45	2.75		150			
2210	3		132	101	36	380
2210:15	3.25		113			
2210:30	3.5		121			
2210:45	3.75		122			
2211	4		122	102		
2211:15	4.25		122	102		
2211:30	4.5		122			
2211:45	4.75		122		34	369
2212	5		122		33	363
2212:30	5.5		122			
2213	6		106			
2213:30	6.5		104	101	34	369
2214	7		92			
2214:30	7.5		88		37.5	388

<u>Time</u>	<u>t</u>	<u>t'</u>	<u>WHP</u>	<u>Temp</u>	<u>Man</u>	<u>Q</u>
2215	8		87	101	36	380
2215:30	8.5		85			
2216	9		82	102		
2217	10		76	102	38	390
2220	13		73	104	36.2	382
2223	16		58	105	37	385
2226	19		57	106	36	380
2230	23		56	106	36	380
2235	28		56	106	35	375
2239	32		55	106	35	375
2240	S h u t - i n					
2240:05	33.08	0.08	148			
2240:10	33.17	0.17	188			
2240:20	33.33	0.33	244			
2240:30	33.5	0.5	278			
2240:40	33.67	0.67	302	108		
2241	34	1	324			
2241:10	34.17	1.17	338			
2241:20	34.33	1.33	346			
2241:30	34.5	1.5	354	106		
2241:45	34.75	1.75	363			
2242	35	2	370			
2242:15	35.25	2.25	376	105		
2242:30	35.5	2.5	382			
2242:45	35.75	2.75	387			
2243	36	3	391			
2243:15			396			
2244	37	4	405			
2244:30			412			
2245	38	5	416			
2245:45			421			
2246	39	6	424			
2247	40	7	429			
2248	41	8	432			
2249	42	9	437			
2250	43	10	441			
2252	45	12	446			
2254	47	14	450			
2256	49	16	453			

Note: Less than 2 gpm estimated to be leaking from pipe connection before manometer.

APPENDIX C

Pierre Water Well #1 Production Test Data June 6-7, 1979

t = time in minutes since start of test
t' = time in minutes since shut-in
WHP = wellhead pressure in psig
Temp = temperature of discharged water in °F
man = manometer reading in inches of water
Q = discharge rate in gallons per minute

Note: Temperature probe was malfunctioning between 0915 and 0935 on June 6, 1979, due to an electrical short (water in electrical connection). It is believed that the temperature during this time is approximately 11°F too high.

<u>Time</u>	<u>t</u>	<u>t'</u>	<u>WHP</u>	<u>Temp</u>	<u>Man</u>	<u>Q</u>
<u>June 6, 1979</u>						
845			436	101		
The well was flowed at 40+ gpm between 2300 June 5 to 915 June 6						
915	V a l v e O p e n					
915:10	0.17		40	112		
915:20	0.33		17			
915:30	0.5		8			
915:40	0.67		6			
915:50	0.83		6			
916	1		5.5			
916:10	1.17		5			
916:20	1.33		5			
916:30	1.5		4.8	112		
916:40	1.67		4.8			
916:50	1.83		4.6			
		Q down				
917	2		4.5	113		
917:15	2.25		14			
917:30	2.5		17	113		
917:45	2.75		33			
918	3		48			
918:15	3.25		53	113		
918:30	3.5		54	113		
918:45	3.75		54			
919	4		54	113		
919:30	4.5		55	114		
920	5		56	114		
920:30	5.5		57	114		
921	6		56	115		
921:30	6.5		55			
922	7		55		41	406

<u>Time</u>	<u>t</u>	<u>t'</u>	<u>WHP</u>	<u>Temp</u>	<u>Man</u>	<u>Q</u>
923	8		54			
923:30	8.5		54			
924	9		54	115	40	401
925	10		53	116		
928	13		51	116	39	396
932	17		36		40	401
935	20		36	117	40	401
938	23		36	106		
941	26		35	106	39	396
945	30		30	106	39	396
		Water sample obtained				
949	34		29	106	39	
952	37		24	106		
955	40		24	106	38.8	394
959	44		16		41	406
1003	48		16	106		
1007	52		16	106		
		Q up				
1010	55		11	106		
1015	60		11	106		
1020	65		11	106	39	396
1025	70		11	106	39	396
1030	75		11	106	39	396
1035	80		10.5	106	38.8	394
1040	85		6.3	106	39.2	400
1045	90		6.2	106	39.2	400
1055	100		6	106	39	396
1115	120		6	106	38.0	390
1145	150		3	106	38.5	393
1225	190		1.5	106	38.5	393
1230	195				38.2	392
		Valve fully open				
1246	211		1.2	106	38.2	392
1253:30	218.5		1.3	106	38.2	392
1254		S h u t - i n				
1254:30	219.5	0.5	126			
1254:40	219.67	0.67	192			
1254:50	219.83	0.83	234			
1255	220	1	260			
1255:10	220.17	1.17	280			
1255:20	220.33	1.33	292			
1255:30	220.5	1.5	305			
1255:40	220.67	1.67	314			
1255:50	220.83	1.83	323			
1256	221	2	330			
1256:10	221.17	2.17	337			
1256:20	221.33	2.33	343			
1256:30	221.5	2.5	347	105		
1256:40	221.67	2.67	352			
1256:50	221.83	2.83	356			

<u>Time</u>	<u>t</u>	<u>t'</u>	<u>WHP</u>	<u>Temp</u>	<u>Man</u>	<u>Q</u>
1257	222	3	359			
1257:15	222.25	3.25	365			
1257	222.5	3.5	369			
1257:45	222.75	3.75	374			
1258	223	4	377			
1258:15	223.25	4.25	381			
1258:30	223.5	4.5	384			
1259	224	5	389			
1300	225	6	395.5			
1301	226	7	410			
1302	227	8	412			
1303	228	9	417	100		
1304	229	10	420.5	99		
1305	230	11	424	99		
1307	232	13	429.5	98		
1310	235	16	436	97		
1315	240	21	443.8	96		
1320	245	26	448.5	95		
1325	250	31	452.2	93		
1330	255	36	455.5	91		
1335	260	41	458.5	90		
1729	494	275	474.2	88		
1730	V a l v e O p e n					
1730:10	0.17		388			
1730:20	0.33		240	96		
1730:30	0.5		180	97		
1730:40	0.67		152			
1730:50	0.83		140			
1731	1		136	97		
1731:10	1.17		150			
1731:20	1.33		148			
1731:30	1.5		147			
1731:40	1.67		145			
1731:50	1.83		146			
1732	2		140	97		
1732:15	2.25		142			
1732:30	2.5		137			
1732:45	2.75		135			
1733	3		136	97		
1733:15	3.25				36	380
1733:30	3.5		134			
1733:45	3.75		132			
1734	4		131	98		
1734:15	4.25		132			
1734:30	4.5		129		34	369
1734:45	4.75		128			
1735	5		114	98	36	380
1735:30	5.5		108			
1736	6		106	96		
1736:30	6.5		108			
1737	7		107	97	34	369
1737:30	7.5		99		37	385

<u>Time</u>	<u>t</u>	<u>t'</u>	<u>WHP</u>	<u>Temp</u>	<u>Man</u>	<u>Q</u>
1738	8		84	98		
1738:30	8.5		84		37	385
1739	9		82	98		
1740	10		81	99		
1743	13		77	103	36	380
1746	16		65	104	37	385
1749	19		64	105		
1753	23		62	105	34	369
1756	26		54	106	36	380
1800	30		54	106	35	375
1804	34		53	106	34.5	372
1808	38		47	106	34.8	374
1812	42		47	106	34.5	372
1816	46		47.5	106	34.5	372
1820	50		48	106		
1825	55		46	106	34	369
1831	61		42.5	106	35	375
1835	65		41.5	106	34.5	372
1840	70		41.5	106	34.5	372
1845	75		42	106	33	363
1850	80		37	106	36	380
1855	85		36	106	35	375
1900	90		36	106		
1915	105		36	106	35	375
1930	120		36	106	34	369

Less than 1 gpm estimated to be leaking
from pipe joints before manometer

1945	135				34.5	372
2003	153		30	107	35	375
2020	170		30	106	34.5	372
2032	182		30.5	106	34.5	372
2108	218		30	106	34.5	372
2130	240		30	107	34.5	372
2135	245				35	375
2200	270		27	106	34.8	374
2300	330		26.5	106	34.5	372
2400	390		27	106	34.5	372
0100	450		27	106	34.5	372
0200	510		27	106	34.5	372
0400	630		27	106	34	369
0712	822		29	106	34	369
0714	S h u t - i n					
0714:10	824.17	0.17	172			
0714:20	824.33	0.33	216			
0714:30	824.5	0.5	252			
0714:40	824.67	0.67	272			
0714:50	824.83	0.83	292			
0715	825	1	304	107		
0715:10	825.17	1.17	312			
0715:20	825.33	1.33	322			
0715:30	825.5	1.5	326			
0715:40	825.67	1.67	328			
0715:50	825.83	1.83	338			

<u>Time</u>	<u>t</u>	<u>t'</u>	<u>WHP</u>	<u>Temp</u>	<u>Man</u>	<u>Q</u>
0716	826	2	346	105		
0716:15	826.25	2.25	353			
0716:30	826.5	2.5	358			
0716:45	826.75	2.75	363			
0717	827	3	367			
0717:15	827.25	3.25	371	103		
0717:30	827.5	3.5	376			
0717	827.75	3.75	380			
0718	828	4	383			
0719	829	5	390			
0720	830	6	403			
0721	831	7	408			
0723	833	9	417			
0724	834	10	424			
0729	839	15	433			
0730	840	16	435			
0733	843	19	441			
0735	845	21	442			
0736	846	22	444			
0739	849	25	447			

APPENDIX B

GEOTHERMAL DIRECT USE PON PROJECTS

Contact Number	Final Report		Project Name	Location	DOE Office
	No.	Date			
ET-78-F-07-1727	1	Mar. 79	Douglas High School	Box Elder, South Dakota	ID
DE-FC07-78ET27054	6	Dec. 82	Monroe	Monore, Utah	ID
DE-FC07-78ET27080			Haakon School	Philip, South Dakota	ID
DE-FC07-79ET28419	7	Sep. 83	Diamond Ring Ranch	Haakon County, South Dakota	ID
DE-AC07-78ET28424	6	May 82	Ore-Ida Foods	Ontario, Oregon	ID
DE-FC07-78ET28441			St. Mary's Hospital	Pierre, South Dakota	ID
DE-FC07-79ET27027			Utah State Prison	Draper, Utah	ID
DE-FC07-79ET27028	5	Aug. 82	Madison County	Rexburg, Idaho	ID
DE-AC07-79ET27030			Pagosa Springs	Pagosa Springs, Colorado	ID
DE-AC07-79ET27033			Elko Heat Company	Elko, Nevada	ID
DE-AC07-79ET27053			Boise	Boise, Idaho	ID
DE-AC07-79ET27055	10		Warm Springs State Hospital	W.S.S.H., Montana	ID
DE-AC07-79ET27056	5	Oct. 82	Utah Roses, Inc.	Sandy, Utah	ID
DE-AC03-78ET27154			Klamath Falls	Klamath Falls, Oregon	SAN
DE-AC03-79ET27029			Moana, Reno	Reno, Nevada	SAN
DE-AC03-79ET27029			Susanville	Susanville, California	SAN
DE-AC03-79ET27045			El Centro	El Centro, California	SAN
DE-AC03-79ET27047			Aquafarms	Dos Palmas, Area, California	SAN
DE-AC08-78ET27059	19	May 83	T-H-S Hospital	Marlin, Texas	NV
DE-FC08-79ET27058			Navarro College	Corsicana, Texas	NV

The DOE report number will usually be of the format: DOE/ET/XXXXX-N, where the X's are the last five digits of the contract number (given above) and N is determined by the number of reports issued by the subject contract. Exceptions are: Douglas High School (DOE/ID/O1727-1)