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RESOURCE ASSESSMENT FOR GEOTHERMAL DIRECT USE APPLICATIONS

By
Christine Beer
William F. Hederman, Jr.
Max R. Dolenc
David W. Allman

April 1984

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Christine Beer
William F. Hederman, Jr.

ICF Incorporated
1850 K Street, N.W., Suite 950
Washington, D. C. 20006

Max R. Dolenc
David W. Allman

Edited by
Ben C. Lunis

EG&G Idaho, inc.
Box 1625
Idaho Falls, ID 83415
April, 1984

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Division of Geothermal and Hydropower Technologies
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ABSTRACT

This report discusses the topic "geothermal resource assessment" and its importance to laymen and investors for finding geothermal resources for direct-use applications. These are applications where the heat from lower-temperature geothermal fluids, 120-200°F, are used directly rather than for generating electricity. The temperatures required for various applications are listed and the various types of geothermal resources are described. Sources of existing resource data are indicated, and the types and suitability of tests to develop more data are described. Potential development problems are indicated and guidance is given on how to decrease technical and financial risk and how to use technical consultants effectively. The objectives of this report are to provide: (1) an introduction low-temperature geothermal resource assessment; (2) experience from a series of recent direct-use projects; and (3) references to additional information. Companion reports describe the phases of project development which follow a positive resource assessment (DOE/ET/12099-4) and an economic analysis of a few selected projects (DOE/ET/12099-5).

Experience for this report was obtained primarily from 23 Department of Energy (DOE) sponsored Program Opportunity Notice (PON) projects. The goal of each DOE project was to build and monitor the initial operation of a direct use geothermal system and to make this information available to the general public. About three-quarters of these projects are operating. Most of the projects which were not completed did not locate an adequate resource with the first well drilled.

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1. INTRODUCTION

This report discusses the topic "geothermal resource assessment" and its importance to laymen and investors for finding geothermal resources for direct-use applications. These are applications where the heat from lower-temperature geothermal fluids, 120-200°F, are used directly rather than for generating electricity. The temperatures required for various applications are listed and the various types of geothermal resources are described. Sources of existing resource data are indicated, and the types and suitability of tests to develop more data are described. Potential development problems are indicated and guidance is given on how to decrease technical and financial risk and how to use technical consultants effectively. The objectives of this report are to provide: (1) an introduction low-temperature geothermal resource assessment; (2) experience from a series of recent direct-use projects; and (3) references to additional information. Companion reports describe the phases of project development which follow a positive resource assessment (DOE/ET/12099-4) and an economic analysis of a few selected projects (DOE/ET/12099-5).

This report describes the general procedures for geothermal resource assessment plus a menu of specific activities which may be used. It notes the dependence of the activities upon the specific conditions at each potential resource site. Technical terms are defined and presented so that they can be understood by the layman with little familiarity with geothermal energy. With this in mind, the report tries to keep the relative importance of activities in perspective and presents them in a logical or chronological manner. The need to match the potential resource characteristics with the requirements of prospective applications is noted. The approximate cost of resource assessment techniques and the effects of other factors on project payback are indicated.

Experience for this report was obtained primarily from 23 Department of Energy (DOE) sponsored Program Opportunity Notice (PON) projects. The goal of each DOE project was to build and monitor the initial operation of a direct use geothermal system and to make this information available to the general public. About three-quarters of these projects are operating. Most of the projects which were not completed did not locate an adequate resource with the first well drilled.

This report is not arranged to provide detailed history of each of the PON projects but rather to address the major activities and concerns in the evaluation of a project, such as defining the needs with respect to the process being considered, the legal aspects, permitting and exploration, as well as the various considerations and risks at each point.

Development, which would follow a positive resource assessment, is discussed in more detail in a companion report.[1]

2. BACKGROUND

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 energy resources. Declining domestic production of crude oil and environmental problems limiting the expanded use of other conventional energy resources have also stimulated the search for viable alternatives. One of the most promising of the alternate energy technologies has proved to be the utilization of our nation's geothermal resources.

These geothermal resources represent a vast energy asset that is free of foreign control or interference. If all of the geothermal resources identified in the United States Geological Survey's Circular 790[3] were utilized, the total energy available at the wellhead from resources above 90°C would be equivalent to 450 billion barrels of oil--more than 16 times the known oil reserves of the entire nation.

Unlike development of some alternate energy resources, the use of geothermal energy does not depend on new engineering or scientific advances, but requires only the minor adaptation of existing technology, the environmental consequences of which are relatively benign.

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 directly applied usually require wellhead temperatures between 120-200°F. Heat pumps can also be used with low temperature geothermal resources to augment the low temperature uses. Electric power generation 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).

3. RESOURCE ASSESSMENT OVERVIEW

Assessment of a geothermal resource requires a careful step-by-step procedure in which low cost activities are used in the first steps to eliminate projects that have an unacceptable risk. Confirmation of geothermal reservoirs by drilling is costly, and the risk of drilling an unacceptable well is significant. Therefore, the prospective developer or user should follow an orderly procedure to minimize the risks.

The first step in the process is resource identification. potential direct-heat users cannot, in general, afford to do the regional geologic work or geothermal data compilation that is needed to identify those 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 geological departments. 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 temperatures, and this information can be used in feasibility studies aimed at the prospective application.

The developer should assure himself that there is a reasonable probability that a resource exists in an area where his intended process can be located. He should also assure himself that there is a reasonable probability that the temperature will be adequate for the intended application. Generally speaking, this initial screening can be accomplished by personnel unfamiliar with geothermal utilization using the aforementioned sources of information.

If the project appears feasible, the developer should next acquire the services of a geological consultant for the site specific geological analysis. A qualified consultant can give valuable assistance for preparation or an update of an economic and engineering analysis by

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

providing expert opinion on probable well depth, temperatures and flow rates. The consultant should also prepare a resource development plan, and he can either assist in an environmental assessment or recommend someone else who can help.

The preceding discussion is meant to emphasize the fact that the development of geothermal resources has an inherent risk, but this risk can be reduced if a good job is done in the work that is performed prior to well drilling. Maximum return on investment requires the rejection of all drilling sites which do not appear to be very promising from the compiled predrilling data. Economic, engineering and environmental limitations should be reviewed at each stage of the project to prevent additional investment in an area which cannot be profitably developed.

4. RESOURCE APPLICATIONS

4.1 General

Numerous direct use applications of geothermal fluids exist, with the three primary use categories being;

(1) Commercial and residential space conditioning

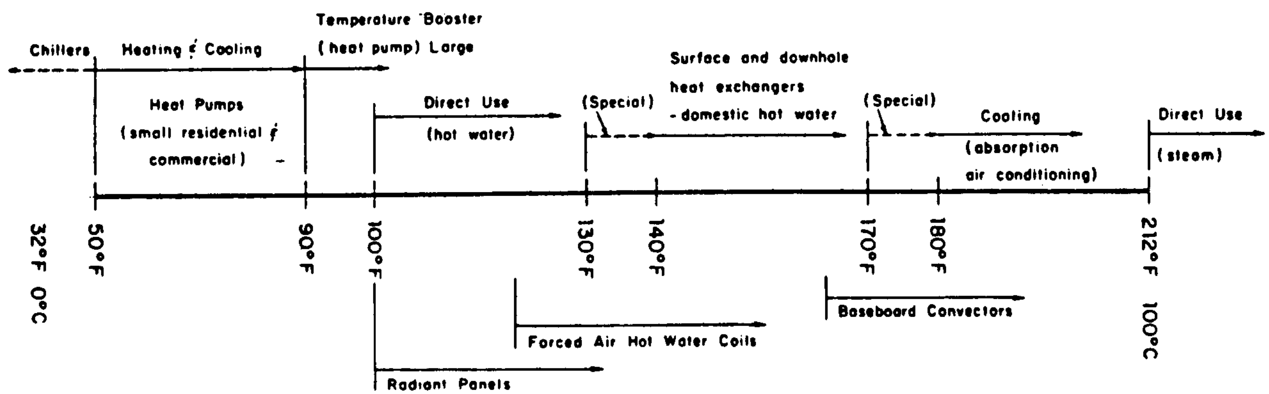
(2) Agricultural and aquaculture

(3) Industrial processing.

This section provides a brief overview of these uses, the applicable geothermal fluid temperature requirements, and comments on PON project activities.

4.2 Commercial Residential Space Conditioning

Geothermal fluids can be used for heating and cooling residential and commercial buildings. Figure 1 compares different types of heating and cooling applications with geothermal fluid temperatures. Cooling of buildings generally require geothermal fluid temperatures above 200°F, but the best economics occur when the refrigeration systems are driven by geothermal steam. Depending upon specific needs and geothermal fluid characteristics, space conditioning can be provided for single or multiple building applications utilizing a variety of systems. Nineteen of the twenty-three PON projects were developed to verify the technical feasibility and economic worth of space and/or hot water heating applications. Several projects have been developed into operating district heating systems in Boise, Idaho; Susanville, California; Philip, South Dakota; Pagosa Springs, Colorado, and Elko, Nevada. A district heating system is under development at Klamath Falls, Oregon under the DOE PON program. In addition, from private development, there are presently more than 500 homes heated geothermally in Klamath Falls, where most of these homes utilize a downhole heat exchanger in a single well to heat a single



Source: Oregon: A Guide to Geothermal Energy Development, op. cit.

Figure 1. Space Heating and Cooling with Geothermal Fluids

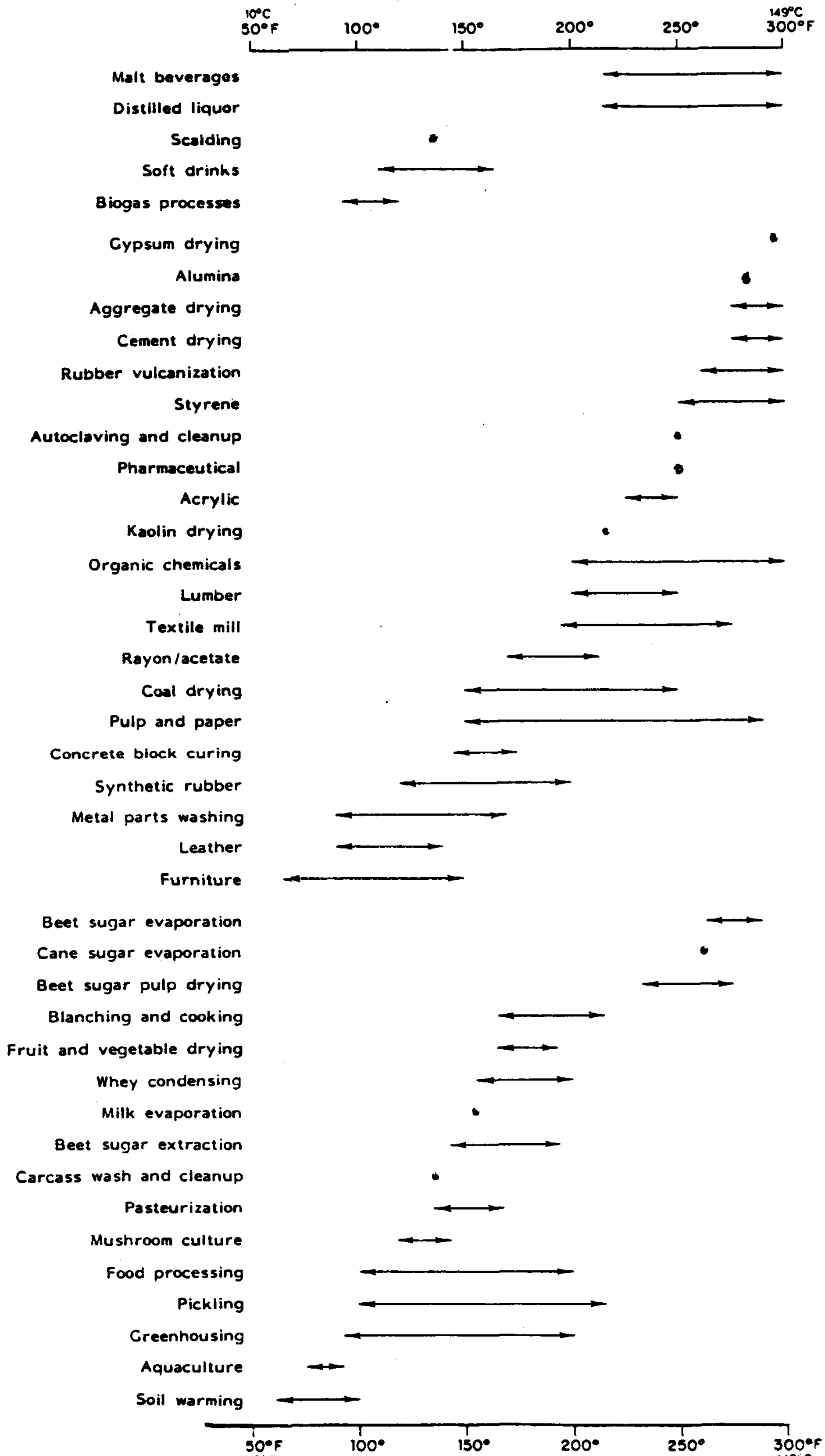
residence. Currently, a typical residential heating system in Klamath Falls uses a 10-in. diameter, 300-ft deep well with two downhole heat exchangers. One is for the space heating system and one is for the domestic hot water system. The heat exchangers are placed in wells with temperatures ranging from 140 to 205°F (60 to 96°C). City water is recirculated in the space heating loop through a heat exchanger in the home's forced-air system, baseboard convectors, or radiant panels.[4]

4.3 Agriculture and Aquaculture Applications

Agricultural and aquacultural uses of geothermal energy for heating include: space heating for greenhouses and animal husbandry, air heating for crop drying, and warm water supplies for fish farming. Industrial applications include food preparation processes, such as pasteurization of milk, beer, and other consumable liquids, as well as dehydration of vegetables; pulp, paper, and wood processing; and heating for kiln drying of lumber. A great potential for use of geothermal fluids exists because there is an abundant supply of geothermal resources that can meet the 80 to 180°F temperature requirements for most of the agriculture/aquaculture uses three PON projects applying to this category were successfully demonstrated: (a) geothermal energy is used to heat a six-acre greenhouse near Salt Lake City, Utah, (b) Diamond Ring Ranch near Midland, South Dakota, utilizes geothermal energy for grain drying and space heating, and (c) Aquafarms International, in the Coachella Valley of California, has exploited a low temperature geothermal resource [86°F (30°C) wellhead temperature] in a successful prawn farming project. Geothermal fluid is used to maintain year-round desired temperatures in 50 acres of ponds.

4.4 Industrial Processing Applications

Industrial processing applications may be more financially attractive than seasonal space heating applications, since they usually operate continuously near peak load and have the potential to generate more revenue than a seasonal system of the same capital cost. However, such applications often require greater resource flow rates and higher temperatures than other direct-heat applications. Temperature requirements for industrial applications range from 60 to 300°F (10 to 150°C). Figure 2 lists a variety of industrial processes and their respective process temperature requirements. Mixed results have been obtained for industrial applications using geothermal fluids as evidenced by the inability to find adequate geothermal resources for the three PON projects (Ore-Ida Foods, Ontario, Oregon; Holly Sugar/TRW, Brawley, California; and Madison County, Rexburg, Idaho) applicable to this category. Other industrial projects have proven to be successful, two of which are the Medo-Bel Creamery (milk pasteurization) in Klamath Falls, Oregon; and Geothermal Food Processors (vegetable dehydration) at Brady Hot Springs, Nevada.



Source: <u>Oregon: A Guide to Geothermal Energy Development</u>, <u>op</u>. <u>cit</u>.

Figure 2. Temperatures Required for Various Direct Geothermal Applications

5. RESOURCE EVALUATIONS

5.1 General

Geothermal resources occur in a variety of geologic environments, and are known to exist through verification and by inference at many locations throughout the United States and the world. Appendix A provides an overview of the different types of resources and their PON project relationship. Figure 3 is provided to give an indication of the magnitude of the geothermal potential in the United States.[5]

Numerous items need to be considered in the development of these geothermal resources, which involve exploration, confirmation, drilling, and testing programs that draws upon the skills of geologists, geochemists, geophysicists, hydrologists, reservoir engineers and others. This section provides information relative to resource evaluations, including flow and water quality risks, resource investigations, resource assessment and exploration, and drilling and testing. Practical applications of these activities are provided through PON project activities, and the experience gained thereby is also included.

5.2 Geothermal Fluid Flow

Geothermal fluid flow, usually measured in gallons per minute (gpm), can be as important a resource requirement as temperature. The rate at which thermal energy can be extracted from a geothermal resource depends not only on the temperature of the fluid, but also on its quantity. (It is proportional to the product of the flow rate and the number of degrees of temperature removed from the fluid.) Insufficient flow, therefore, can make an otherwise economical and desirable geothermal project infeasible.

5.3 Geothermal Fluid Quality

Geothermal fluids contain chemicals or dissolved solids which can greatly affect project economics. Generally the solids content of geothermal fluids increase with temperature but there can be a wide

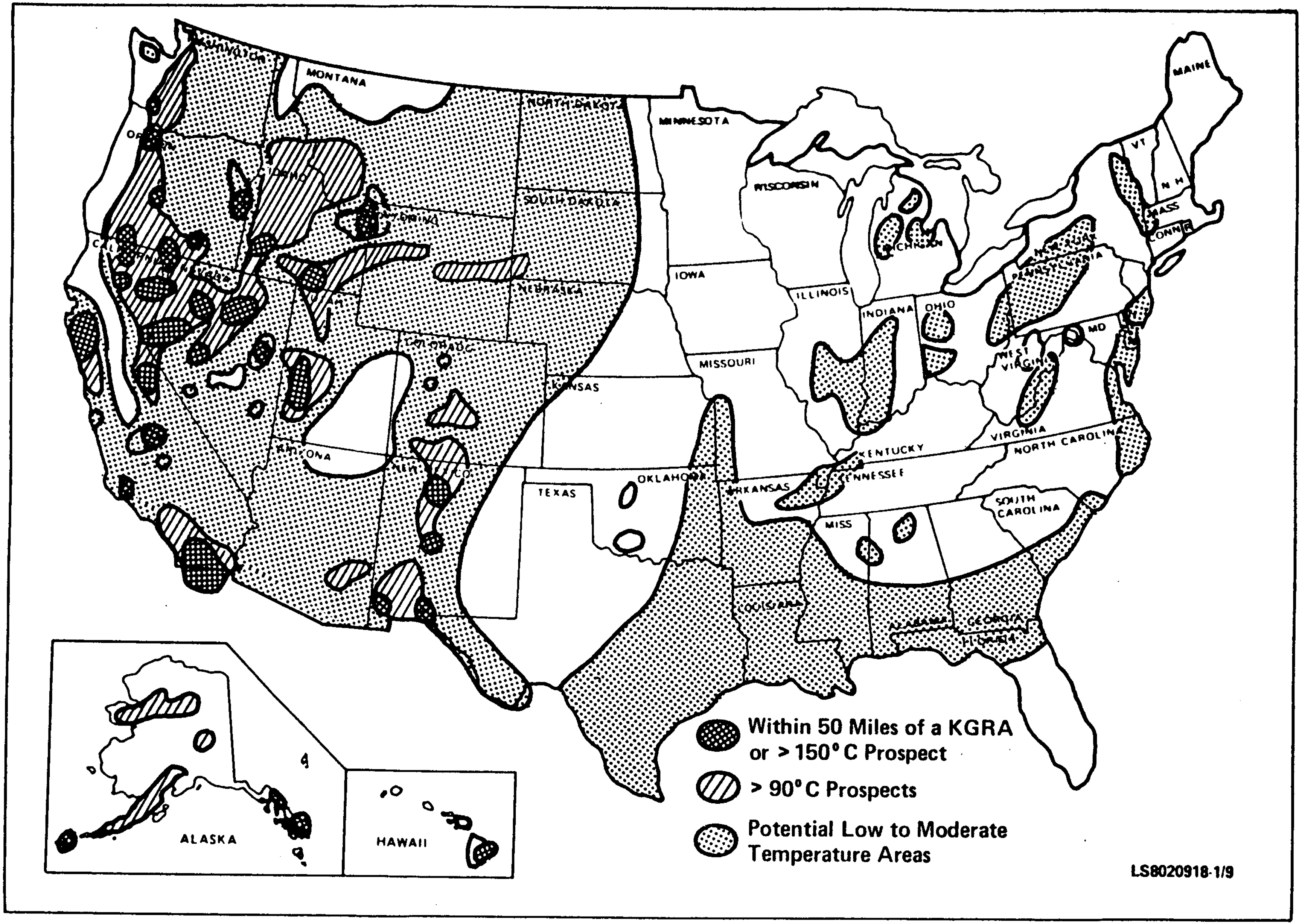


Figure 3. Known and Potential Hydrothermal Resources

variation in solids content at any temperature. A developer should investigate as soon as possible the expected solids content of fluids in an area because of their potential adverse effects. Five considerations are as follows:

1. System design and project economics will be impacted if fluid treatment is required.

2. Water quality may limit fluid disposal alternatives, especially in light of meeting EPA and state environmental standards.

3. Corrosive fluid or fluid that causes scaling influences materials selection and design of the system, as well as project economics.

4. Fluid composition can provide valuable information that usually helps define the ground-water flow system(s) in the vicinity of the geothermal resource.

5. Geothermometry can provide estimates of the maximum possible resource temperature that can be expected.

Techniques for dealing with corrosive and/or scaling geothermal fluids are still being developed. Fluids with the highest temperatures are usually the most desirable for project applications, yet as temperature increases there is typically an increase in total dissolved solids (TDS) and other undesirable constituents and gases. Poor quality water can pose barriers to resource utilization. Table 1 lists some major constituents that are of use in defining the resource and some of the problems these constituents may present. For further information on the significance of individual chemical constituents, the referenced Geothermal Resources Council Special Report Number 7 provides additional data.

The determination of concentrations of particular dissolved species is necessary in the resource assessment process. Significant concentrations of sulfates, chlorides, and other chemical species can result in a highly corrosive fluid for which special and perhaps costly piping systems might

TABLE 1. CHEMICAL CONSTITUENTS IN GEOTHERMAL FLUIDS--EXPLORATION LOSSES AND PROBLEMS

Constituent/Parameter	Uses
H Ion Concentration (pH)	d e
REDOX Potential (Eh)	d
Specific Conductance	b d e
Total Dissolved Solids (TDS)	b d e f
Calcium (Ca^{++})	a b e
Magnesium (Mg^{++})	a b e
Sodium (Na^{+})	a b
Potassium (K^{+})	a b
Chloride (Cl^{-})	b d f
Sulfate (SO_4)	b c f
Bicarbonate (HCO_3)	b d e
Carbonate (CO_3)	b d e
Fluoride (F^{-})	b f
Lithium (Li^{+})	b
Boron (B^{+++})	b f
Arsenic (As^{+})	b c f
Mercury (Hg^{++})	b c
Oxygen 18 (O^{18})	a b
Deuterium (D)	b
Helium (He)	b c
Radon (Rn)	b c
Tritium (H^3)	b
Silica (SiO_2)	a b e

TABLE 1. (continued)

Constituent/Parameter	Uses
Hydrogen sulfide (H_2S)	d f
Carbon dioxide (CO_2)	d
Ammonia (NH_3)	d
Sulfides	e
Oxides	e
Gross α and β Radioactivity	f

a. Geothermometry.

b. Ground-water flow system(s)/mixing.

c. Exploration using soil gases/particulates if constituents exist in the geothermal fluid.

d. Corrosion potential.

e. Scaling potential.

f. Common environmental problems.

be necessary. Similar difficulties arise with the presence of silicates, carbonates, sulfides, and oxides which can cause scaling. Exposing the geothermal fluid to oxygen in the air will increase corrosion activity. Flashing the geothermal fluid may permit dissolved CO_2 and other dissolved gases to come out of solution and cause the precipitation of calcium carbonate or other minerals. Excessive concentrations of boron, arsenic, lead, or radium-226 will cause environmental problems, thus necessitating injection and/or chemical treatment, which will increase system costs. Therefore, in addition to temperature and flow characterization, chemical analysis and corrosion coupon tests with candidate materials of construction are generally required in the development of a new resource.

6. RESOURCE ASSESSMENTS

6.1 General

A logical approach to resource assessment (Figure 4)[7] is provided for the potential developer or investor. With this approach, it is assumed that the developer/investor is aware of a thermal anomaly within a reasonable pipeline distance for application in one or more intended end uses or markets. The major uncertainty at this stage is, "can the potentially available geothermal fluids be employed in an economical manner?" If replacing a current fuel source is the issue, the cost of retrofit and the selling price of the geothermal fluid versus the present and projected cost of the competitive fuel must also be considered. These are general investment decisions typical of most applications associated with energy or fuel requirements.

The potential developer/investor at this stage has the problem of how to assess the thermal anomaly with minimum investment. It is the goal of this section to provide information about the key tasks involved in the decision making process.

6.2 Legal Considerations

One of the first steps in proceeding with an assessment of the resource is to determine the legal definition of geothermal fluids in the state in which the development is to occur. Some states consider geothermal energy as a "mineral resource," others as a "geothermal resource." Another consideration that differs between states is that the temperature of the fluid or the use of the fluid determines the project's legal status. Coupled to these are a number of major constraints that include permitting regulations, tax treatment, and other factors which may affect the project economics.

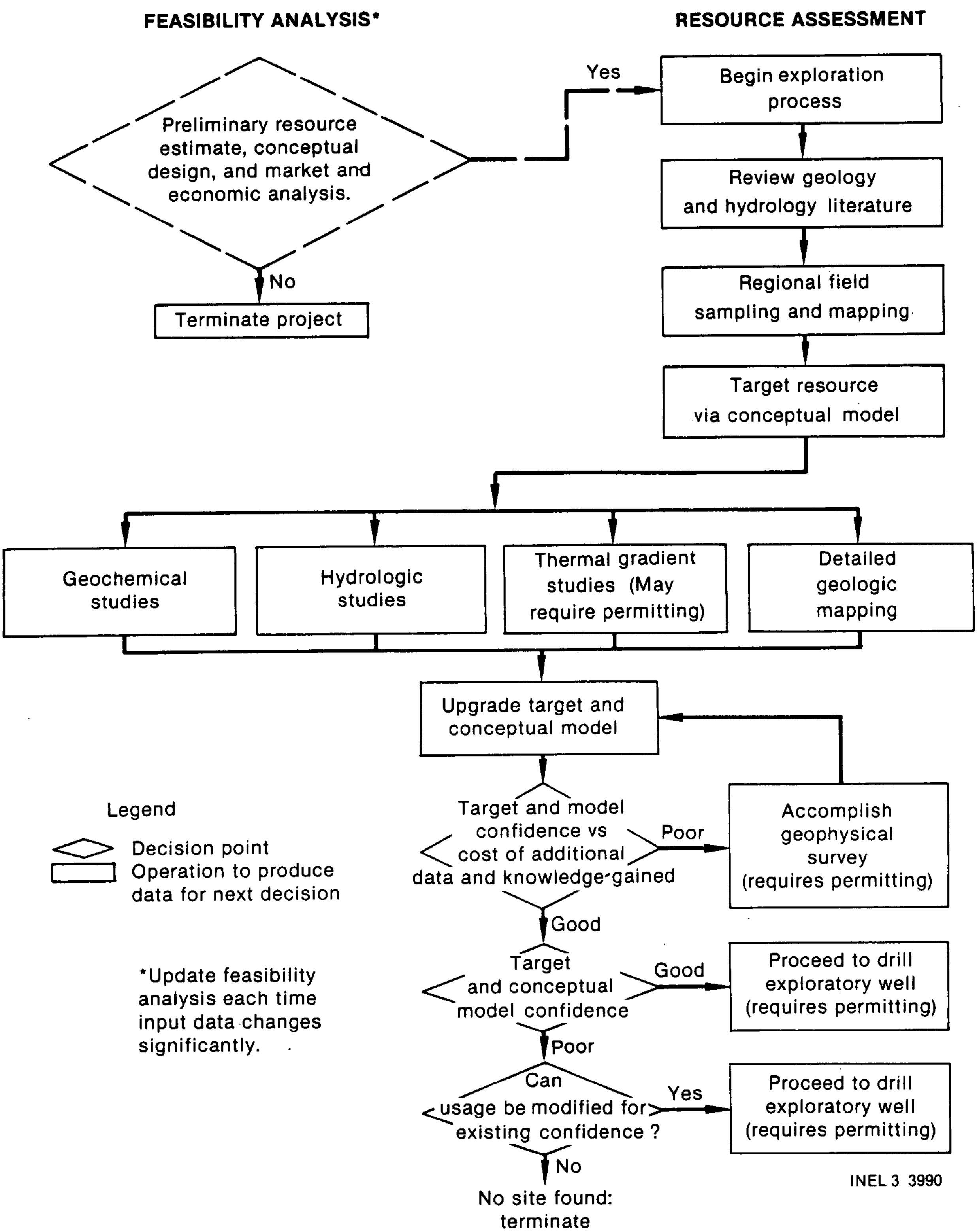


Figure 4. Resource Assessment Decision Tree

The land and resource ownership needs to be established after determining the legal definition of the geothermal resource. Information on land ownership may be obtained from sources such as:

1. Bureau of Land Management (federal lands)

2. State land and water rights offices (state and private lands)

3 Municipal offices (private lands)

4 County offices (private lands).

6.3 Permitting

The procedure for obtaining lease permits varies according to state laws when the land is private or state owned, to federal laws when the land is federally owned, and to other regulations (and the agreement between the owner and the developer) if the land is privately owned. When mineral rights have been severed from the surface ownership, subsurface rights must be obtained in addition to surface rights. If field exploration is conducted before obtaining a lease, it may increase the cost of the lease, especially as resource discovery becomes apparent. If negotiations for the desired leases/rights do not result in an economically satisfactory agreement, the only recourse is to terminate the proposed project at this stage. The exploration process may begin if negotiations are successful.

Requirements for permitting are usually associated with considerations of leasing and land ownership. This activity is a function of the regulatory agency having jurisdiction (i.e., state or federal). State permit requirements vary; therefore, this discussion will center on obtaining federal permits. State agencies should be individually consulted for information pertaining to specific states.[8]

"Casual use activities" during pre-lease exploration require no permits on federal lands. Casual use involves activities that (a) do not appreciably disturb the land, improvements, or other resources, (b) do not require heavy equipment or explosives, and (c) confine vehicles to established roads.[9] If temperature gradient holes (shallower than 500 ft) are drilled, geophysical surveys are conducted, new roads are necessary, or other intensive exploration is carried out, a "Notice of Intent and Permit to Conduct Exploration Operations" must be filed with the Minerals Management Service (MMS) of the Bureau of Land Management.

Beyond the above listed activities allowed on a pre-lease basis, all future activities require permit approval by the MMS. All well drilling, alterations, and abandonment methods, plus a detailed plan of operations, are regulated and require approval. Appropriate state agencies are consulted by MMS to insure compliance with state law on the federal leaseholdings. Assurance of conducting all operations in a prudent manner is implicit in the carrying out of these regulations.

Depending on the specific locality, some counties require "land use" approvals, particularly where affected by strict zoning laws. Similarly, if wells or operations are conducted within city limits, approvals are necessary from city administrators. It is best for the developer to consult appropriate state and federal officials before pursuing development on a given property.

6.4 Preliminary Geotechnical Assessment

The next step in assessing a resource is to develop an exploration target concept. This is best accomplished by a geoscientific consultant(s). (Consultants are discussed in greater detail in Reference 1.) The consultant will initiate the exploration process by means of a literature search to obtain all existing hydrogeologic information on the potential geothermal site. Before contracting with geologists, geophysicists, and geochemists, the developer/investor may decide to search federal, state, county, and municipal records, and if available, local driller's logs for technical information and advice. (Drillers logs are often on file with the state.)

The purpose of this early exploration stage literature search is to aid in reducing the time and financial investment of the developer.

Desired information would pertain to the location and distribution of thermal and mineral springs, warm water wells, faults, and chemical analyses of thermal and nonthermal waters. The consultant may use a regional field sampling and mapping program to obtain such information if it is not available.

6.5 Conceptual Model Development

The consultant will hopefully be able to formulate a conceptual model of the resource from the accumulated data base that will provide a general indication of target depths, temperatures, and fluid composition. This is a decision point as to whether to proceed, terminate the project, or pursue a more detailed exploration program. It is also a major technical data input point which should be used to reassess the project economics.

6.6 Exploration

Given favorable conditions, especially with regard to resource temperature, depth, and potential well yields, geothermal exploration can begin. Table 2 lists the general applicability of exploration/assessment techniques to two geographical regions.[10] There are three basic exploration techniques--geographical, geophysical, and geochemical--each of which will be discussed below with emphasis on procedural methods and technical importance. Table 3 lists approximate cost figures for exploration activities.

Geologic site evaluation and aerial reconnaissance aid in determining the possible size and nature of a hydrothermal system. Often much of the geologic exploration process can be avoided by gathering and analyzing existing geological surveys which cover the site of the hydrothermal system. If existing data are unavailable, conventional field methods should be used to determine the existence of those geologic conditions which are usually associated with geothermal energy, e.g., young volcanic

TABLE 2. EVALUATION OF APPLICATION OF EXPLORATION/ASSESSMENT TECHNIQUES FOR TWO REGIONS[a]

Technique	Basin and Range	Wasatch Front
Thermal method	1	1
Surface geological mapping	2	2
Gravimetry	7	7
Electrical methods	4	4
Borehole logging	8	8
Seismic method	5	5
Liquid geochemistry	3	3
Air photogeology	6	9
Age dating	9	6
Magnetics	10	10
Gas geochemistry	13	13
Remote sensing	12	11
Thermal infrared	11	12
Other	14	14

Legend: 1 - Most applicable: 14 = Least applicable

Basin and Range is the geologic province which covers Nevada, western Utah, and southeastern and east-central Idaho.

The Wasatch Front is the eastern boundary of the basin and range. It is the western foot of the mountain range which runs north-south through the middle of northern Utah.

The Basin and Range and Wasatch Front region are typical of a fracture-controlled deep-circulatory system.

a. (After Dhillon et al., 1978.)[9]

TABLE 3. COST OF EXPLORATION ACTIVITIES

Method	Time	Expense	Area
Consulting Geologist	< Month	$200 - $400/day	Regional/Detailed
Airphoto Interpretation	< Month	$5/mi^2	Regional/Detailed
Water Analysis	Month	$100 - $200/sample	Regional/Detailed
Surface Geochemistry	Month	$30/sample	Detailed
Volatile Geochemistry	Month	$20/sample	Detailed
Temperature Gradient/Heat Flow Boreholes	> Month	$10 - $100/ft	Regional/Detailed
Electromagnetic Methods	Month	$200 - $1,500/line mi	Detailed
Resistivity	Month	$200 - $1,500/line mi	Detailed
Magnetics - Airborne	< Month	$25/line mi	Regional
- Ground	< Month	$200/line mi	Detailed
Seismic - Refraction	< Month	$5000/line mi	Detailed
- Reflection	< Month	$500 - $10,000/line mi	Detailed
- Micro-Earthquakes	3-6 Months	$1,200/day	Regional/Detailed
Gravity	Month	$30 - $70/station	Regional/Detailed
Magnetotellurics	Month	$1,200 - 2,000/line mi	
Geophysical Logging	< Week	$2,000 - $20,000/hole	Detailed

Note: Costs shown are approximate and will vary as a function of many factors including survey detail, location, accessibility, and weather. The costs for geothermal exploration include sample collection and chemical analysis.

Source: Geothermal Resources Council Special Report No. 7, Direct Utilization of Geothermal Energy: A Techniçal Handbook, 1979, p. 2-14.

formations, faults, tufa mounds,[a] hydrothermally altered rock,[b] hot springs, etc. Aerial and satellite photography can be extremely useful in locating fault zones and hot spring deposits.

The characteristics of the exploration techniques in Figure 5 are briefly addressed below. Resistivity surveys are concerned with the subsurface distribution of the apparent soil-water resistivity. Low resistivity anomalies are normally associated with geothermal resources because of the elevated ground-water temperature, degraded ground-water quality, and hydrothermally altered rock. In the geochemical soil survey, soil particulate and gas samples are collected and analyzed for constituents such as mercury, radon, helium, and other inert gases commonly associated with geothermal activity. Abnormally high concentrations of one or more of these constituents can be expected in a geothermal discharge area. Thermal gradient holes can be used to delineate where elevated subsurface temperatures can be attained with the least amount of drilling. (In some states, these wells may require permitting.) Gravity surveys are used to delineate subsurface geologic structures based on rock density differences. Seismic techniques use the different seismic velocity transmitting characteristics of rocks to indicate geologic structures such as buried fault scarps[c] or geothermal rock alteration. Magnetics are used to define magnetic anomalies associated with the geothermal resource. With passive seismic exploration, micro-earthquakes are monitored to determine a seismically active area possibly associated with a fault. Audio magnetotellurics (AMT) and magnetotellurics (MT) are used to locate basement rock anomalies that might be associated with a geothermal

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a. Tufa mound--mound formed around the mouth of a hot spring. Formed by chemicals deposited from the spring water (calcium carbonate or silica).

b. Hydrothermally altered rock--rock changed in chemical composition by long-time contact with hot geothermal fluid.

c. Fault scarps.

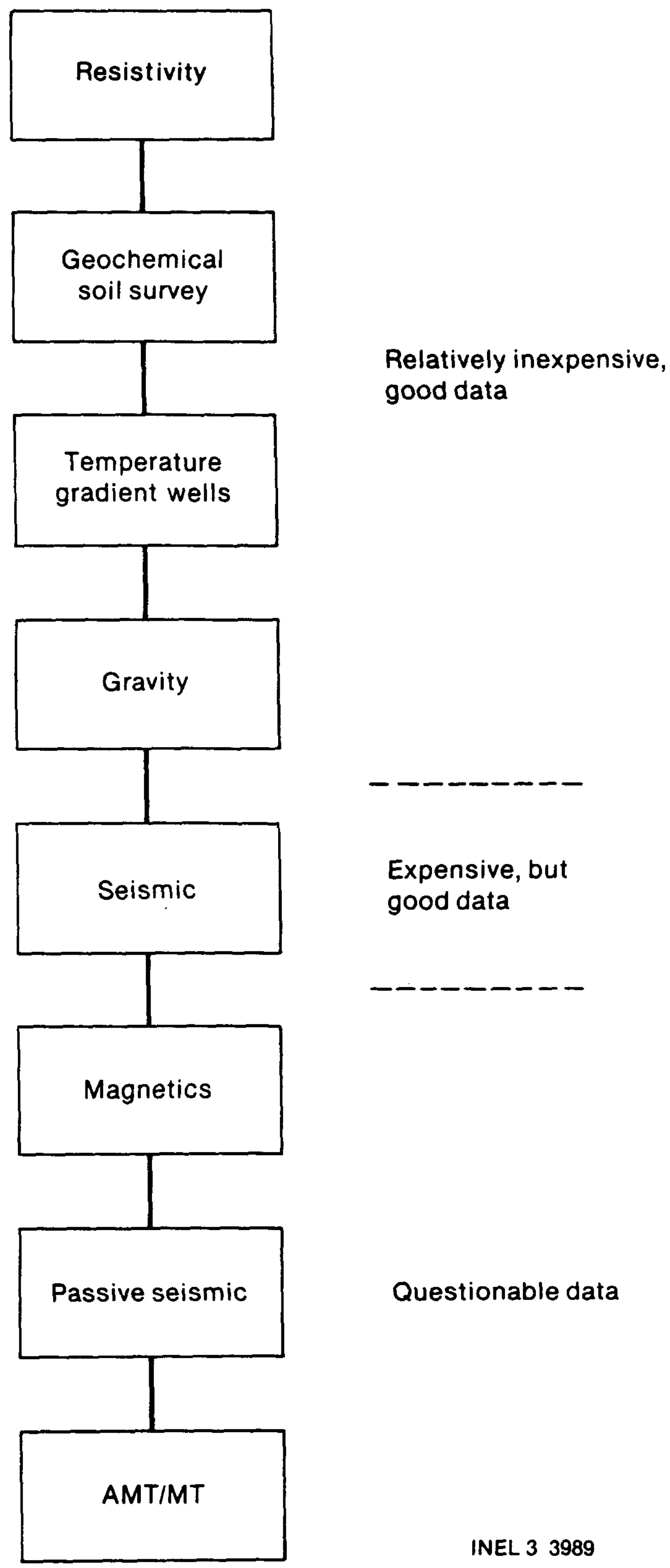


Figure 5. Recommended Order of Geophysical Surveys

resource. The information obtained by the above geophysical methods can, under suitable conditions, provide the investor with additional data to aid in the decision making process.

Geochemical investigations entail sampling any available geothermal fluids, determining the concentrations of chemical constituents, and then interpreting the results. The chemical constituents provide data necessary to indicate the suitability of the expected geothermal fluid for the intended application(s), the system design and construction, and the method of disposal. Fluid constituents are of interest in (a) geochemical thermometry, (b determination of ground-water flow systems, (c) exploration using soil gases and particulates, (d) corrosion, (e) scaling, and (f) common environmental problems (See Table 1).

The target and conceptual model is revised to incorporate the data obtained through the aforementioned activities to determine if the project development should be continued, halted, or investigated further.

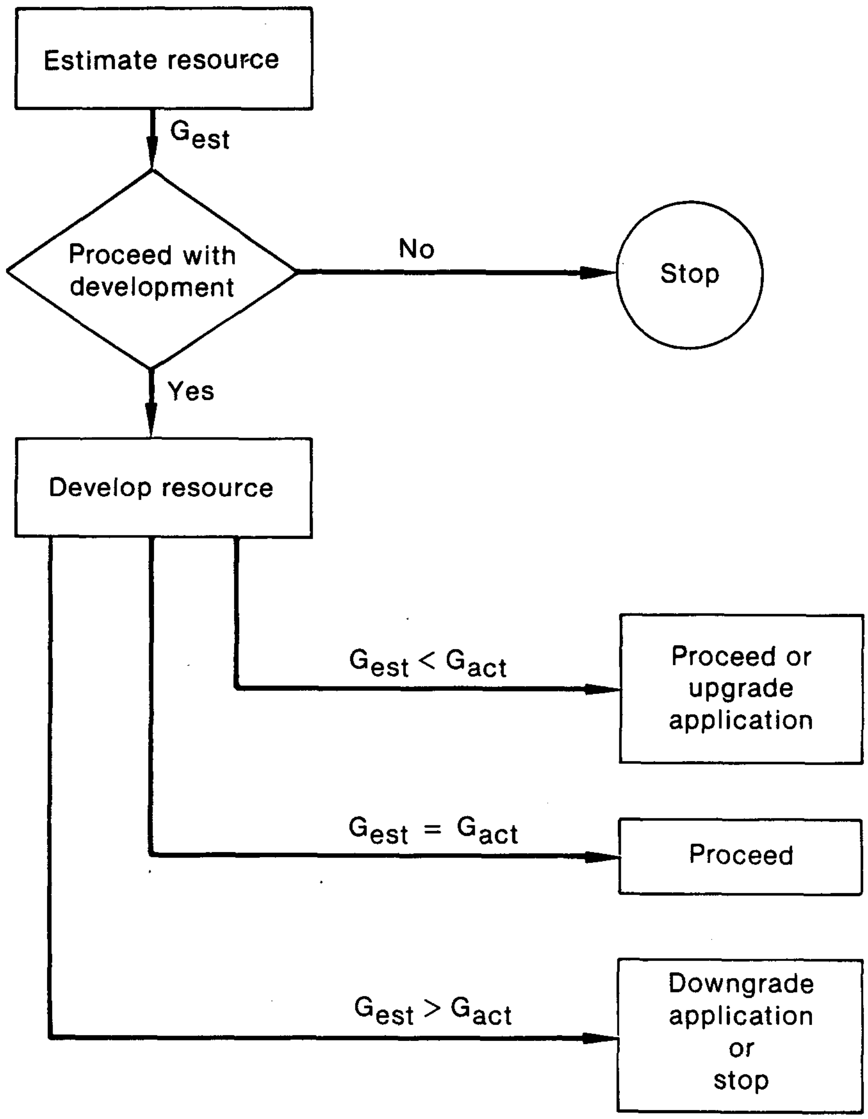
6.7 Exploratory Well Drilling

Positive indicators obtained from the exploratory activities can result in the drilling of an initial (exploratory) well. An initial or wildcat well in any particular area where a minimal data base on ground-water temperature, well production rates and water quality exists, will usually be regarded by state regulatory agencies as an "exploration" well. Such terminology (a) does not inhibit well construction design or size, (b) often facilitates disposal of well fluids during testing, and (c) may limit the initial test duration. Regulatory agencies, upon obtaining data on water quality, reservoir parameters, and basic production characteristics from the initial well, will usually approve applications for extended testing periods and later conversion to a production well permit if the test results merit the change. However, in the initial drilling permit application, it may be best to use the term "exploration well" to define the well type.

6.8 Reservoir Testing

The next continuing element in resource assessment (covered in greater detail in Reference 1) is that of reservoir testing. It is in this portion of the work that the developer determines the well and resource characteristics; i.e. temperature, discharge rate versus drawdown relationship, and water quality. These reservoir parameters are a key to assessing the economics of the project in greater detail because they will help determine (a) if multiple wells will be required, (b) if fluid can be disposed into a surface water body or if an injection well will be required, (c) if pumping the production well will be necessary, and (d) if corrosion/scaling will be major project constraint.

Reservoir testing results are factored into the economic analysis of the proposed project and a go, no-go decision is made. Positive results will generally lead to resource development as shown in Figure 6.



G_{est} = Estimated geothermal resource
G_{act} = Actual geothermal resource

Figure 6. Outcomes of Resource Assessment

7. PROJECT CONSIDERATIONS AND RISKS

7.1 General

The investor, in the course of performing resource assessment, naturally seeks to avoid any unnecessary risks. There are, however, inherent risks to geothermal resource development and some of these risks are discussed in this section.

Four major risk areas are (a) technical, (b) cost, (c) the market place and (d) institutional. Technical risks arise from the chances that available technology will not permit performance of the required tasks. Cost risks are related to greater than expected costs to develop the resource, construct the system, or finance the project. Market risks concern the prices of both geothermal energy and alternative energy supplies, and also consumer acceptance. Institutional risks occur because of environmental, economic, and other forms of regulation that geothermal development faces. In the resource assessment stage,an investor would most likely face technical and cost risks. However, all risks and economics should be reevaluated as new data become available to avoid unnecessary spending, if a project should become impractical.

7.2 Resource Development Considerations and Risks

The most direct risks are caused by a divergence between expected resource characteristics and actual conditions. There are a number of factors that contribute to this. Nonuniform water supply characteristics of fractured and unfractured rock structures exist. Prolific ground-water aquifers may mask the deeper geothermal resources, making it difficult to predict at-depth temperatures. Low geothermal fluids production rates, excessive pump-lift needs, lower than needed resource temperatures, and other undesired fluid characteristics could affect use and/or disposal. There are other risks but these are less important during the resource development stage. For instance, the developer accepts a risk when he decides to initially assess the resource and obtain leasing rights, but the magnitude of the investment is low. There is also a risk that the assessment could indicate a poor resource when a suitable resource exists.

It is important that a phased approach to development, using qualified technical support, be followed in order to proceed through a series of decision points that will minimize risks to the developer. Major investments are related to production well drilling and system design and construction, and cost risks can be reduced by characterizing the geothermal resource as accurately as practical. Actual project experience stresses the economic worth of adequate geological and geophysical surveys.

The development of geothermal resources, although faced with certain risk considerations, is proving to be a reliable and cost effective energy source. Prudent and reasonable management practices will help reduce the resource development risks.

8. PON PROJECTS EXPERIENCE

8.1 General

Resource assessment development and considerations have been generally discussed in the previous sections. Experience gained from the 23 DOE-funded PON projects verify much of that which has been stated, and relative information about these projects is provided to help tie the discussions to specific examples.

Reviewing the experiences gained at the sites is important for two major reasons. First, there appears to be many additional sites, especially in the western United States, where potentially usable geothermal resources exist. Secondly, there are lessons to be learned from the pioneering geothermal direct-use heat resource assessment activity, which should be applied to any future efforts to use geothermal energy directly.

Fifteen of the PON projects are in operation, seven were abandoned, and one was awarded but did not begin. Table 4 lists these projects, their location, administering DOE field office, and status. Although certain of the PON projects were abandoned, valuable resource assessment data were obtained for the benefit of future developers; the projects therefore cannot be considered failures. A private development at Kelley Hot Springs, California was successful after the PON project was stopped when it encountered archaeological artifacts. A good quality resource with a peak flow rate of 600 gpm at 165°F was found at Monroe, Utah, but the town was not able to find an economical use for it. (It is still available for use.) The Moana/Reno, Nevada project obtained a resource, but it required too long a pipeline to be constructed within available funding. Injection problems caused the El Centro, California city council to lose interest in their project. The Douglas, South Dakota High School project was not pursued because a drill string became stuck in the well prior to contract commitment between the school and DOE.

TABLE 4. GEOTHERMAL DIRECT USE PON PROJECTS

Project	Location	DOE Office	Status
Agribusiness			
Aquafarms, Intl.	Dos Palmas Area, CA	SAN	Operating. Growing prawns.
Diamond Ring Ranch	Haakon County, SD	ID	Operational. Not in use. Ranch for sale, unoccupied.
Kelley Hot Springs Agriculture Center	Kelley Hot Springs, CA	SAN	Discontinued. Archaeological site interference.
Utah Roses, Inc.	Sandy, UT	ID	Operating. Growing roses.
Industrial Processes			
Holly Sugar	Brawley, CA	SAN	Discontinued. Inadequate flow, deep resource.
Ore-Ida Foods	Ontario, OR	ID	Discontinued. Inadequate flow deep resource.
District Heating			
Boise	Boise, ID	ID	Operating: city and water district systems operating.
El Centro	El Centro, CA	SAN	Discontinued. Marginal, sandy resource.
Elko	Elko, NV	ID	Operating.
Klamath Falls	Klamath Falls, OR	SAN	Operating on temporary permit
Madison County	Rexburg, ID	ID	Discontinued. Inadequate temper- ature resource.

TABLE 4. (continued)

Project	Location	DOE Office	Status
District Heating (continued)			
Moana	Reno, NV	SAN	Partially completed. Suspended for renegotiation.
Monroe City	Monroe City, UT	ID	Discontinued. Resource, cost and market problems.
Pagosa Springs	Pagosa Springs, CO	ID	Operating on temporary state production permit
Susanville	Susanville, CA	SAN	Operating.
Institutional			
Douglas High School	Box Elder, SD	ID	PON scope not started. Drilling failure.
Klamath County YMCA	Klamath Falls, OR	SAN	Operating.
Navarro College	Corsicanna, TX	NV	Operating.
Philip School	Philip, SD	ID	Operating.
St. Mary's Hospital	Pierre, SD	ID	Operating with 108°F resource
T-H-S Hospital	Marlin, TX	NV	Operating.
Utah State Hospital	Draper, UT	ID	Operating.
Warm Springs State Hospital	Warm Springs, MT	ID	Operating. Partial load on artesian flow.

8.2 Initial PON Project Interest

Initial interest for most of the PON projects occurred as a result of surface manifestations or the existence of nearby warm water wells, and Table 5 lists the primary reason for the initial interest in each project's. Warm water wells already existed on the property in three cases; in two, warm water wells were known to exist in the area near the potential geothermal project; hot springs were located in the immediate region for seven projects. Geothermal developers had chosen sites in KGRA including an area aquifer for six applications; developers, in four cases, apparently began the project based on existing geological and geophysical records and surveys; and, in three used area aquifers. This experience demonstrates the significance of surface manifestations as a catalyst for project development.

8.3 PON Project Resource Characeristics

Geothermal resource interest resulted in the eventual development of 22 PON projects. (The 23rd project at Douglas High School in Box Elder, South Dakota was stopped very soon after its start. The school district could not develop a production well, due to a drill stem being trapped in the well, which could not be removed or bypassed.) The geothermal fluids obtained from the wells drilled for the PON projects were generally in the expected temperature range with adequate flow. This is shown in Table 6 which summarizes the available resource characteristics for the PON project wells. A few of the wells did not achieve the desired characteristics, but valuable information and experience were obtained to enhance the technological data base for the geothermal industry. Some of the lessons learned and project characterization observations are provided for the reader's benefit.

Well yield predictions were inaccurate in more cases than those for temperature, reflecting the relative risk. Project sites are often selected primarily on existing or expected resource temperature information that is based on temperatures indicated by chemical geothermometers. The geophysical techniques, however, do not yield data that can be used to

TABLE 5. REASONS FOR PON PROJECTS INITIAL INTEREST IN RESOURCE DEVELOPMENT

Project	Reason
Aquafarms	WWP
Boise City	WWP/WWN
Diamond Ring Ranch	WWP/AA
El Centro	KGRA
Elko Heat Company	HS/ER
Holly Sugar	WWN
Kelley Hot Springs	HS/ER
Klamath County YMCA	KGRA/WWN
Klamath Falls	KGRA/WWN
Madison County	ER/WWN
Monroe City	HS
Navarro College	ER
Ore-Ida	ER
Pagosa Springs	HS
Philip School	KGRA/AA
Reno, Moana KGRA	KGRA/HS/WWN
St. Mary's Hospital	KGRA/AA
Susanville	HS
T-H-S Hospital	WWN
Utah Roses	ER
Utah State Prison	HS/WWN/KGRA
Warm Springs State Hospital	HS

Key:

WWP = existing warm water wells on property

WWN = existing warm water wells nearby

HS = hot springs in the area

KGRA = known Geothermal Resource Area (as designated by the U.S.G.S.)

ER = existing records and surveys

AA = area aquifer.

TABLE 6. EXPECTED VS. ACTUAL RESOURCE CHARACTERISTICS

Project Wells	Wellhead Temperature (°F)	Temperature Outcome	Discharge (gpm) Artesian	With Pump	Flow Outcome	Comments
Aquafarms - F-1	79-92[f]	In expected range	--	--	Adequate	--
F-2	83[f]	In expected range	--	--	Adequate	--
F-3	107[f]	Greater than expected	--	--	Inadequate	--
F-4	86[f]	In expected range	--	--	Adequate	--
Boise City - BWSWD 1	170[f]	N/A	--	--	Adequate	Existing well
BWSWD 2	170[f]	N/A	--	--	Adequate	Existing well
BWSWD 3	134[f]	Lower than expected	--	--	Inadequate	Abandoned
BGL - 1	155[f]	In expected range	None	--	Inadequate	--
BGL - 2	172[f]	In expected range	1300	1500	Adequate	--
BGL - 3	166[f]	In expected range	None	2000	Adequate	--
BGL - 4	170[f]	In expected range	200	500	Adequate	--
Diamond Ring Ranch	152	N/A	170	--	Adequate[f]	Existing well
El Centro	250	N/A	--	730	Inadequate	abandoned
Elko Heat Company - EHC No. 1	178	In expected range	485	700	Adequate[f]	--
Haakon School (Philip, SD)	157	In expected range	340	--	Adequate[f]	High Radium-226
Holly Sugar	--	Lower than expected	3	--	Inadequate[f]	Dry Hole
Kelley Hot Springs	110	N/A	--	--	--	Not drilled
Klamath County YMCA	147-133[f]	Greater than expected	--	250	Adequate	Temperature decreased
Klamath Falls CW-1&2	212-230[f]	N/A	--	680	Adequate[e]	--
Madison County	70	Lower than expected	--	600	Inadequate[e]	--
Monroe City	164	Lower than expected	100	600	Inadequate	Economics limited
Navarro College - Production	124[h]	In expected range	--	315	Adequate[c,d,f]	Low flow; low temperature
- Injection	--	N/A	--	60	Inadequate	Injection limited

TABLE 6. (continued)

Project Wells	Wellhead Temperature (F)	Temperature Outcome	Discharge (gpm) Artesian	Discharge (gpm) With Pump	Flow Outcome	Comments
Ore-Ida	--	In expected range	1	--	Inadequate	Dry Hole
Pagosa Springs - PS-3	131	In expected range	600	--	Adequate	Interference limited
PS-4	118	Lower than expected	228	--	Inadequate	Plugged/abandoned
PS-5	148	Greater than expected	1150	--	Adequate[b,e]	Interference limited
Reno; Moana KGRA						
Salem-1	160[h]	In expected range	--	900	Adequate[b,h]	--
NNB-1	185[h]	In expected range	108	600	Adequate[h]	--
St. Mary's Hospital	108	Lower than expected	375+	--	Adequate[f]	--
Susanville - Susan I	175	Greater than expected	--	750	Adequate	--
THS Hospital	153	In expected range	75	315	Adequate[f]	--
Utah Roses	123	In expected range	--	230	Adequate[c,f]	--
Utah State Prison	180	In expected range	600+	288	Adequate	--
Warm Springs State Hospital	156	Lower than expected	35	60	Adequate[c,d]	Corrosive and Scaling

N/A = Not available

a. Given the temperature.

b. Greater than expected.

c. Less than expected.

d. Adequate for project to continue at reduced scope.

e. DOE Geothermal Direct Heat Applications Program Summary, September 1981, Op. Cit.

f. DOE Geothermal Direct Heat Applications Program Summary, August 1982, Op. Cit.

g. Morrison - Knudsen Company, Inc., Utah State Prison Geothermal Test, September 1982.

h. Personal communication with project personnel by EG&G Idaho, Inc., December 1983.

estimate well productivity. Only production wells in the area can be used to provide even a crude estimate of expected well productivity. Occasionally, development may continue by modifying the planned project even though results are less than expected. For example, the expected temperature and pumped flow were 171°F and 300 gpm for space and hot water heating at the Warm Springs State Hospital. When 156°F and 60 gpm were obtained, only water heating was used. The scope was cut to fit the resource.

Sometimes, when resource characteristics are different than estimated, tradeoffs can be made. For instance, a higher temperature can allow a lower well discharge rate, because the extractable energy for a given use is the product of the temperature change (drop) of the geothermal fluid passing through a heat exchanger, and the flow rate. Higher than expected temperatures and flow rates may make it economically feasible to include measures to remove an unexpected undesirable chemical from the fluid. If the temperature and/or well productivity is lower than expected, it may be possible to reach project heat demands by one or more of the following; (a) increasing the geothermal fluid flow rate through the heat exchangers by using a larger pump and motor which might be set deeper in the well because of more drawdown of the fluid level in the well, (b) enlarging the heat exchangers, (c) increasing the insulation on pipelines to minimize transmission heat losses, (d) installing a variable speed pump to minimize well drawdown, (e) installing a second well, and (f) installing a heat pump, at the wellhead or after initial use, to raise the temperature of the geothermal fluid. There are many courses of action that can be taken to mitigate the effects of low well productivity/temperature. Cost-to-benefit ratio evaluations will help make the proper choices.

Wellhead temperatures that were unexpectedly low were due to overestimating the resource temperature using geothermometry, such as at Monroe, Utah, or having a prolific cold water aquifer system which prevents heat buildup, as at the Madison County, Idaho project.

The process of site selection and exploration used at the Ore-Ida project demonstrates the value of reviewing existing data.[11,12] The surface geology was already mapped in the area. Subsurface geology was interpreted from existing oil and gas exploration holes that were up to 11,935 ft deep. A detailed private gravity survey was obtained and was found to be compatible with previous public surveys. A magnetic anomaly map of the area was produced using data obtained from Oregon State University. A reflection seismic survey was the major active work undertaken for the project. The geochemistry of thermal and nonthermal waters from wells and springs was obtained by a project survey and from available public surveys. However, even with all the data obtained during exploration, the site was not satisfactory because the completed well, which was over 10,000 ft deep,[13] had a low fluid yield.

The experience gained through the Pagosa Springs, Colorado project[14] exemplifies some of the uncertainties that exist in the development of a geothermal resource in a complex fracture-flow dominated media. It also illustrates the significant level of uncertainty associated even with resources that have been previously exploited. In this project, a new well drilled only 30 ft from a test well produced geothermal fluid that was 10°F cooler than that of the test well at comparable depth. A second well located 350 ft from the first one had such low temperature and flow that it was abandoned. A third new well, drilled 180 ft from the first one and 30 ft from an existing old well, produced a much higher temperature and greater flow than either. The hydrogeologic flow system in that case is very complex and heterogeneous in regards to the water yield from fractures and their associated fluid temperatures. The only reliable method to determine the temperature and discharge characteristics is by means of an exploration or production well. The extensive interconnection of the wells necessitated extensive interference flow tests as a prerequisite to obtaining a production permit for a new well.

The presence of Radium 226 in the fluid at the Philip South Dakota project not only required the installation of special treatment facilities, but also resulted in schedule delays and cost increases. A more common problem is corrosion or scaling caused by the geothermal fluid. Well casing corrosion is commonly the factor limiting the expected life of a well, and special consideration in the purchase of materials and equipment is often necessary to minimize the adverse effects of corrosion or scaling. (Corrosion problems can be minimized by about three months of corrosion coupon tests in piping flowing the geothermal fluid and analyzing the test data prior to designing the system.)

A major lesson learned from the PON projects experience to date is the importance of an accurate resource assessment. The resource assessment stage is a relatively low cost operation, but through this effort, an investor decides whether and where to proceed with the next step in project implementation, which is production well drilling. Well drilling is a major cost component of a geothermal energy supply system, and project success or failure can depend on the quality of the resource assessment's guidance for the drilling program. The geothermal resource characteristics that are important to project performance include fluid wellhead temperature, discharge rate, drawdown characteristics and fluid chemistry (e.g., salinity, dissolved solids, radioactive elements). Some of these items may be determined by drilling small test wells prior to drilling the production well. The PON project experience indicates that, although resource assessment remains an art, where results are associated with significant uncertainty, the resource estimate has generally proved accurate enough to provide a basis for investment decisions. Reference 1 provides additional experiential information about the PON projects.

8.4 Cost Information

Cost information, specifically for the resource assessment part of the PON projects, is not readily available, and varied considerably from project to project. Some of the projects required very little additional resource assessment work due to the availability of existing geological data. Where exploration is a small part of the total project, costs were not separately identified. Information is provided for three of the PON projects to give an overall idea of resource assessments costs.

The Philip, South Dakota school project is located over an easily sited area aquifer (the Madison); however, little detailed, local data existed. About $3000 was spent in 1978 on geological and geophysical surveys. Borehole geophysical logging in 1979 cost about $8400 after drilling, $1300 was spent on flow testing equipment. The Klamath Falls, Oregon YMCA project utilized a well defined, fault dominated resource. Several local geothermal users already existed in the area. The cost estimate for this project identifies only one resource assessment activity, well testing after drilling. The cost was approximately $3500 in 1978.

The Ore-Ida Foods project at Ontario, Oregon, at the other extreme, was for a large industrial application in an area that had very poorly defined indications of a resource. Prior to drilling, about $10,000 was spent gathering and assessing available data. In addition, an active seismic survey, using small dynamite charges, cost over $112,000. However, this expenditure is small in proportion to the production well cost of $2.3 million, which included $180,000 in well testing.

Additional prospect cost information is provided in ICF's report "An Economic Assessment of Nine Geothermal Direct-Use Applications".[15]

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The most significant conclusions derived from the PON projects follow.

1. About 75% of the PON projects started are currently operating and are technically successful.

2. Most of the unsuccessful projects were stopped because an adequate resource was not obtained from the first production well drilled by the project.

3. The initial interest in most of the projects was the result of nearby hot springs or warm-water wells.

4. The design of the geothermal systems is within the state-of-the-art if corrosion coupon tests are made with the subject geothermal production well.

5. Small compromises in the design of the users system can often offer the flexibility to accommodate deviations from the original estimate of the resource characteristics. This can result in successful projects which might otherwise be dropped.

6. Making use of available resource data and a structured decision process can minimize the cost and number of unsuccessful wells and projects.

7. Applications which require a continuous, fixed heat input have better economics than space heating or district heating applications which are seasonal and only use about 20 to 30% available annual capacity of the geothermal systems.

9.2 Recommendations

The following recommendations are made to investors and developers of direct-use geothermal systems.

1. Match expected resource characteristics with the requirements of prospective uses and review economics.

2. Update the resource/use match and economics whenever new resource data becomes available.

3. Initially, assume that injection of the spent geothermal is required for a conservative economic evaluation, but attempt to find resources which meet surface disposal requirements. Surface disposal will significantly improve project economics.

4. Make full use of available geological and geophysical data from universities and public agencies.

5. Investigate and fully understand permitting requirements and lead times for original permits and for modifications.

6. Hire experienced consultant(s) for resource assessment prior to initial drilling. Siting the initial exploration/production well is one of the most significant project decision points since drilling is the first major financial commitment.

10. REFERENCES

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APPENDIX A
OVERVIEW OF GEOTHERMAL RESOURCE TYPES

CONTENTS

FIGURES

APPENDIX A
OVERVIEW OF GEOTHERMAL RESOURCE TYPES

1. INTRODUCTION

Considerable heat is stored and generated within the earth. This heat results from natural radioactive decay and friction as well as possible residual heat from the time of the formation of the earth. Heat from the earth's interior is lost through a relatively thin crust which is approximately 30 km (19 miles) thick in continental landmass area. A developable geothermal reservoir can result: (a) where steeply dipping permeable faults extend into a high temperature portion of the earth, (b) where near horizontal permeable zones occur in a high temperature portion of the earth, and (c) as a combination of the two. Surface features such as tufa mounds,[a] hot springs, geysers, fumaroles,[b] hot wells, and hydrothermally altered rock[c] may result. Basically, hot rock can be found everywhere (if a well is drilled deep enough). However, a resource can only be exploited where a high temperature fluid of suitable chemical composition exists in a high yielding zone at an economically shallow depth.

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a. Tufa mound--mound around mouth of a hot spring. Formed by chemicals deposited from the spring water (calcium carbonate or silica).

b. Fumarole--hole, vent, spring or geyser which emits considerable quantities of gases, vapor or steam.

c. Hydrothermally altered rock--rock changed in chemical composition by long-time contact with hot geothermal fluid.

2. TYPES OF GEOTHERMAL RESOURCES

The geothermal areas which should be considered first for exploration and resource development, for direct-use applications, are those where the highest temperatures are found at shallow depths (less than 1500 ft). The geologic phenomena contributing to the high energy potential of geothermal resources will not be explained in more detail in this report, but the interested reader may find a detailed discussion in "Direct Utilization of Geothermal Energy: A Technical Handbook".[1]

One system for classifying geothermal resources follows:[2]

1. Hydrothermal convection[a] systems related to young igneous intrusions[b]/volcanics

2. Fault-controlled systems

3. Deep regional aquifers

4. Geopressured reservoirs

5. Hot dry rock.

The heat associated with young igneous intrusions and/or volcanic activity may be retained in the rock for many thousands of years. Fracturing or faulting of this rock may permit the development of a shallow hydrothermal convection system. In this system, naturally-occurring ground water circulates through the rock along faults, absorbing thermal energy. At another location it returns to or near to the earth's surface at a much higher temperature.

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a. Hydrothermal convection--water which is hot and flowing.

b. Igneous intrusions--a body of molten rock which pushed (intruded) into a body of older rock and then solidified.

In deep fault-controlled systems, thermal energy is obtained by the deep circulation of fluid along faults or stratigraphic beds. This circulation permits fluid to extract heat from a large volume of rock. The temperature attained by the circulating ground water depends on the depth to which a fault allows the water to circulate, the magnitude of the regional heat flow, the residence time of the water, and the amount of mixing with colder ground waters as it returns to the surface.

Another type of geothermal resource is found in deep regional (large area) aquifers, such as the Madison Aquifer, mainly in Montana, Wyoming, and the Dakotas. This type of aquifer is sufficiently deep and permeable that the water it contains is warmed by the normal heat flow of the earth. These aquifers are rare but have the advantage of relatively low risk in siting the geothermal well to produce from the resource since they cover large areas.

The Gulf Coast area is characterized by geopressured resources, which are localized occurrences where hot water is confined in deep sedimentary strata where the pressure exceeds that of a column of water to that depth (hydrostatic head) and may approach the pressure of the overlying rocks (lithostatic head). These resources are in very limited use for combined geothermal energy and methane production, as the technology is unperfected and exploitation is costly with depths on the order of 15,000 ft.

Also unexploited, at present, are hot dry rock systems. Hot dry rock systems can be developed within a large volume of hot rock with low natural permeability. The permeability is artificially induced by hydraulic/thermal fracturing. Cool water is injected down one well, heated in the fractured volume and returned to the surface via a second well. This type of resource system is still in experimental development and has not been economically demonstrated in direct heat applications of geothermal energy.

3. CURRENT GEOTHERMAL RESOURCE ASSESSMENT

Of the different systems of geothermal resources, the hydrothermal convection and the fault-controlled systems are the most commonly exploited for direct heat use at this time. A general assessment of U.S. geothermal resources by type was performed by the U.S.G.S.[3] in 1975 and was updated in 1978.[4] Another assessment,[5] directed towards low-temperature resources, was issued by the USGS in 1983. These studies indicate that hot water-dominated hydrothermal systems are considerably more common than vapor-dominated systems e.g. steam systems such as the oysters in Northern California.

Virtually all of the major hydrothermal systems identified in the U.S. are located in the western third of the country. The map on the following page (Figure 1), reprinted from an Interagency Geothermal Coordinating Council report,[6] indicates the locations of potential hydrothermal resources. Potential low and moderate temperature geothermal waters [<194°F (<90°C,) and 194 to 302°F (90 to 150°C) respectively], identified on the map, are widely scattered through the U.S., but are still located predominantly in the western U.S.

Very little of the identified geothermal resource base is currently being exploited. From identified hydrothermal convection systems (excluding those found in and near national parks), the amount of potentially available heat energy at the wellhead is estimated to be 375 $\times 10^{24}$ Btu.[7] This figure over estimates the amount of beneficial heat that could be provided because the development of many reservoirs may not be economically feasible due to excessive resource depths, and piping costs and transmission line heat losses from remote locations. On the other hand, the estimate understates the potential geothermal resource base by excluding undiscovered hydrothermal systems, as well as all other types of deposits, such as hot dry rock or geopressured resources.

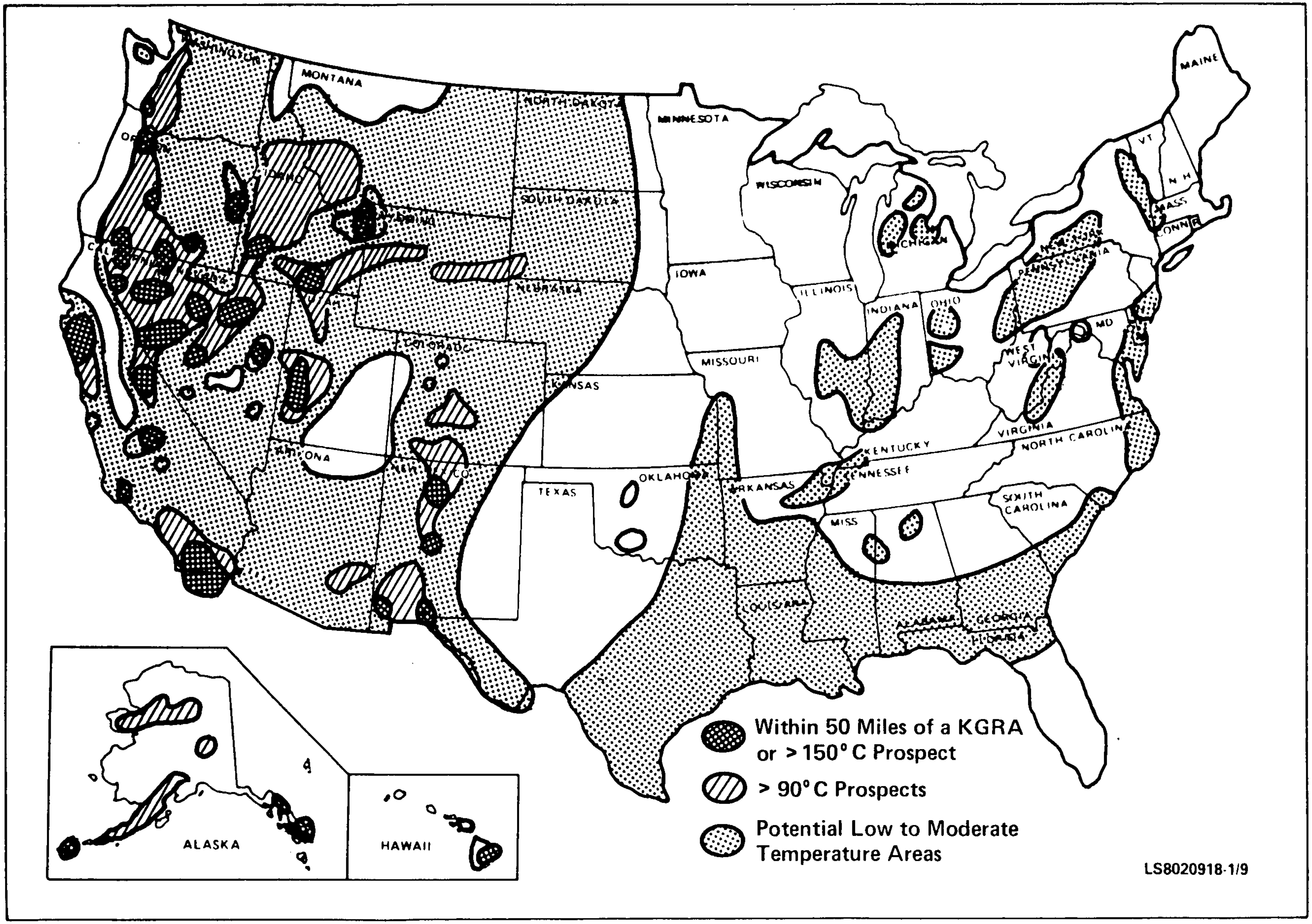

Figure 1. Known and potential hydrothermal resources

For a resource that must be used close to its source, attractiveness depends not only upon the nature of the resource, but also on the energy demand in the surrounding area. The incentive to exploit the geothermal resource is greater in regions of the U.S. where the price of fossil fuels is very high.

4. KGRA DEFINITION

The U.S. Geological Survey (USGS) has designated certain lands as Known Geothermal Resource Areas (KGRAs). A KGRA is defined as having geothermal energy equivalent to 8.18×10^8 Btu (about 1.5×10^9 barrels-of-oil equivalent). In the Federal "Geothermal Steam Act of 1970," a KRGA is legally defined as "an area in which the geology, nearby discoveries, competitive interests, or other indices would, in the opinion of the Secretary, engender a belief in men who are experienced in the subject matter that the prospects for extraction of geothermal steam or associated geothermal resources are good enough to warrant expenditures of money for that purpose."

5. PON PROJECT EXPERIENCE

Of the types of geothermal resources previously described, none of the PON direct heat applications exploited geopressured reservoirs or hot dry rock. However, the other three types of systems were exploited in the PON projects, either singularly or in combination. For example, the geothermal aquifer of largest aerial extent in the U.S. is the Madison Aquifer, which extends under the western half of South Dakota and into the bordering states of Wyoming, Montana, and North Dakota. Of the 23 PON projects referenced in this report, three obtain their geothermal resource from this aquifer: Diamond Ring Ranch, Philip School, and St. Mary's Hospital, all in South Dakota. All the other PON projects were located in fault-controlled systems. (It is necessary for the well to penetrate a fault in a fault-controlled system in order to obtain a flow rate sufficient for an economically viable project.)

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