UNITED STATES GEOTHERMAL TECHNOLOGY

EQUIPMENT
AND
SERVICES
FOR
WORLDWIDE
APPLICATIONS

U.S. DEPARTMENT OF ENERGY
ASSISTANT SECRETARY FOR
ENERGY EFFICIENCY AND
RENEWABLE ENERGY

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WASHINGTON, DC 20585

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Geothermal energy, heat from the earth's interior, is an attractive source of energy, with resources widespread among both developed and developing nations. This environmentally benign resource can alleviate the critical shortages of power in some nations and contribute significantly to achieving sustainable development.

Since the early 1960s, the United States has been a world leader in research, development, and commercial use of geothermal energy technologies. Close collaboration between government and private industry has resulted in technological advances including new production equipment, sensors, analytical techniques, and customized software. Cost, which in the past was a serious impediment to geothermal development, is now less of an obstacle with appropriate use of these new technologies. Since 1980, U.S. geothermal companies have installed 2,000 MWe of new capacity on a cost-competitive basis in some 60 projects within the U.S. and overseas.

The U.S. geothermal industry, with its solid experience and proven technology, reaffirms its commitment to extend its services and assist in the development of this environmentally friendly energy resource on a worldwide basis. This document describes currently available geothermal technologies, improvements in cost, and the policy and regulatory framework that have assisted geothermal development in the U.S. Readers are encouraged to contact American geothermal industry representatives to obtain additional information or other assistance needed to implement technological innovations.

This document has two intended audiences. The first part, "Geothermal Energy at a Glance," is intended for energy system decision makers and others who are interested in wide ranging aspects of geothermal energy resources and technology. The second part, "Technology Specifics," is intended for engineers and scientists who work with such technology in more detailed ways. The glossary at the end of the document defines many of the specialized terms. A directory of U.S. geothermal industry firms who provide goods and services for clients around the world is available on request (see page 44).

Geothermal Energy At A Glance

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Geothermal Energy Technology Today

Many decades ago, scientists recognized that *geothermal energy*, the heat of the Earth, had great potential as a substitute for fossil fuels to generate electricity. Non-electric uses of geothermal energy date back to prehistoric times; they include bathing, cooking, and medicinal uses. However, until the 1960s, the mechanics and economics of broad-scale geothermal energy use were not well understood.

The earliest geothermal power generating projects were built at Larderello, Italy, in 1904 and at Wairakei, New Zealand, in 1950. The Geysers project, begun in California in 1960, was the first U.S. geothermal development. These initial ventures worked reasonably well and continue to do so. However, research and development since 1960 have introduced many new technologies that now allow widespread economic use at geothermal sites of varying quality.

U.S. industry experience, combined with government and privately sponsored research, has created and improved the technologies needed to harness most known geothermal reservoirs. As these technologies continue to evolve, development of the full range of geothermal resources has become increasingly cost-effective. In the past three decades, geothermal technology has made enormous progress in exploration techniques, drilling tools and methods, brine handling technologies, power system components, and the development of environmental control technologies able to meet high U.S. standards.

Technology advances have resulted in the construction of safe, environmentally acceptable geothermal projects. Examples of the geothermal industry's solid record of accomplishments are shown below.

- The economics of geothermal direct-heat use have become increasingly attractive. Geothermal reservoirs close to population centers are being developed for large direct-use projects.
 - Geothermal Heat Pumps (GHPs), also known as ground-source heat pumps, are proving to be an excellent heating/cooling option. GHPs reduce the need for new electric generating capacity by performing at greater efficiencies than air source heat pumps.
- Modern U.S. geothermal technology, equipment, designs, services, and technical expertise are now commercially available to develop geothermal resources rapidly and economically in any region of the world.
- Geothermal energy has experienced steady growth worldwide, with 6,200 megawatts (MWe) of installed capacity at the end of 1994, a 31 percent increase since 1985.
 - Dry-steam and flash technologies are now commonplace and many moderate-temperature, liquid-dominated reservoirs can produce electricity economically using "binary" technology.
 - Most brine handling and potential environmental problems have been solved. Corrosion, scaling, injection-well plugging, and environmental control are no longer barriers to the development of geothermal systems.

The first operational geothermal power plant at The Geysers in northern California (top). This venture began a series of breakthroughs in geothermal design that led to the three state-of-the-art geothermal plants at Coso Hot Springs, California (bottom).

Worldwide Locations of Major Geothermal Systems

Geothermal resources are distributed unevenly across the Earth. High-temperature geothermal resources occur within well-defined regional belts where the earth's crustal plates pull apart or collide. Geologic forces push very hot or molten rock toward the earth's surface in those regions. Such activity is seen at the surface as volcanoes, geysers, fumaroles, lava flows, mud pots, and hot springs.

The Circum-Pacific Belt rings the Pacific Ocean and is one of the Earth's most tectonically active regions. The belt contains many of the world's largest and hottest geothermal resources. Oceanic spreading centers, such as the East Pacific Rise and the Mid-Atlantic Ridge, also give rise to hot crustal material. Continental spreading produces elongated zones of crustal thinning or "rifts" that serve as pathways for molten rock. Iceland, the Azores, the East African Rift and the Imperial Valley in California have high-quality, rift-related geothermal resources. Geothermal resources also occur at (1) regions with local magmatic disturbances that give rise to hot spots, (2) regions where the crust is thin and aquifers are heated to above normal temperatures, (3) regions with abnormally high proportions of radioactive rocks, and (4) deep basins where heat is trapped by a thick blanket of sediments.

"Hydrothermal" systems, the most commonly used geothermal resource, consist of hot water or steam trapped in fractured or porous rocks. Fluid temperatures from these systems vary

considerably but can be as high as 350°C. High-temperature systems, used for generating electricity, often occur near young volcanoes or where the earth's crust has thinned. Low- to moderate-temperature systems occur at the margins of higher-temperature hydrothermal fields, in basins with thick sediments, and where water is able to circulate to depths of several kilometers along fractures. Geothermal fluid from these lower-temperature systems can be used directly for greenhouse, aquaculture, and other applications.

The most widespread geothermal resource in the world is hot dry rock (HDR). This resource consists of rocks rich in thermal energy but lacking entrapped water or steam. To harness HDR energy, a deep well is drilled into the hot rock and the rock is fractured by injecting water under great pressure. The fractured zone becomes an engineered reservoir. Surface water is continuously injected into the fractured reservoir and is recovered as hot water or steam through production wells. In the United States, the most readily accessible hot dry rock resources lie in the Western states. At sufficient depths, HDR resources are found virtually everywhere. Researchers estimate that the HDR resource in the United States is about 6,000 times the total amount of energy the U.S. now uses each year. Potential hot dry rock resources are also known to occur throughout Europe, and in the countries of the Pacific Rim.

Advantages of Geothermal Energy

Geothermal resources are continuous sources of energy regardless of climatic or weather conditions. This fact makes geothermal energy especially attractive as a source for baseload electricity generation or direct-use applications that need consistent heat. Geothermal power plants compete economically with coal, oil, and nuclear plants in meeting baseload capacity needs, with significant environmental advantages. Some geothermal power plants are used for load-following. Geothermal energy direct-use systems can be competitive with other sources of energy for many space heating, agricultural, and industrial applications. Geothermal heat pumps provide home and commercial heating and cooling services relatively inexpensively, and are attractive to electricity utility companies because they can reduce the peak loads on electric systems.

Specific advantages of geothermal systems include:

Indigenous Energy - Geothermal energy helps reduce dependence on imported oil, gas, coal, or nuclear fuels.

Clean Energy - Use of geothermal energy helps reduce combustion-related emissions from conventional fuels.

Diversity of Use - Geothermal energy has three common economic uses -- electricity generation, the direct use of heat, and as a source of heat for ground-coupled heat pumps.

Long Term Resource Potential - With optimum development strategies, geothermal energy can provide a significant portion of a nation's long term (30 to 50 years) energy needs.

Flexible System Sizing -

Geothermal space heating system sizes range anywhere from 30 kilowatts-thermal for heating a single house to several megawatts for large district heating systems. In the case of electricity, power generation projects range in capacity from a 200 kilowatt system in China to the largest geothermal power plant complex in the world, now producing about 1,200 megawatts at The Geysers in California.

Modularity - Modularity is the use of multiple, small, easily transportable units. A single

good geothermal well can support between 3 and 10 MWe (net) of electric capacity. A 3 to 50 MWe power plant can take less than a year to build. Modular plants provide flexibility allowing incremental responses to demand growth and an optimum resource use strategy.

Power Plant Longevity - Geothermal power plants are designed for life spans of 20 to 30 years. With proper resource management strategies that minimize reservoir depletion, life spans can exceed design periods.

High Availability - "Availability" is defined as the percentage of time that a system is capable of producing electricity. Geothermal plants are extremely dependable. Availabilities of 95 to 99 percent are typical for modern geothermal plants compared to 85 percent for coal and 80 percent for nuclear plants.

Combined Use - Geothermal energy can be simultaneously used for both power generation and direct-use applications. Depending on the resource temperature and the process temperatures, different applications can be served from a common set of wells. The combined use of geothermal energy results in higher thermal efficiencies and associated cost savings.

Low Operating and Maintenance Costs - Geothermal electric system annual operation and maintenance (O&M) costs are typically 5 to 8 percent of the capital cost. This is approximately the same as the non-fuel O&M costs for conventional systems. Industry trends are in the direction of increased automation of production field and power plant control systems to reduce O&M costs.

Compact modular binary power plants, such as this 300 kW unit at Fang, Thailand, are available to meet power needs in even very remote locations.

Keys to Project Success

THE BASIC TECHNOLOGIES

The development of a successful geothermal energy project relies on a variety of specialized technologies. Cost-effective use of each technology requires its own special expert scientists and engineers. The technologies are discussed briefly here, and described in detail in the second part of this report: "Geothermal Technology Specifics."

Exploration - Geothermal development begins with exploration to find a reservoir at an economically useful temperature and depth, with adequate permeability and volume. Exploration relies on surface measurements of subsurface geological, geochemical, and geophysical conditions to develop a conceptual model of the system.

Well Drilling and Testing - The next step in development is the drilling of wells. Wells are used to measure subsurface temperatures and flow rates, measure other subsurface conditions, and to produce and reinject the geothermal fluid. After each well is completed, production and/or injection tests are run. Reservoir characteristics related to temperature, pressure, chemistry, and permeability are measured and used to plan resource utilization.

Reservoir Engineering - Reservoir engineering uses information gathered from subsurface measurements and well testing to generate and refine a model of how the reservoir works. These models are used to optimize energy extraction and maximize the economic lifetime of the resource. Major design considerations determined by reservoir engineers include the locations, depths, flow rates, configurations, and numbers of production and injection wells.

Power Plants - Geothermal power plant design depends on the physical characteristics of the geothermal fluid. Dry steam power plants at The Geysers field in California have been on-line since 1960 and proved to be competitive with other generating sources. Single- and dual-flashed steam power plants are widely used in the U.S. and worldwide. Binary technology has proven successful in generating power using resource temperatures as low as 100°C.

Brine Handling - Chemical constituents in some geothermal fluids can cause scaling, corrosion, or mechanical erosion of wells, gathering/injection systems and surface plant equipment. Special materials and process treatments are used to overcome such problems. Recent research in the area of brine chemistry has yielded major advances. These include: the continuous injection of carbonate-scale inhibiting compounds into production wells, the use of crystallizer-clarifier technol-

Polycrystalline diamond cutter (PDC) drill bit. Research is in progress on Thermally-Stable PDC (TSP) bits, to enable the very high rates of penetration of these bits to be applied in geothermal drilling.

ogy and pH modification to control silica scaling, polymer-concrete liners for pipes, and carbon dioxide resistant cements for production wells.

Environmental Control - Effects on water resources, air quality, and noise during geothermal development and operation must be understood and mitigated. Among these are emissions to air (particularly of hydrogen sulfide), land use, and disposal of solid wastes. Effects can vary greatly from site to site. U.S. development of appropriate environmental control technologies has facilitated sound geothermal projects in areas with strict environmental regulations.

Recent Technology Improvements - To help the reader gain a sense of the degree to which some technologies have improved recently, a number of estimates of improvements in the 1986 to 1991 period are included in the text of the second, more technical, part of this report. These are drawn from a recent survey of the geothermal literature [1].

MAJOR PLANNING CRITERIA

For a geothermal energy development project to be commercially viable, the five parameters listed below have to lie within acceptable ranges. These parameters have an overriding effect on initial project development costs.

Temperature - Useful geothermal temperatures range from 10°C for Geothermal Heat Pumps (GHPs) to more than 300°C for electricity generation. In general, the higher the temperature the better the economics for generating electricity.

Energy Production Rates - The amount of energy that can be economically extracted from geothermal fluids depends on the fluid's temperature, flow rate, and the energy conversion technique. The useful output per well can range from a few kilowatts for shallow low-temperature wells to tens of megawatts for deep, high-temperature, highly productive wells.

Utilization Factors - Because of the substantial capital investment in drilling and power conversion, geothermal power plants are best suited for baseload applications which generally provide greater economic returns than applications with low utilization factors, such as peaking plants.

Well Depth - The deeper a geothermal well, the more it costs. However, wells as deep as 3,000 meters can be drilled economically, provided that the energy production rates from the wells are high. Wells in use today range in depth from 60 to 3,000 meters.

Energy Transport - Electricity can be transported over long distances. Thus, a geothermal power plant can serve distant customers. Hot water can be transported over moderate distances (typically 1 to 2 km, but up to 50 km if the system capacity is very large), depending on resource and end-use temperatures, terrain conditions, and local climatic conditions. Geothermal steam must be used within one to two kilometers of the production wells.

Other variables, including regulatory requirements, finance rates, and environmental constraints, also affect project economics.

WINNING TACTICS

Experience has shown that careful attention to specific aspects of project design and operation are important contributions to the long-term success of geothermal projects. Some of the major lessons learned over the past decade are described below.

Exploration - Most important here is the integration of data from a wide variety of sources into a good conceptual model of the reservoir. All types of geoscientific data, including geological, geochemical, geophysical, and reservoir engineering information are important for designing and carrying out effective exploration programs.

Drilling - Engineers and drillers who are familiar and experienced with geothermal rather than petroleum wells should be part of the project. Geological conditions, casing plans, drilling procedures, and cementing materials for geothermal wells are very different from those used for oil and gas wells. Geothermal experience makes a very big difference in the success and cost effectiveness of drilling and well completion programs.

Reservoir Assessment - The predictive power of well flow test data increases with the length of the test, so relatively long (20 to 40 day) tests can provide much better information about reservoir characteristics than short (1 to 3 day) tests. Injection tracer studies of flow paths between wells have become increasingly common as a means to optimize which wells should be used for production or injection over time. Successful geothermal development firms now rely on computer-based reservoir simulation models to integrate the large amount of data that results from geological analyses, flow tests, and fluid production monitoring and to predict the behavior of geothermal systems under production and injection.

Power Plants - Costs are especially important here, because the cost of the power plant tends to dominate the overall costs of the project. Plants also need to be designed with some ability to accommodate changes in fluid pressure, enthalpy, and noncondensable gas content that may take place in the later years of system life.

Brine Handling and Materials - Extensive experience with effects of geothermal fluids on component materials is essential in selecting the materials to use on each project. Many effects of geothermal fluids on materials, and cost-effective solutions for avoiding long-term problems, are not obvious but are well-known to experienced geothermal engineers.

PROJECT PHASES AND RISKS

The precise characteristics of a geothermal resource can not be determined from the ground surface prior to drilling and flow testing. To control investment risk, geothermal development projects are typically undertaken in phases. As each successive phase is completed, the investment requirements for continued

project development increase, while knowledge of the resource increases and risk decreases. Risks can never be eliminated, but phasing helps reduce them progressively to acceptable levels.

The initial activities for geothermal field development are: reconnaissance, discovery, confirmation, and preliminary power plant design. These phases include land acquisition,

permitting and licensing, and financial commitment. Once the initial phases have been completed, the three main aspects of detailed design and construction of system components are conducted in parallel: well field and fluid handling system; power plant with environmental control technologies; and electricity transmission lines. Long-term operation and maintenance of the project is the final phase.

Development Phases, Technologies, and Costs

Phase of Development	Years per phase	Technologies						Cost, per phase \$ million (for a 50-MWe plant)
		Exploration	Drilling	Reservoir engineering	Conversion	Brine handling	Environmental	
1. RECONNAISSANCE: Do geological, geochemical, geophysical, and temperature gradient analyses, at 5 to 20 sites.	1-3	●	●					1-2
2. DISCOVERY: Drill 1 to 4 deep holes at best site(s) to find hot fluid. Do initial flow tests.	1	●	●			●	●	1-5
3. CONFIRMATION: Drill more deep wells to prove field can support the application. More flow tests.	1/2 - 2	●	●	●		●	●	5-9
4. DESIGN: Design and cost plant and field to allow decisions on feasibility and financing. Design costs are highest for the first plant at a new site.	1/2 - 2			●	●	●	●	3-12
5A. PRODUCTION DRILLING Drill production and injection wells.	≠		●	●	●	●	●	15-30
5B. PLANT CONSTRUCTION Build the plant.	1 - 2				●	●	●	45-75
6. OPERATION: Operate and maintain system. Drill replacement wells as needed.	30		●	●	●	●	●	Annual cost is 5-8% of capital (costs are in 1994 dollars)
Total Initial Cost (for 50 MWe, net, field and plant):								70-130

The dots indicate the relative importance of different technologies at each development phase.

Direct heat projects often use fewer wells. In some cases, interest in a direct heat application does not arise until a reservoir has been confirmed. In such cases, the investors in the surface plant have no interest in phases 1 and 3, but are very interested in the result of phase 3. When the end use, e.g., direct heating, already exists, phases 2 and 3 are more important, and phases 4 and 5 are reduced to retrofit work.

Annual O&M costs are 4 to 6 percent of plant capital costs, and 6 to 10 percent of field capital costs, and thus are 5 to 8 percent of total capital costs.

≠ In parallel with plant construction

The Future

Since 1904, when the first geothermal power plant at Larderello, Italy, became operational, geothermal energy has developed into a proven technology. It has become economically competitive with other forms of energy and an increasingly important contributor to the world's fuel mix.

Recent forecasts suggest about 4,200 megawatts (MWe) of geothermal capacity will be added worldwide between 1994 and 2000. Some of this increase in electricity production will come from an improved ability to harness lower-temperature geothermal resources. Countries that have announced plans for relatively large amounts of new geothermal generating capacity include the Philippines, Mexico, Indonesia, Italy, and the United States. Guatemala, Costa Rica, El Salvador, Japan, and Kenya are also expected to complete significant projects within the next few years. By the start of the year 2000, world geothermal electric capacity is likely to reach about 10,200 MWe, an increase of more than 70 percent over the 1994 level.

Direct-use applications are expected to become even more widespread, primarily because they are technologically simple and highly adaptable to differing environmental and economic conditions. Further, the greatest amount of accessible geothermal energy occurs at temperatures below 150°C, the range most useful for direct-use applications.

Geothermal heat pumps (GHPs) are expected to gain significant markets. They are an effective means of heating and cooling buildings, and providing domestic hot water. The ability of GHPs to reduce daily and seasonal peak electricity demands make them increasingly popular as a load management tool for utilities.

Geothermal hot dry rock (HDR) systems extract energy from man-made fractures in hot rock. Today, HDR systems are experimental. However, as the technology and economics of hot dry rock systems become viable, thermal energy harnessed from these systems can make significant contributions to the existing fuel mix. Results of reservoir tests at the Fenton Hill Site in New Mexico will improve our understanding of man-made reservoirs, their associated flow patterns, and other factors necessary for long-term production.

Continued research and industry experience are key to the continued success of geothermal energy. Improvements in the following areas are expected to have significant impacts: 1) techniques to identify and locate hidden geothermal resources; 2) improved equipment and methods for well drilling and completion; 3) improvements in reservoir engineering, modeling, and management techniques; and 4) advanced materials development and improved power conversion cycles.

Geothermal energy can reduce the risks of sudden fuel supply interruptions or price increases. In such events, the modular feature of geothermal generating equipment becomes attractive. Modularity allows power additions to be made in comparatively small increments while at the same time proving and evaluating the capacity of specific reservoirs. Further, the short lead times, reduced planning uncertainties, and comparatively small capital outlays over short time periods are additional attractions.

Geothermal is a "here and now" energy resource that offers exceptional future opportunities to those nations endowed with this natural legacy. To date, U.S. geothermal firms have installed about 2,800 MWe of domestic electric capacity, and have helped to install at least 700 MWe of international capacity. This experience gives these firms the knowledge and expertise necessary to provide the entire range of equipment and services needed to ensure geothermal project success.

Aerial view of the Fenton Hill Hot Dry Rock site in New Mexico.

Technology Specifics

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Exploration Technology

Exploration is key to the discovery of new geothermal resources. Exploration identifies geothermal resources, estimates resource potential, and establishes resource size, depth, and potential production. Refinements of exploration techniques that evolved from those used in the petroleum and mining industries have made U.S. companies highly skilled in the discovery and characterization of geothermal resources.

Important technology innovations in this area in the past few years include:

- Improved algorithms for interpreting data from geophysical surveys, especially seismic and self-potential surveys; and
- Emphasis on slim-hole drilling as a less expensive method for drilling discovery and resource confirmation wells.

Geothermal exploration of unmapped regions typically proceeds in two basic phases: 1) Reconnaissance, or delineation, of one or more geothermal provinces, and 2) Detailed exploration for exploitable reservoirs within the provinces.

During the first phase, *reconnaissance*, regional geology and fracture systems are studied; such as young volcanic features, tectonically active fault zones (as deduced from seismic information), and overt or subtle geothermal manifestations. To design specific exploration programs, information is collected from various sources, including:

- Regional geologic and geophysical maps;
- Satellite imagery;
- Geochemical sampling of thermal and non-thermal waters and gases;
- Analysis of surface rocks and soils;

- Aerial photography; and
- Measurements of thermal gradients in existing wells.

If the reconnaissance phase confirms that the province has geothermal potential and that specific sites in the province should be explored further, the second phase, *detailed exploration*, focuses on one or more individual prospects.

The first step in detailed exploration is geologic mapping on scales of about 1:6000. The objectives are to understand the broad distribution of rock types, alteration zones, faults, fractures, and thermal features. In conjunction with this work, field geochemical studies are undertaken. The collected information is analyzed and integrated to produce a preliminary model of the area.

Geophysical surveys are then undertaken. Analysis of results of the geologic, geochemical, and geophysical surveys allows refinement of the preliminary model of the area. If all signs remain encouraging, thermal gradient wells are drilled to depths of 100 to 600 meters. These wells provide the first, strong, direct evidence of the location and intensity of thermal energy.

If indications of a hot resource are strong, the first deep hole, a "wildcat well," is drilled. This well is sited based on the integration of all preceding information, and drilled to a depth where production-quality fluids are believed to exist. If the wildcat well is successful, it is followed by additional, production-sized wells to confirm, delineate, and further assess the resource. If all indicators are positive to this point, the geothermal energy project proceeds into the design, financing, and construction stages.

Core samples from a geothermal well. Subsurface rock is collected by installing a core barrel above the drill bit and retrieving cylindrical rock samples to facilitate direct studies of reservoir rock characteristics.

During the late 1960s and early 1970s, geothermal exploration consisted essentially of drilling holes near hot springs. Since then, research, development, and field experience have led to the use of increasingly sophisticated surveys and data interpretation techniques. It is estimated that more effective exploration has resulted, in the last five years, in about a three percent reduction in the overall cost of electricity from geothermal resources. [1]

Detailed Geothermal Exploration Techniques

Surface Geological Mapping - By walking over a prospective area, a geologist can map the various rock and alteration types, sample them for later petrographic study and/or age dating, and note the existence of well developed fault trends. Findings can be combined with observations made using overlapping (stereographic) aerial photographs and available geophysical data (gravity or magnetics). A preliminary geologic model incorporating geologic/geostructural cross sections can then be generated. This model provides a framework for the geothermal system model that will be superposed upon it.

Geochemical Surveys - Usually, while geologic mapping is underway, an accompanying geochemist obtains water and gas samples from thermal and non-thermal springs and wells in the interest area. Waters from streams, lakes, including seawater (if available) are sampled for background purposes. Other samples include rocks for age dating and petrographic studies, hydrothermal alteration products, and possibly soil surveys for mercury or helium.

Geochemists analyze fluid and rock samples for a suite of about 20 elements and geothermally meaningful compounds, such as chlorides of sodium and potassium, arsenic, boron, mercury, silica, lithium, and fluoride. The results are interpreted to obtain: 1) geothermometric subsurface equilibration temperatures, 2) ratios of certain elements (Na:K, Cl:SO₄, etc.) to predict whether the resource is liquid- or vapor-dominated and to understand the thermal history of the sampled fluid, 3) clues regarding reservoir rock types, 4) information regarding the chemical aggressiveness of res-

ervoir fluids, 5) locations of possible recharge sources for the reservoir, and 6) maps of possible fault-controlled upflow zones where hot fluid flows upward from the geothermal reservoir.

Electrical Resistivity Surveys - The spatial distribution of variations in resistivity of the ground can be measured. Measurements can be made using several geometric configurations that include a source and receptors of electrical current. The results are used to identify the most likely location(s) of actively convecting geothermal cells.

Because hot fluids tend to leach salts out of their host rocks, rock conductivity increases and resistivity decreases in geothermal areas. Dry-steam reservoirs are harder to find, since their resistivities can be virtually infinite. Unfortunately, the presence of clays and/or graphite in some rock formations can cause low resistivities similar to those of geothermal systems. In such cases, electrical resistivity survey results can be ambiguous. Nonetheless, electrical resistivity surveys are relatively inexpensive -- in 1994 they usually cost less than \$12,000 per square kilometer. They remain a cost-effective, indirect method for locating geothermal resource concentrations.

Self-Potential (SP) Surveys - SP surveys use inexpensive equipment to measure electrical voltage variations on the earth's surface. These variations are caused by electrical fields within the earth's interior that are generated from and can help to localize: 1) the presence of hot subsurface bodies, 2) the movement of thermal fluids within convecting cells

An Electrical Self-Potential (SP) survey is a geophysical method that can indirectly help locate fracture zones that conduct thermal fluids and/or convecting thermal fluid cells.

and/or along fracture conduits, and 3) the existence of hydrothermally altered rocks. The naturally occurring voltage differences of the electrical fields can be inexpensively measured on the ground surface using the self potential method. The method has been widely used in the mining industry and is now used for geothermal, engineering, hydrologic, and environmental studies. SP measurements on the surface facilitate mapping of underlying areas with positive, negative, and bipolar anomalies. Once an SP anomaly has been correlated with a geothermal cell by drilling, the method can then be used with more reliability to explore for extensions of the known field.

Magnetotelluric (MT) Surveys - Variations in the earth's natural electrical and magnetic fields can be caused by: 1) changes in porosity (and degree of saturation) in reservoir rocks, 2) changes in the degree of rock alteration, and 3) by the effects of elevated temperatures on the magnetic state of rocks. These variations can be measured and the results interpreted using algorithms of two-dimensional finite element or three-dimensional integral equations. The ambiguities that pertain to the resistivity method also apply to the MT system. Results should be combined with those of other surveys to minimize possible false interpretations.

Seismic Surveys - There are two types of basic seismic surveys -- active and passive. Active surveys involve the introduction of energy into the earth by means of explosives, specially equipped "thumper" vehicles, or even hand held hammers. The time taken for different wave forms to bounce off reflecting strata and return to the surface is recorded at various distances from the energy input site. Passive surveys involve monitoring of natural microearthquakes to locate them spatially and temporally in the area of interest. They also involve monitoring attenuation patterns in wave forms emanating from naturally occurring earthquakes centered far from the interest area.

Both active and passive techniques seek to identify the attitudes, thicknesses, fracture density, and degree of saturation of subsurface formations. The methods used are very similar to those in the petroleum industry.

Magnetic Surveys - The earth's remanent magnetism can be measured by very sensitive instruments, either from the air or along the earth's surface. Magnetic highs, regions where the magnetic field is stronger than the local average, may indicate the presence of buried intrusive rocks containing significant amounts of ferromagnetic minerals, especially magnetite. These may constitute heat sources of geothermal importance. Magnetic lows mean that such rocks are not present or, alternatively, that the magnetite in the intrusive body has

changed to non-magnetic minerals through the effects of heat and attendant hydrothermal alteration. Thus, both magnetic highs and lows can be positive geothermal signs; magnetic surveys should always be combined with other surveys to resolve ambiguities.

Gravity Surveys - Dense rocks exhibit a greater gravitational pull than do less dense rocks. Surveys that measure variations in the gravitational field can therefore identify, in three dimensions, the subsurface locations of denser and lighter rocks. Since geothermal systems are commonly found in the vicinity of relatively dense igneous rocks, gravity highs are usually considered to be encouraging. Additionally, they can indicate the presence of siliceous deposits, mobilized by thermal waters, within otherwise low-density rocks. Gravity lows can indicate structural basins in which thermal fluids can collect. Again, ambiguity requires that gravity surveys be interpreted in tandem with the results of other indirect surveys.

One relatively unambiguous attribute of gravity surveys is their ability to locate the traces of major fracture systems (such as the range front faults common in the Basin and Range geomorphic province of Idaho, Nevada, and Utah) that frequently juxtapose heavier and lighter rocks. These fractures can be part of the conduit system needed to keep geothermal cells actively convecting.

Thermal Gradient Well Drilling - After conducting the surveys described above, preferably in combinations, a specific area of interest within a prospective geothermal province is defined. The next recommended exploration activity is the drilling of thermal gradient wells. These are usually small diameter (about 10 cm. or less) and anywhere from 30 to 600 meters deep. They are normally drilled with inexpensive rotary techniques, although occasionally core samples are obtained at greater cost. Once completed, an iron or plastic perforated pipe is set to bottom hole and filled with water. Temperatures are measured after they equilibrate.

A period of thermal equilibration, generally equal at least to the time required to drill the well, is allowed for before further activity. After this period, a thermometer or thermocouple is lowered slowly into the well and temperatures are measured going down and coming up, at predetermined depth intervals. The data are plotted as depth versus temperature, and thermal gradients are calculated for various intervals as well as for the entire well. Wells showing high, conductive gradients are encouraging. Generally, gradients in excess of 4°C per 100 meters are considered geothermally important.

Exploratory Drilling - Once a drill site is selected, a decision must be made whether to drill a slim diameter well (diameter

of about 10 cm.) or to invest in a full-bore well (production diameter) as the first deep exploratory “wildcat” well.

The *slim hole* will yield geologic, temperature, and chemical data. It can not be as accurately flow tested as a full-bore well (especially in situations where a downhole pump is required) and its usefulness as a production or injection well is limited. However, since two slim holes can usually be drilled for the cost of one full-bore well, this is increasingly the procedure of choice. Whichever route is taken, the geoscientific information yielded will determine project continuation.

The first, full-bore, deep, exploratory well drilled in a new geothermal prospect has important repercussions, because it will allow collection of all types of geologic, chemical, physical, and reservoir-related information. Well results will confirm or deny the presence of a resource that previous exploration surveys have postulated to exist. Thus, its success or failure will strongly influence funding for further work at the site. Although the full-bore well costs about twice a slim hole, if the well proves to be productive, it can be used to provide fluid for a temporary wellhead power generating unit. Alternatively, it may be used in the future as a production or injection well.

Confirmatory Drilling - After the first exploratory well (slim or full scale) accesses a geothermal resource, determining the size and degree of uniformity of the resource becomes paramount. To begin delineating and characterizing the new reservoir, confirmation wells (usually three to five) are sited based on the latest conceptual model of the reservoir. At least two offset wells are drilled to facilitate the acquisition of valid reservoir-related information during well testing. As a rule of thumb, these wells are drilled in a triangular arrangement to simplify three dimensional data interpretation.

Confirmation wells are almost always of full bore and are carefully tested to determine their suitability as production or injection wells. If, at any time, the information accumulated during the different stages of exploration indicates that a prospect has little or no potential for commercial development, the work on the project should be

halted, until projects having more favorable signs are evaluated and/or developed. In this way, funds are devoted to exploration of the most deserving prospects and overall cost-effectiveness is maximized. The chart, below, is an exploration decision tree that diverges somewhat from the scheme discussed above, but achieves the same objectives.

When sufficient resources have been confirmed to produce the quantity of energy needed to fulfill power sales or direct use contracts, the exploration phase is finished.

Drilling Technology

U.S. drilling firms, under the direction of geothermal operating companies, have proven to be the world's foremost experts at cost-effective geothermal drilling. This capability has been achieved through experience gained in a wide range of environments -- from the soft rock and high-salinity fluids of the Imperial Valley, California, to the extremely hard abrasive rock and 340°C reservoir temperatures penetrated on the island of Hawaii. Government-funded research has also been key in facilitating the development of advanced concepts and new technology for geothermal drilling.

Important technology innovations in this area in the past few years include:

- Improved drilling bits for medium and medium-hard rock;
- Emphasis on development of methods based on fast-acting cements to handle episodes of lost circulation; and
- Improved high-temperature cements for casings, especially carbon dioxide resistant cements.

Geothermal wells producing fluids for low-temperature, direct-use applications are usually less than 300 meters deep. Often they can be drilled and completed (casing and wellheads) using conventional water-well rigs. Because of the shallow nature of these wells, the only precautions that need be taken are to select proper casing material that can withstand chemical attacks by the geothermal fluid and to plan hole sizes large enough to accommodate pumps capable of producing the desired fluid volumes.

In contrast, power generation systems require deep production and injection wells to produce and dispose of the geothermal fluids. The predominant method for drilling these deep wells is rotary drilling, adapted from the oil and gas industry.

Geothermal drilling technology has been developed by improving certain aspects of petroleum drilling equipment. The major differences between geothermal well drilling and oil and gas well drilling are described below.

- Temperatures of geothermal fluids may reach 400°C compared to 200°C for deep oil and gas basins. These high temperatures cause rapid degradation of ordinary drilling equipment and drilling fluids. The direct temperature effect on materials or the temperature-elevated reactivity of corrosive chemicals in the rocks and brines account for such degradation.
- Production pressures for geothermal reservoirs are usually very low, in many cases sub-hydrostatic. The under-pressured reservoirs can become plugged if ordinary high-density drilling muds are used. To overcome this situation,

Typical Geothermal Well Design

Geothermal well designs, materials, and drilling practices must be closely matched to formation and fluid characteristics. Substantial drilling experience is the best guarantee of success. U.S. firms have completed successful production wells at over 30 diverse worldwide locations.

the use of compressed air, aerated fluids, or foam is required.

- Geothermal formation rocks are usually more abrasive and harder than petroleum formation rocks. These formations severely degrade bits and tubular materials, especially when air is used as the drilling fluid.
- High temperatures cause elongation or expansion of the wellhead and casing. This fact needs serious consideration during the course of well completion, and tolerance for casing motions must be accommodated when designing the wellhead.
- Unlike oil and gas wells in which casing is cemented to provide isolation of potential production zones, geothermal

wells must be cemented from top to bottom to control the effects of casing elongation or expansion due to temperature changes.

- Geothermal fluid production rates are very high -- 100,000 to 500,000 kg/hr compared to 100 to 6,500 kg/hr for oil and gas. Geothermal wells, therefore, must have larger diameters at depth and be cased in ways that minimize erosion.

A number of additional factors and operations affect the drilling and completion costs of geothermal wells including:

- Running slotted production liners;
- Repeated occurrence of lost circulation;
- Frequent conventional fishing operations in a high-temperature environment;
- Disposal or reinjection of geothermal fluids;
- Well testing; and
- H₂S gas production during air or aerated drilling.

U.S. drilling engineers and equipment manufacturers are making steady progress in overcoming problems associated with the difficult conditions of geothermal drilling. Better techniques and equipment have reduced rig time on location by about 15 percent per well from 1986 levels [1].

About one geothermal well is drilled for every 500 oil and gas wells. Therefore, employment of drillers with specific experience in producing *geothermal* wells is critical to the success of a project. Present, deep, geothermal well drilling costs in the U.S. range from about \$300 to \$560 per meter. Geothermal footage costs are two to four times those of oil wells, and tend to vary by year in proportion to changes in oil well footage costs.

Drilling Hardware

Drilling Bits - The ideal bit for an individual well may range from long-tooth bits for soft rock (e.g., shale) to button or insert bits for hard formations (e.g., granite). A major problem when dealing with highly variable formations is selecting the bit which gives best average performance to maintain an acceptable average penetration rate.

Improvements in bearing design and gauge protection have enabled bits to accept greater loads and cut formations faster. Diamond-coated tungsten carbide buttons, the Stratapax bit, and the new Rolling Cutter bit are available for drilling in hard abrasive formations. Diamond-coated tungsten carbide buttons can reduce the overall cost of drilling by about five percent [1]. Further, the reduced gauge wear of some special-

ized drill bits can cut an additional five percent from the total cost of drilling in many relatively deep wells [1].

Bearing Seals - The Y-276 EPDM elastomer is a recent modification of older EPDM made to enhance performance in hot environments. Commercially available Y-276 and other elastomeric materials are used in drill pipe protectors, rotating head seals, and blow-out preventers. The use of new metal-on-metal seals for bit bearings may reduce the total cost of drilling by about five percent in relatively deep wells [1].

Drilling Fluids (muds) - Bentonite, a clay mineral which is gel-like when stationary in water and liquid when in motion, is used as a drilling fluid in relatively benign geothermal environments. Sepiolite clays are used in more difficult conditions and have the following advantages: higher temperature stability; ease of rheological control; less lost circulation problems; and lower mud costs. Surface mud cooling systems are required if the return mud temperature exceeds 75°C. To avoid oxygen-induced corrosion, oxygen-stripping chemicals are included in the mud formulation. Recent improvements in mud formulations have reduced mud costs by as much as 50 percent and have reduced drilling time as well. These savings amount to a five percent reduction in overall drilling costs for most mud-drilled wells [1].

Pipe and Casing Materials - Steels that maintain their strength when exposed to high temperatures and H₂S, and polymer concretes which can be used as corrosion-resistant pipe linings (up to 260°C), are now commercially available. Efforts to develop materials adaptable to geothermal environments have resulted in a 15 percent increase in the mechanical life of production wells (casings and production liners) since 1985 [1]. Hardbanding (reinforcement) of drill pipes can reduce the overall cost of drilling by about five percent in typical, deep, geothermal wells penetrating abrasive formations [1]. Hardbanding is effective and commonly used at The Geysers, California.

Cements and Cementing - The purpose of cementing is: 1) to completely fill the space between the casing and the well wall and between casing strings with a strong impermeable supporting material; 2) to resist aggressive environmental conditions; and 3) to anchor the casing firmly. API class "G" and class "H" cements, together with additives, are commonly used for cementing geothermal wells. The hardened cement sheath must protect the casing against possible corrosion by thermal brines and gases. It must further prevent the uncontrollable flow of thermal water and steam outside the casing. Silica flour, the primary constituent added to reduce strength retrogression, is supplemented with additives such as perlite to reduce cement density. Well cements being used

presently reduce cementing failures by an estimated 20 percent compared to previously used cements [1]. Development of more advanced high-temperature, lightweight, and CO₂-resistant cements is in progress.

Logging Equipment - High-temperature (to 300°C) electronic components and insulators are now available and enable almost all existing well measurement procedures to be applied to geothermal wells. Logging tools are used to measure parameters such as downhole temperature and pressure, geological formation characteristics, flow rates, and the casing condition (degree of scaling or corrosion) during production. Sophisticated acoustic borehole viewers recently have become available to measure more accurately the thickness of fractures associated with lost circulation and production zones. The viewer helps developers detect better flow zones, increasing the average flow rate of production wells by about three percent [1]. At the same time, use of viewers may decrease well cementing problems by about five percent [1].

Rolling Float Meter - This device accurately, simply, and economically measures the rate of drilling fluid outflow from a well. The meter produces an output voltage proportional to the angle of a pivot arm to which a float is attached. The buoyant, counter-balanced float rides the surface of the fluid in the return line. The output voltage is related to the float height, itself a function of the fluid level and, therefore, the flow rate in the pipe. This meter and its software system acquires and analyzes wellbore hydraulic data, advising the driller of lost circulation as it occurs, the magnitude of the loss, its location, and possible remedies.

Drilling Procedures

Lost Circulation Control - Geothermal fluid production zones are relatively underpressured, and are often intersected at unpredictable intervals within a well. Therefore, care must be taken to prevent mud from plugging production zones and from being lost in intermediate fractures. This is usually accomplished by using low density muds, air, or aerated fluid systems whose properties are adjusted when drilling different portions of the well. How-

ever, cementing of selected intervals is often required to seal off zones of substantial lost circulation. Various lost circulation materials, for plugging undesirable fissures, are available and new materials are being developed.

A recent system analysis has found that the lowest overall cost for lost circulation control would generally result from controlled cementing techniques. As a result, two new advanced packers are being developed at Sandia National Laboratories:

- *The Drillable Straddle Packer*: This is an assembly for directing and confining the flow of cement to a lost circulation zone. It prevents channeling of the cement through the mud to the bottom of the wellbore. During operation, cement flows down the drill string, through the upper packer element, out the exit ports, and into the wellbore and loss zones. The differential pressure that develops across the exit ports and into the wellbore causes both the upper and lower packer elements to inflate. This makes the drillable straddle packer different from other commercial packers, which use downhole valving to inflate the packer -- a relatively expensive and cumbersome technique. The drillable straddle packer remains downhole after the cementing operation. Once the cementing operation is finished, the connection between the packer assembly and the drill string is released. The packer assembly is drilled out of the hole after the cement has set.

The Rolling Float Meter measures the rate of drilling fluid outflow from a well.

- **The Porous Packer:** This is a single-element packer assembly made of a permeable fabric. It is deployed either as a wireline-emplaced or drill-string-emplaced assembly. A fast-setting fluid such as polyurethane foam or other polymer is pumped into the packer element. As the packer becomes pressurized and expands, the setting fluid leaks through the fabric at a rate controlled by the fabric permeability, fluid viscosity, and downhole pressure. Once the packer has expanded against the wellbore wall it temporarily prevents or retards the flow of wellbore fluids. Leakage of the setting fluid through the fabric allows the fluid to enter the loss zone and bond with the wellbore and fracture walls. Upon completion of the cementing operation, the packer assembly is uncoupled from the service module or drill string, and drilled out when drilling resumes.

Directional Drilling - Directional drilling provides numerous advantages including: 1) a simpler and cheaper fluid gathering system, reduced land use, and less rig-moving time by drilling multiple wells from a single pad; 2) an increased chance of intersecting major fractures by drilling wells perpendicular to the reservoir formation fractures; 3) improved wellbore deviation control by minimizing unwanted contacts between the drillpipe and the formation; and 4) drilling of very straight wells for the deep setting of line shaft pumps.

Directional drilling methods are adequate for soft and medium formations, and have been improved for harder formations. Current directional drilling tools are still overly temperature-sensitive, requiring further improvements. Downhole motors are effective tools for directional drilling and deviation control in moderate depth and temperature wells. Use of this technology can result in a 15 percent cost reduction of surface piping systems.

Blow-out Prevention - In geothermal drilling, a well can become steam-filled through a sudden loss of circulation and an inflow of hot geothermal fluids. In such cases, cold fluids must be injected immediately and the displaced hot fluids must be released slowly through a surface choke valve. It is also not uncommon to drill through potential production zones under blow-out conditions until adequate production is achieved. This situation is referred to as drilling under "controlled blow-out conditions." Emergency supplies of drilling mud and weighting material should be on site for blow-

out prevention use. Precautions include a conservative casing program, adequate and well maintained blow-out prevention (BOP) equipment, high-quality cementing, and adherence to good cementing practices.

Once a geothermal resource has been identified and undergone preliminary testing, confirmation of the reservoir's extent, fluid flow patterns, and chemical characteristics become the objectives of reservoir engineering studies. These studies start following the drilling of the exploratory well and continue throughout the production lifetime of the field. In fact, substantial analytical and strategic work is continuously required to plot and re-plot optimal field development plans.

Truck-mounted rigs like this can drill geothermal exploration and production-diameter wells down to 2,500 meters in remote locations and difficult terrain.

Reservoir Engineering and Development

Reservoir engineering involves: 1) formation evaluation, 2) reservoir modeling to forecast productivity and longevity, 3) consideration of possible production scenarios (reservoir management), and 4) analysis of production trends. Information derived from these activities is used to formulate a production strategy that balances the cost of delivered power (or fluid) with reservoir longevity.

Important technology innovations in this area in the past few years include:

- Improved methods for conducting and analyzing injection tracer tests; and
- Improved numerical simulation codes for fractured reservoirs.

Accurate quantification of reservoir production and longevity help assure financiers that further investment is warranted. In the past, drilling programs, usually combined with a trial operation period using a relatively small power plant, were the only means available to provide such assurance. Presently, interest has focussed on identifying additional kinds of information to define reservoir characteristics and performance. To assist in information gathering, new sensors, improved logging tools, and analytical software are gaining widespread use. However, long-term production data are still needed to confirm and refine the reliability of reservoir engineering predictions.

Reservoir modeling has become a standard reservoir engineering tool. This technique involves computer simulations that represent the geological structure, permeability, heat input and output, and fluid content of the reservoir. Early hydrodynamic numerical simulations borrowed from the oil and gas industry were based on the theory of porosity-based (matrix) permeability. There is now an increasing awareness that many geothermal reservoirs are associated with fracture-based permeability. Accordingly, the U.S. geothermal industry and research community are currently improving fracture-based permeability simulation models.

Reservoir Evaluation Technologies

Reservoir engineering employs a wide variety of analytical methods and tools to improve the definition of a reservoir, its characteristics, and its governing parameters. The United States has emerged as a world leader in geothermal reservoir engineering through the development and implementation of innovative techniques.

Formation Evaluation

A number of techniques are used prior to production to evaluate the properties and flow parameters of the reservoir host rock, to identify major fluid-bearing fractures and permeable rocks, and to understand reservoir/well interactions. Some of these techniques are listed below.

- Analyses of well logs, drill cuttings, and drill cores derive reservoir parameters such as permeability, porosity, and fracture characteristics.
- Borehole televiewer, caliper, and spinner (flowmeter) surveys confirm the presence and depth of fractures that may be major entry points for steam and hot water.
- Experimental geophysical and geochemical techniques, employing surface surveys and downhole instrumentation, locate and map fractures and other geologic features.
- Analyze deep roots of reservoirs using large-scale seismic arrays that record the patterns of seismic waves passing through and beneath the reservoir.
- Conduct a magnetotelluric analysis of the reservoir structure.
- Monitoring and analyzing injected tracer return patterns define the movement of fluids in the reservoir.
- Laboratory analyses of reservoir rocks and fluid samples determine their constituent properties.
- Pressure-transient well tests determine the controlling flow and storage capacity of the formation, and delineate reservoir boundaries and heterogeneity. The most commonly used tests are:
 - i) Pressure/drawdown - The well is discharged at a constant rate and the downhole pressure drop is measured as a function of time.
 - ii) Pressure/buildup - After a period of discharge at a constant rate, the well is shut-in and the subsequent increase in downhole pressure is measured as a function of time.
 - iii) Injection - Fluid is injected into the well at several constant flow-rate steps while the increase in downhole pressure at each rate-step is determined.

iv) Pressure/falloff - After a period of injection at a constant rate, the well is shut-in and the downhole pressure decline is measured as a function of time.

v) Interference - A well is discharged (or injected) at a constant rate and the pressure drop (or rise) at neighboring wells is monitored as a function of time.

Resource Capacity Estimation and Reservoir Modeling

An initial conceptual model of the reservoir, used to estimate its production capacity, is generated in the early stages of production and continuously updated. The early reservoir model is then expanded from conceptual to a complex two- or three-dimensional numerical model. A variety of methods can be called upon to model a reservoir and estimate its resource capacity, including:

- Conceptual geologic modeling to define the geometry and physical properties of the system;
- Numerical simulation of reservoir behavior under production and injection conditions;
- Geochemical modeling to analyze changes in reservoir fluids and rocks, and to predict the movement of chemical fronts through the reservoir in response to production and recharge;
- Computer analysis of well test data to determine key reservoir parameters; and
- Wellbore simulation to analyze fluid flow and heat transfer inside the well.

Well Field Management and Production Engineering

Well field management optimizes production strategies. Production engineering enables its efficient use. Field management begins with the initial production stage and continues through the entire production period. Techniques include:

- Well field design optimization considering appropriate variations in well locations and depths, production rates and methods, fluid injection locations and rates, and production and injection control strategy;
- Cost/benefit studies of energy extraction rates versus the cost of flashing flow or pumped production;

- Improved injection techniques and injection well replacement strategies to increase production through heat sweep from the reservoir rocks;

- Experimentation with reservoir-permeability increasing methods;

- Use of high-precision cryogenic gravimeters to monitor subsurface fluid movement by changes in mass distribution;

- Studies of water/rock interactions, sources of corrosion, and corrosion mitigation;

- Use of liquid-phase and vapor-phase tracers to understand and trace patterns of fluid movement within the reservoir; and

- Monitoring microseismic activity from production or injection wells to understand the stress vectors in the reservoir area and the distribution of productive and/or receptive fractures.

Determination of Reservoir Production Trends and Longevity

The monitoring of long-term production histories helps to understand a number of key reservoir parameters including: reservoir production trends, reservoir/power plant system performance, and reservoir longevity. Recent advances in computer technology facilitate data storage and analysis, and enhance the use of reservoir simulators. The following methods are also used as part of this effort:

- Long-term monitoring through geophysical measurements and geochemical sampling to detect fluid depletion and recharge ratios;

- Microseismic monitoring of injected fluid to trace flow patterns and associated fracturing processes;

- Numerical simulation of non-isothermal flows of multicomponent, multiphase fluids in porous and fractured media; and

- Numerical simulation of multiphase, multi-component aqueous species and noncondensable gases to model phase partitioning of components, conductive and convective heat flow, relative permeability effects, capillary pressure and flow in fractured media.

Electric Power Plants

Electricity generation using geothermal fluids is a well developed technology. Selection of specific power conversion processes depends on the nature of the resource. Power extraction from steam-dominated resources uses dry-steam plants. Flashed-steam or binary plants are used for liquid-dominated resources. The resource temperature dictates the conversion process to be used and is also a significant driver in the economics. Higher-temperature resources produce lower-cost electricity.

Additional considerations in selecting a power conversion process include brine chemistry and cooling water availability. Adverse brine chemistry increases plant cost if fouling, scaling, or corrosion are significant, or if emission abatement is required. Therefore, the chemical nature of geothermal fluids affects the amount of heat that can be extracted economically from an identified resource. While emissions of undesirable or toxic gases from geothermal plants are insignificant compared to those from other conventional plants, emissions abatement may be required to meet air quality standards in some places. The availability of non-thermal cooling water will enhance performance of the condensing process, contributing to higher output. Adequate quantities of cooling water are thus required for geothermal plants designed with wet or wet/dry cooling systems.

Important technology innovations in this area in the past few years include:

- Modest cost reductions in both flash-cycle and binary-cycle power plants;
- Research on ammonia-based cycles to further reduce binary-cycle plant costs; and
- Conversion of upstream energy through radial-flow or rotary separator turbine-generators.

Energy Conversion Cycles

Steam-Dominated Systems

Dry-Steam Process - Steam-dominated resources are the least common geothermal resource, but the simplest and least costly to develop. Naturally occurring dry steam can be used directly in a fairly standard steam turbine to generate electricity. The steam is produced via geothermal wells and fed to the turbine through insulated pipelines.

Liquid-Dominated Systems

Liquid-dominated geothermal resources are more common. If resource temperatures are sufficiently high ($> 170^{\circ}\text{C}$), the liquid can be partially flashed to steam for use in a steam turbine. If temperatures are moderate (100°C to 180°C), the heat in the liquid can be used to vaporize a secondary organic working fluid, and produce power using a binary cycle plant.

The 50 MWe Heber flash plant, in the Imperial Valley of southern California, is surrounded by farmlands. The plant causes minimal disruption to highly productive agricultural activities in its vicinity.

Single-Flash Steam Process - If the geothermal reservoir fluid is in a compressed liquid state, it partially flashes to steam in the wellbore as it rises to the surface. Additional steam is separated in surface flash tanks and fed to the turbine. The remaining liquid is then disposed of on the surface or injected back into the reservoir.

Double-Flash Steam Process - If resource temperatures are sufficiently high, the fluid can be flashed twice. Flashing occurs in the well and in a first separator at the surface. This separated high-pressure steam is fed to the high-pressure stages of the turbine. The liquid fraction from the first separator is flashed again in a second, low-pressure separator. The additional steam is fed to the low-pressure stages of the turbine. The addition of a second flash stage increases plant efficiency by about 20 percent compared to a single-flash system.

Binary Cycle (Organic Rankine Cycle) - In these systems, the geothermal fluid is used to heat a working fluid with a low boiling point, such as refrigerants, isobutane, or propane. The heat of the geothermal brine is transferred to the pressurized working fluid in heat exchangers. The working fluid is vaporized and expanded through a turbine to produce power, and then condensed and recycled through the heat exchanger in a closed cycle. The cooled geothermal brine is injected into the reservoir.

Hybrid Process - Geothermal waters pass through a heat exchanger, transferring heat to non-thermal waters. Fossil or biomass fuel is then used to boil the geothermally pre-heated water, generating steam that is piped to a turbine. Hybrid plants may be appropriate for resources too cool to generate electricity economically from the geothermal fluid alone. The geothermal fluid may play an economic fuel-saving role in such plants.

Combined Cycles - Flash and binary cycles are sometimes combined to maximize the efficiency with which energy is extracted from a single stream of thermal fluids. Typically, the binary cycle operates in a "bottoming" mode, using the underflow from a flash plant as its input.

Plant Design

An optimum design for geothermal plants requires maximizing the power output for a given geothermal fluid flow rate, while ensuring that the plant capital costs, and operating and maintenance costs are minimized. It also requires sufficient flexibility to permit efficient operation if reservoir conditions change over time.

In sizing large geothermal power plants, it is important to note that: 1) the cost of fluid collection and injection increases as more wells are required, and 2) the relative cost of piping and the amount of heat lost in fluid transmission both increase as the distance between the resource wells and the plant increases. With increased system size, beneficial economies of scale of larger turbine-generators are traded off against the increased cost of the brine gathering system. Currently, the upper limit is about 135 MWe for dry-steam plants and about 55 MWe for liquid-dominated plants.

Plant Cost and Efficiency

Geothermal power costs are sensitive to wellhead temperatures, well flow rates, and well costs. These three parameters determine to a large extent, the economic value of a geothermal resource.

The thermodynamic efficiency of a conversion process (i.e., heat to electricity) increases with higher resource temperatures. The size and cost of many power plant components vary inversely with temperature and directly with total fluid flow through the plant. Power plant costs increase as resource temperature decreases because 1) thermodynamic efficiency declines, and 2) the heat content of the geothermal fluid is also less, requiring more mass per kilowatt. At some reservoirs, however, shallow low-temperature wells can be inexpensive and very productive. Therefore, in some cases low-temperature geothermal resources may still provide cost-effective power.

There are many indications of quantitative improvements in geothermal generating plants. Overall cost-effectiveness is believed to have increased on the order of 10 to 15 percent since 1985 for flashed steam plants [1]. The improved cost-effectiveness for binary plants is believed to be similar.

Continued research is addressing improvements of wellhead separators and two-phase flow lines, and optimizing the interaction between wells and surface facilities. Such improvements will help make power plant inlet temperatures more consistent in the face of long-term fluctuations in the pressure and flow from specific wells. Further, they will reduce energy losses in the fluid gathering system. Much of the improvement in field layout and pipe design comes from computer models of thermodynamic relationships among wells, pipes, and power plants.

The use of distributed control systems is giving rise to highly automated and remote controlled geothermal production facilities. Automation has also enabled increased availability and capacity factors. Computer-assisted fluid production operations are installed at The Geysers in California and are being incorporated at other geothermal facilities.

Small Geothermal Generators

Small-scale (5 to 10 MWe) modular power generating units are serving as "field opener" plants in proving geothermal fields. These units have become valuable in the project development process by providing electricity and revenues quite early in the process.

Modular units can be moved from one reservoir to another or from site to site at the same reservoir. Their use as start-up technology reduces construction costs. They are especially useful in remote areas, where the majority of known geothermal reservoirs capable of power generation are located. The long, non-revenue-producing, lead times associated with larger plants will be reduced with use of modular units. Significant energy and cost savings can also be achieved by using well-head generating units, which eliminate the need for long, costly pipelines.

By adding small incremental units over time, field development can be staged less expensively while generating data with which to refine the reservoir model. Most importantly, the risk element in geothermal development is reduced with the reduction in size and cost, and with the advantages that accrue from mobility.

Recently, much interest has arisen over the possibility of providing very small (100 to 1,000 kWe), self-contained binary units for general use in remote locations. While relatively few geothermal binary plants with capacities less than 1,000 kWe have been built, their on-line availability has been on the order of 98 percent over an operating history of seven to eight years. Such systems, with their high degree of reliability, can be very useful and cost-effective de-

pending on the site-specific nature of the resource. Important markets exist for these systems in both developing and developed countries.

U.S. Experience

The United States leads the world in the generation of electricity from geothermal resources. Starting in 1960, 175 generating units with a total operating capacity of 2,865 MWe had been installed by 1995. The electricity output is equivalent to the use of 25 million barrels of oil per year. Of this total capacity, binary plants generate 172 MWe.

A dramatic increase in the U.S. generating capacity occurred between 1987 and 1990. This increase was primarily due to development in the Coso Hot Springs and Salton Sea liquid-dominated fields in California. Close to 433 MWe of capacity was added in these two fields.

With over thirty years of experience, U.S. manufacturers provide high-performance binary-system turbines, condensers, cooling towers, gas extraction systems, and auxiliary equipment for both binary and flash cycles. They also supply various types of modular and wellhead turbine/generator units. U.S. firms have been engaged in the design and construction of plants throughout the world, and they plan to expand their roles.

Installed geothermal electric capacity has been steadily increasing over the years. The small recent decline in capacity is due primarily to reservoir pressure depletion at the 33-year-old "Geysers" field in California.

Brine Handling

The chemical composition of geothermal fluids varies greatly from one reservoir to another. Similarly, the salinity of geothermal fluids varies greatly, ranging from nearly potable geothermal waters to highly saline brines. Variations in chemistry and salinity affect the design, maintenance, and longevity of wells and surface equipment.

During the early years of geothermal development, limited knowledge of brine chemistry restricted project choices. Projects were selected at high-temperature sites containing chemically benign fluids to avoid scaling and corrosion problems. For example, the high-temperature, high-salinity (150,000 - 200,000 ppm) resources at Salton Sea, California, were discovered more than thirty years ago, but the severe brine chemistry impeded commercial development. Continued research in materials development and brine chemistry has resulted in a number of techniques to mitigate chemistry-related problems. Most of the chemistry-related problems encountered two decades ago are now handled successfully.

Important technology innovations in this area in the past few years include:

- Use of scale-inhibiting chemicals to reduce carbonate scaling of flashing wells;
- Development of acidization approaches ("pH modification") to control silica scaling in power plants;
- Development of highly accurate computer codes to estimate and predict chemistry effects in geothermal systems; and
- Continued development of polymer cement coatings to reduce corrosion in heat exchangers and process piping.

Brine Effects on Materials

Geothermal fluids frequently contain dissolved solids and gases that originate as a result of fluid interaction with the host rock. These dissolved solids and gases include corrosive species such as HCl, H₂S, chloride, and sulfate. The corrosive nature and, at times, high acidity of geothermal brines cause material failures such as stress-corrosion cracking, hydrogen embrittlement, and corrosion fatigue. Problematic chemical reactivity is worsened by higher brine temperatures (150° to 350°C). Temperature and brine chemical characteristics can dictate the selection of power conversion cycles (e.g., flash, binary).

Today, as a result of continued research, a wide variety of corrosion-resistant materials are available. Corrosion and embrittlement can be controlled by proper material selection and appropriate sizing of pipe and vessel walls.

Deposits of scale in pipes presented problems before current brine handling measures were available.

The chemistry of geothermal brines is liable to significant change over the life of a geothermal reservoir. Therefore, a corrosion/material performance evaluation process should be continuously conducted. This evaluation process facilitates material selection for power plant components by providing information about the capacity of materials to survive the anticipated chemical environment.

Geothermal systems are site-specific. However, for a brine falling within well-defined bounds, the technical approaches used at other sites should be sufficient to identify cost-effective power cycles, equipment, and materials. With this in mind, the U.S. geothermal industry has integrated the lessons learned from geothermal power systems placed on-line since the early 1980s, and is capable of handling brine-related problems anywhere in the world.

Silicate Scaling

Geothermal brines can be assumed to be saturated with silica (quartz) at reservoir temperatures. The silica precipitates as temperatures decrease during flashing or heat exchange. Brines saturated with silica are notorious for fouling heat exchangers, scaling flash tanks and surface pipes, precipitating in injection wells, and eventually plugging injection formations. Such problems can occur even when the concentration of total dissolved solids is relatively low. Two technologies -- the crystallizer-clarifier, and the much newer pH-modification process -- are used to control silicate scaling.

- The *crystallizer-clarifier process* forces silicate precipitates to form and remain in the brine stream rather than on equipment surfaces. Silica seed crystals taken from the clarifier solid effluent stream are injected into the first flash vessel. The precipitates are removed from the brine effluent stream in stirred clarifier tanks; the resulting siliceous sludge is dewatered and disposed in landfills. This system has been proved at the Salton Sea geothermal area in California. Plant shutdowns for scale removal are essentially eliminated and injection well life improves markedly.
- The principle of the *pH-modification process* is to keep the silica and other elements in solution by adding hydrochloric acid. This process was first employed by Union Oil of California (UNOCAL) at its Salton Sea Unit 2 facility. At this facility, over 126 kg/s of brine is treated by injecting hydrochloric acid diluted with hot-well condensate at the outlet of the steam separators. At the acid mixing point, the pH of the brine is reduced from 5.9 to about 5.0 by adding HCl equivalent to 100-120 ppm of the brine weight [2]. The

pH-modification process is proving to be an effective method for stabilizing the Salton Sea hyper-saline brines before injection.

An important precaution, when using the pH-modification process, is to use carefully selected corrosion-resistant materials. The potentially higher cost of the corrosion-resistant materials is justified by the cost savings from elimination of some vessels, tanks, pumps, and other equipment required by the crystallizer-clarifier system. Similarly, some of the added operating costs that come with acid use are offset by the elimination of the solids disposal requirement of the crystallizer-clarifier.

The corrosive chemistry of geothermal brines can result in material failures. R&D for corrosion-resistant materials is in progress.

Carbonate Scaling

Many geothermal brines are almost saturated with calcium carbonate, which tends to precipitate whenever brines are produced by flashing flow. When this precipitation occurs in production wells, calcite scaling chokes off the flow very rapidly. Downhole pumps can be used to keep the brine at a pressure high enough to prevent flashing. Their use will minimize scale formation in wells and surface equipment. However, since current downhole pump use is limited to temperatures below 205°C, higher-temperature resources require production by flashing flow. Scales formed in high-temperature wells can be removed by reaming or acid treatment.

The usual present practice is to reduce scaling in flashing wells by using high-temperature, scale-inhibiting chemicals. The inhibitors are injected through small-diameter tubing lowered into the well to a depth below the flashing point. These chemicals appear to have reduced the cost of controlling carbonate scale by approximately 45 percent [1].

Non-Condensable Gases

Geothermal fluids typically contain non-condensable gases (NCGs) consisting primarily of carbon dioxide, but also contain hydrogen sulfide and other undesirable gases. The presence of NCGs reduces turbine efficiency by exerting backpressure at the steam exhaust point. Further, air quality standards can require careful monitoring of NCG emissions, particularly hydrogen sulfide. To overcome this problem, the NCGs must be economically and efficiently removed from the system. Two methods for NCG removal are common.

The first method involves the use of steam-jet or motor-driven gas ejectors to extract NCGs. When the exhaust steam from the turbine is condensed, NCGs accumulate in the gas cooling section of the main condenser. Two-stage steam-jet ejectors are usually used to extract the NCGs from this location. If the NCG quantity is high, a combination of steam-jet ejection (1st stage) and gas compression (2nd stage) is used to reduce the amount of geothermal steam that must be diverted for this purpose.

The second method involves the use of pre-flash separators. If the reservoir brine contains a large amount of NCGs, the gas lifting effect of the NCGs will permit production at high wellhead pressures (300-400 psi). The high pressure will allow the use of a pre-flash separator to vent off most of the NCGs before the brine is flashed to produce high-pressure

steam. The flashed steam is thus relatively free of NCGs. As a result, gas extraction equipment sizes and motive steam consumption are reduced to that required to handle the nominal amount of air leakage into the main condenser.

The high-pressure NCGs resulting from the pre-flash separation can be used to drive a gas expansion turbine and deliver additional power. Alternatively, or additionally, the heat in the NCGs can be recovered in a reboiler to generate more clean, high-pressure steam. Thus, the use of a pre-flash separator and a reboiler can minimize the negative effects of NCGs and maximize the efficiency of flash steam cycles. The pre-flash removal system is used in at least five flash plants at Salton Sea, California.

Chemical Analysis and Modeling

Chemical interactions within the brine as well as reactions between the brine and plant equipment can be complex during flashing. Precipitation of substances causes scaling or erosion, and can also increase or decrease corrosion rates. The composition and rate of precipitation depends on changes in fluid composition, exsolution of NCGs, and operating pressures and temperatures. In the past, only direct field experiments could evaluate the impacts of such interactions.

Recent research has defined some of the necessary parameters to predict the complex chemistry of scaling [3]. The ability to predict when and where scale will form provides numerous benefits: 1) Chemistry-related problems in the design of geothermal wells, pipes, and power plant equipment can be avoided. 2) Scaling and corrosion can be reduced. 3) Handling of non-condensable gases can be improved. 4) Costs can be lowered.

A variable-temperature brine chemistry model has been developed for this purpose. The model can:

- Predict solubility of CO₂ and CH₄ in NaCl, and behavior of CaCO₃ scale formation in NaCl and CaCl₂ brines to 250°C;
- Predict solubility and scaling potential of amorphous silica, NaCl, CaSO₄ in seawater type brines;
- Calculate dissolution-solution characteristics of rock-water systems containing Na, K, Mg, Cl, and SO₄ to 250°C;
- Predict onset of two-phase behavior (breakout) in NaCl brines, including those with substantial loads of dissolved gases, and the gas-liquid equilibrium in the CO₂-CH₄-H₂O system;

- Predict solubility of hydrogen sulfide in the $H_2O-H_2S-HS^-$ system to 90°C and 60 atm;
- Predict enthalpies of brines to 250°C and gases to 1000°C; and
- Predict partial fugacity in the mixed gas system $CO_2-CH_4-H_2O$ to 1000°C and 1000 bar.

Such new understanding of brine chemistry, when applied appropriately, can help increase the life-span of wells and surface equipment.

Additional R&D Progress

Major efforts are underway to develop corrosion and scale-resistant materials. U.S. laboratories are testing thermally conductive polymer cements. These cements have potential applications as corrosion- and scale-resistant liners in heat exchangers and injection pipelines. They can also be used to mitigate corrosion caused by hydrochloric acid in geothermal fluids. Testing of CO_2 -resistant, lightweight cements is also underway. These are expected to substantially increase the mechanical lifetimes of wells at some sites.

Geothermal Brine Handling Technologies

Brine Handling Need	Available Technologies and Practices
Fluid transport and control systems	Wellhead separators Two-phase flow design codes Automated control systems
Production well corrosion, erosion, collapse	Selection of casing materials High temperature cementing Minimizing thermal shocks to wells Minimizing sand scouring Corrosion inhibitors
Production well scaling	Downhole production pumps Scale inhibitors Reaming Cavitation descaling Acidification
Surface equipment corrosion	Materials selection Control of O_2 contamination Chemical treatments Fluid velocity control Corrosion allowance
Dissolved solids handling	Conversion cycle selection Crystallizer-clarifier Chemical treatments Surface coatings, treatments
Noncondensable gases	Gas ejectors Compressors Gas expander turbines Preflash/reboiler Abatement
Injection well and formation plugging	Brine stabilization Filtration Chemical treatments Bioleaching

Direct-Use Systems

Historically, geothermal resources have been used for various non-electric "direct uses" including bathing, cooking, healing, and recreation. Today, low- and moderate-temperature resources ($<150^{\circ}\text{C}$) are used on a much larger scale for applications including district heating and cooling, light industrial and agricultural use, and aquaculture. The diagram on page 30 indicates various low-temperature applications and the required temperature range.

Most direct-use applications employ shallow geothermal waters with low heat contents, and operate on smaller fluid volumes in contrast to electric power generation. Cooler and shallower geothermal waters are also less mineralized, resulting in fewer chemistry-related problems. The reliability, economics, and environmental acceptability of direct-use systems have been demonstrated throughout the world. Conventional fuel price increases over the years have further helped direct-use applications become more cost-competitive and attractive.

Important technology innovations in this area in the past few years include:

- Use of lower cost plastic and concrete pipes for some portions of the system;
- Application of geothermal fluids in heap leaching of precious minerals;
- Modest increases in the overall cost-effectiveness of geothermal heat pumps; and
- Innovative approaches to the installation of the ground-loop part of geothermal heat pump systems.

In the United States, over 300 identified direct-use projects provide about 4,000 GWh of geothermal energy annually -- equivalent to the combustion of more than 4 million barrels of oil per year. Geothermal heat pumps are installed in most states.

In Iceland, an estimated 80 percent of the population enjoys the benefits of geothermal heating. France has become a major user of geothermal energy to heat and cool blocks of buildings in Paris, Lyon, Bordeaux, and Strasbourg. The U.S., Hungary, the former Soviet Union, and Turkey use geothermally heated greenhouses to grow vegetables and flowers. These are but a few examples of nations that are using low-temperature geothermal resources.

Space and District Heating

District heating works by distributing heat (hot water or steam) from a central location, through a network of pipes, to

On the Oregon Institute of Technology (OIT) campus in Klamath Falls, Oregon, 11 buildings are heated and cooled by geothermal energy. The savings amount to an estimated \$250,000 per year over natural gas costs.

individual houses and blocks of buildings. The distinction between *district* and *space heating systems* is merely that space heating systems serve only one building, while district heating systems serve many structures from a common set of wells.

An important consideration in district heating projects is the thermal load density, defined as the heat demand (in kilojoules per hour) divided by the area of the district. A high load density makes district heating economically feasible, because the cost of the distribution network transporting hot water to consumers is shared.

Geothermal district heating systems are capital intensive in the early stages. The principal costs are the initial investments for production and injection wells, downhole and circulation pumps, heat exchangers, and pipelines, as well as the distribution network. The latter includes flowmeters, valves, and control equipment. Operating expenses, however, are comparatively low and consist of pumping power, system maintenance, control, and management. Geothermal district heating systems offer significant life-cycle-cost savings to consumers, as much as 30 to 50 percent of the cost of using natural gas or oil.

One very successful district heating system is in San Bernardino, California. The water production system, consisting of two wells, yields an average flow of 5,200 l/min of 54°C water. The system currently serves 33 buildings including government centers, a prison, a new blood bank facility, and other private buildings. Overall these buildings used 11 GWh of geothermal energy (11,000 barrels of oil equivalent) in 1992. Uses other than district heating include the provision of 1) heat for an anaerobic digester at a sewage treatment plant, and 2) hot water for cleaning the city animal shelter. In 1994, three more facilities were being connected to the system, including two large laundries. This will triple the total heat load of the district.

San Bernardino's successful implementation of a geothermal district heating system in its mild climate is noteworthy. This development demonstrates the very favorable prospects for the hundreds of other geothermal sites located in much colder climates. Currently, over 433 GWh of annual end-use energy is supplied by geothermal fluids for space and district heating in the United States.

U.S. manufacturers provide high-performance downhole pumps and heat exchangers adaptable to geothermal environments as well as high-quality fan coils for heating and cooling purposes. U.S. experts also consult with a number of countries wanting to develop district heating and other direct-use applications.

Industrial Process Heat

Industrial processes can be heat intensive, and commonly use either steam or superheated water with temperatures of 150°C

or above. This makes industrial processes the highest temperature users of geothermal direct-heat applications. However, lower temperatures can suffice in some cases, especially for some drying applications.

Although attractive in terms of fuel savings, widespread industrial use of geothermal energy has not occurred. Part of the difficulty is in situating commercial enterprises close to geothermal sites. Optimum industrial use would result if the geothermal resource occurs near a suitable industrial process or within a short distance.

Two of the largest industrial users of geothermal heat are a diatomaceous-earth drying plant in Iceland and a paper and pulp processing plant in New Zealand. The United States has 13 sites where industrial processing using geothermal heat is conducted, including an onion drying plant in Nevada and a milk pasteurization plant in Oregon. The U.S. uses about 220 GWh of geothermal direct heat annually.

Another attractive application for geothermal heat is heap leaching for gold and silver recovery. Heap leaching is a fairly simple process that eliminates many complicated steps in conventional ore milling [4]. A typical heap leaching operation places crushed ore on an impervious pad. Diluted sodium cyanide solution is sprayed onto the heap and trickles through the material, dissolving the gold and silver in the rock. The metal-laden solution is collected in plastic-lined ponds, and pumped over activated charcoal that absorbs the metals.

Without additional heat, cyanide solutions freeze at low ambient temperatures. In the western U.S., operations have to be suspended up to six months per year, severely reducing the amount of precious metals that can be recovered annually. Of

1993 U.S. Geothermal Direct-Use Projects

Application	No. of Sites	Thermal Capacity (MWt)	Annual Energy (GWh)
Geothermal Heat Pumps	most states	2072	2402
Space and District Heating	126	188	433
Greenhouses	39	66	166
Aquaculture	21	66	346
Resorts/Pool	115	68	426
Industrial Process	13	43	216
Totals		2503	3989

Idealized Thermally Enhanced Heap Leach Process

the 32 active gold mines in Nevada that use heap leaching, 10 are collocated with known geothermal resources. To date, two operations (Round Mountain and Florida Canyon) use nearby geothermal water to heat cyanide and increase recovery. The temperature of geothermal water at these two facilities ranges from 82°C to 98°C. Conventional plate and/or shell and tube heat exchangers are used to transfer heat to the cyanide solution. The cooled geothermal water is injected back to the reservoir.

Greenhouses

Greenhouse heating is one of the most common worldwide applications of geothermal energy. Fruits, vegetables, flowers, and ornamental plants are successfully grown year-round in geothermally heated greenhouses using low-temperature (<38°C) geothermal resources. Even in the coldest weather, the temperatures necessary for optimal plant growth remain stable. Geothermal energy can extend short growing seasons and significantly reduce fuel costs.

The Geothermal Greenhouse Research Facility of New Mexico State University is working to improve the energy efficiency of traditional forced hot air heating and allow greater control of heat delivery. Researchers have found that significant benefits are possible with benchtop heating systems. The benchtop system supplies heat to the bottom of the plants and permits greater temperature control. Root zone heating stimulates plant growth. The system has demonstrated energy savings, increased plant production, and lower maintenance costs during its first year of operation.

A 650-square-meter greenhouse has been built as part of an agricultural park in Lake County, California. A geothermal well 150 meters deep supplies 67°C water. The well is capable of supplying heat for an additional 1,800-3,700 square meters of greenhouses. The facility will be used by the Mendocino-Lake Community College to teach programs in greenhouse management, plant propagation and other vocational activities.

Aquaculture

Aquaculture is the raising of freshwater or marine organisms in a controlled environment. A controlled rearing temperature in aquaculture operations increases growth rates by 50 to 100 percent, increasing the number of harvests per year. Geothermally heated water produces excellent yields of high

This geothermally heated greenhouse near Buhl, Idaho, uses a 44 °C geothermal resource. Geothermal fluid flows untreated through pipes to supply heat that enhances plant growth rate and productivity.

Direct-Use Application Temperatures

quality fish and crustacea under accelerated growth conditions. Further, geothermal aquaculture permits breeding in the winter, allowing fish farmers to harvest their products when product availability is low and market prices are high.

Geothermally heated water is used to raise catfish, tilapia, bass, trout, sturgeon, giant freshwater prawns, and tropical fish. The required water temperature varies with species type. Typically, catfish grow to marketable sizes in 4 to 6 months in 17°C to 24°C water, trout in 4 to 6 months in 12°C to 17°C water, and prawns in 6 to 9 months in 26° to 30°C water [6].

California has six geothermal aquaculture operations. The largest, the Hot Creek Hatchery near Mammoth, uses water from four springs with temperatures of 11°C to 16°C. The warm water feeds directly into raceways and hatcheries and is used to accelerate egg hatching and fish growth. Other successful aquaculture operations are found in Nevada, Idaho, and Colorado.

Geothermal Heat Pumps

The geothermal heat pump (GHP) uses the earth as a heat source for heating or as a heat sink for cooling. A water and anti-freeze mixture circulates through a pipe buried in the ground (vertically or horizontally) and transfers thermal energy to a heat exchanger in the heat pump. The heat exchanger works through a water-to-refrigerant loop. In a typical reversible heat pump, the ground loop heat exchanger rejects heat from the condenser or delivers heat to the evaporator, depending on the mode of operation.

Geothermal heat pumps offer a distinct advantage over the use of air as a source or sink because the ground is at a more favorable temperature. Compared to air, the ground is warmer in winter and cooler in summer. Therefore, GHPs demonstrate better performance over air-source heat pumps. GHPs also reduce electricity consumption by approximately 30 percent compared to air source heat pumps. They can reduce summer peak electric loads by 4 to 8 KW for the typical American residence. This impressive load-reducing capability has led GHPs to become excellent demand-side management (DSM) tools for electric utilities. In recognition of this fact, many U.S. electric utilities and rural cooperatives are promoting the use of GHPs through marketing programs and financial incentives to buyers.

Aided by utility-sponsored campaigns, GHPs are becoming increasingly popular and the U.S. GHP industry is expanding at a rate of 10 to 20 percent

OIT's aquaculture pond used the outflow from the campus' geothermal heating system to raise giant prawns and trout -- an example of cascaded use.

annually. GHPs are installed in most states. At the end of 1993, about 200,000 geothermal heat pumps were supplying 3,200 GWh annually to residences and commercial buildings in the U.S.

The Boise, Idaho, City Hall Annex, a 1,440-square-meter building, uses a closed-loop GHP system for heating and cooling. The system has advanced features that enable it to redistribute heat within the building. Microprocessor-based programmable thermostats keep energy usage at a minimum by gathering data about the building's environment and energy needs, and by controlling several auxiliary functions simultaneously.

Environmental Technology

Geothermal energy is one of the cleanest and safest means for generating electric power. It uses a natural heat source, requires no combustion, and causes minimal disruption to the environment.

Air pollution caused by emission of gases such as oxides of sulphur, oxides of nitrogen, carbon dioxide, and undesirable particulates is extremely low for modern geothermal power plants. Sulphur emission rates are only a few percent of those from fossil fuels, about 0.2 kg/MWh of SO_x compared to 4.7 kg/MWh for oil and 5.4 kg/MWh for coal plants [8]. Nitrogen oxides are essentially not emitted. Carbon dioxide emissions are typically about 45 kg/MWh, compared to 660 kg/MWh for oil and 900 kg/MWh for coal plants [8].

California, a bellwether state for environmental protection, is host to the three largest geothermal power complexes in the world -- The Geysers, Coso, and Salton Sea -- and to numerous direct-heat applications. California's stringent state environmental standards were met, demonstrating that U.S. environmental technology enables geothermal operations to comply with the most rigid environmental regulations.

Land Use

Land use requirements often determine the level of environmental effects. Geothermal development requires only a fraction of the land required for most other energy sources. Only during construction is land disruption noticeable. Once wells are drilled and the construction phase completed, the effects on land begin to diminish. For example, farming or

most other land use practices can continue around wells, pipelines, and power plants after completion of construction work.

The impact of geothermal development on land fertility also has, to date, been minimal. During most of the ninety years of development at Larderello, Italy, the surrounding land has been used for various agricultural purposes. Irrigated crops are also grown immediately next to power plant property lines in the Imperial Valley of California.

Wastes

Hyper-saline geothermal brines produce modest amounts of chemically aggressive solid wastes. This problem occurs at a few geothermal sites and especially at Salton Sea, California. Expensive removal and burial methods were needed to overcome the problem.

Recent advances in biotechnology research are finding solutions to treat and dispose of toxic geothermal sludges. As part of the research, selected species of bacteria are introduced to the geothermal sludge in a bioreactor. The bacteria assist in dissolving the toxic elements found in the geothermal residues. Once the required level of detoxification is reached, the geothermal sludge is suitable for surface disposal or injection, use in inert construction materials, or processing to recover valuable minerals. Such use of biotechnology is expected to be less expensive than disposal of sludges at hazardous waste dumps.

NCG in the circulating cooling waters is dissolved entirely because of the action of introduced "BIOX" agents as shown in the diagram above.

H_2S Abatement

The common H_2S abatement systems used in the U.S. are the Stretford and the Liquid Redox processes. The Stretford process uses an iron catalyst and a rotary filter to remove sulfur and dispose of it as a wet-cake in a land fill. The Liquid Redox process is used to abate both primary and secondary emissions. Gas streams (primary emissions) are abated by absorbing the H_2S in the vent gas and oxidizing it to form water and elemental sulfur. Secondary emissions, from the sulfide-laden cooling tower circulating water, are controlled by adding oxidizing agents to the circulating water and converting the sulfide to sulfur.

In 1987, Union Oil Of California (UNOCAL) discovered that by adding chlorine and bromine-stabilized oxidizing ("BIOX") agents to cooling tower circulating water, secondary emissions of H_2S were entirely abated. This process works by converting dissolved sulfide to a soluble sulfate salt. The oxidizing agents appear to acid-catalyze the reaction, with only a minor consumption of oxygen in the cooling water. Mass balances show that a 90 to 95 percent H_2S abatement, both in the circulating water and vent gas, is achievable by employing the BIOX process. Adding 7 kg of BIOX agents and 54 kg of lime daily converts over 90 kg of H_2S into soluble sulfate [2]. This conversion simplifies waste disposal since the sulfate in the cooling tower can be blown down and pumped to an injection well.

Geothermal Environmental Control Technologies

Potential Problem

Suspended particulate matter during air drilling

Runoff and siltation due to land disturbance

Rock cuttings, spent drilling fluids, oils from wells

H_2S emissions from power plants

Mineral particles in cooling tower drift

Spent geothermal brine and cooling water

**Residues from brine treatment, scale removal,
and H_2S abatement systems**

**Subsidence from large volume withdrawal of
geothermal fluids and hydrological changes**

Seismicity due to fluid extraction or injection

**Noise from operations in which steam
is released to the atmosphere**

Land use conflicts

Wildlife conflicts

Control Technologies Available

Efficient wellhead particulate separators (cyclones)

Modern erosion control techniques such as seeding, mulching, drains and matting

Impermeable sumps, site cleanup

Patented abatement systems available from U.S. manufacturers

Mechanical drift eliminators; acceptable guaranteed drift rate from tower manufacturer. Blowdown control of concentration cycles

Usually subsurface injection with prior surface treatment if needed; biotechnology; surface discharge of innocuous direct use fluid when suitable water body is available

Chemical analysis to determine nature if unknown; biotechnology; disposal in approved hazardous disposal facility if required; land-fill disposal if innocuous

Proper site selection; appropriate well spacing; controlled fluid extraction and injection rates; effective monitoring

Careful siting; knowledge of local seismic history; controlled fluid extraction and injection rates; effective monitoring

Mufflers and silencers

Fencing allowing multiple use; mufflers and silencers

Careful siting, pipeline design modifications. Regional mitigation programs

Socio-Economic Factors

During the past two decades, U.S. firms have gained considerable experience regarding the socio-economic effects of geothermal energy. These effects, in most respects, compare favorably with those from systems using fossil fuels. The main economic difference is that geothermal energy systems substitute initial capital investments for long-term fuel costs. The primary social difference is that geothermal energy has typically fewer environmental side effects.

Electric Power Systems

The cost of geothermally generated power is sensitive, as discussed previously, to a number of reservoir parameters including temperature, permeability, depth, and brine chemistry. Electric power conversion equipment cost is primarily dependent on temperature and chemistry. The overall project cost also depends on the number of wells, their depth, and the length of the gathering and injection pipelines, as determined largely by reservoir permeability. Using current technology, power generation begins to be economically viable at temperatures above 110°C and becomes increasingly profitable as temperatures rise, provided that brine chemistry remains fairly benign.

At U.S. hydrothermal reservoirs now being developed, the 1994 total cost of electricity generation is on the same order as that from coal-fired plants. For geothermal, the first year busbar cost ranges from about \$0.045 per kWh for the best, hottest resources to about \$0.07 for lower-temperature resources. This presumes a reservoir temperature of not less than 150°C, well depths of about 2 km, and average flow rates on the order of 200,000 kg/hr per well. The recent average cost of electricity produced from new coal-fired plants in the U.S. is about \$0.065 per kWh.

Direct-Heat Utilization

Low-temperature geothermal resources have been used in the western United States since the late 1800s for district and space heating schemes. Examples of these early geothermal uses include: the Warm Springs heating district in Boise, Idaho; hotel heating in Ouray, Glenwood Springs, and Steamboat Springs in Colorado; and spa/hotel/residence heating in Calistoga, California. Typically, shallow inexpensive wells were drilled in the vicinity of hot springs and wooden pipes were used to conduct thermal waters to their end-users. The costs of such early systems were nominal and the benefits of not importing coal were many.

Today, geothermal direct use has been taken to great lengths in the United States. District heating costs range from about

\$1.00 to \$4.00 per million kJ, and are competitive with alternative energy sources in many regions.

Geothermal direct-heat utilization is common in many other parts of the world. Iceland uses naturally occurring thermal waters, transported up to 50 kilometers, for district heating. In Denmark and Sweden, large heat pumps are used to boost the temperatures of largely non-thermal waters for use in district heating. Hungary, Poland, and the former Czechoslovakia also have highly developed heating projects that use geothermal fluids from deep geopressured reservoirs.

Geothermal Heat Pumps

There are two basic types of geothermal heat pumps: closet-sized units for small buildings and building-sized installations for district heating use. The social impact of the small units is virtually nil. Once installed, they are less visible and less troublesome than a conventional furnace. The larger heat pumps can be housed in attractive buildings, harmonizing with the nearby community.

Geothermal heat pump economics can be very favorable compared to conventional electric heat or propane, with payback periods as low as three years. The relative advantage of GHPs is greatest in the heating mode. Thus, northern climate installations stand to benefit most. Lower but still substantial economic benefits, with four to seven year paybacks, are enjoyed by users of geothermal heat pumps operating in the cooling mode in southern climates. The fact that increasing numbers of GHPs are being installed from Florida to Canada demonstrates that local electricity economics, not climate, determine the rate at which GHPs obtain market share.

Social Acceptance of Projects

Electric power and direct-use projects can take on special social visibility when they are located near cities or areas with high intrinsic values, such as national parks. Among the design considerations related to geothermal development that affect social acceptance are:

- The siting of an industrial facility in a non-industrial area;
- Waste disposal method/practice;
- Air emissions;
- Siting of transmission line;
- Visibility of facilities and/or condensate plumes;
- Possible drawdown of fluid sources for nearby hot springs or spas; and
- Increased vehicular traffic.

Such considerations can be addressed, and acceptance of projects markedly enhanced, if local communities are consulted during early planning and throughout the project cycle. Federal, State, and local authorities, in partnership with the geothermal industry, should inform the general public about the type of development, its impacts, and its benefits. To avoid any issues that might impede development, public hearings and project-related briefings are essential.

Given the relatively mature state of the geothermal industry, effective mitigation measures do exist for all of these concerns. Mitigation measures can be economically implemented to eliminate and reduce impacts to acceptable levels.

Policy and Regulatory Incentives

Policy and regulatory incentives have helped spur development of geothermal energy in the United States. Similar incentives may have comparable effects in other countries.

Geothermal Steam Act of 1970 - This Act authorized the Secretary of the Interior to issue leases for the development and utilization of geothermal resources on Government lands. It established lease terms such as royalties, duration, acreage limits, and extension of the lease. The Act also defined a Known Geothermal Resource Area (KGRA) as an area in which the geology, nearby discoveries, competitive interests, or other indicators would engender a belief in experts 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. The Act requires competitive bidding for leases of Government lands within KGRA's.

Geothermal Energy Research, Development, and Demonstration Act of 1974 - The Act recognized the Nation's geothermal resources as a potentially significant source of environmentally acceptable energy. It established the Geothermal Energy Coordination and Management Project to coordinate and manage a national geothermal RD&D program. The program included: 1) determination and evaluation of the resource base; 2) research and development with respect to exploration, extraction, and utilization technologies; 3) the demonstration of appropriate technologies; and 4) a geothermal loan guarantee program. The project was managed through the collaboration of Government energy, land management, and natural resources management agencies.

Public Utilities Regulatory Policies Act of 1978 (PURPA) - One of the most important incentives for geothermal development occurred in 1978 with the passage of PURPA. This act established a special category of electrical generators -- Quali-

fying Facilities (QF). A QF is an individual (or corporation) owning and operating a small power production or cogeneration facility, but not primarily engaged in the generation or sale of electric power, i.e., not an electric utility. PURPA further defined a Small Power Production Facility as one where the primary energy is from biomass, waste, renewable resources, geothermal resources, or any combination and where at least 75 percent of the total energy input is from these resources.

PURPA provides a number of benefits to small power producers and cogenerators who become Qualifying Facilities. Specifically, PURPA: 1) requires utilities to purchase the output of small power producers or cogenerators at buy-back rates based on the utility's avoided cost; 2) guarantees the small power producer or cogenerator an interconnection with the host electric utility; 3) guarantees the availability of back-up and supplemental service from the utility; and 4) exempts small power producers and cogenerators from cost-of-service regulation and associated reporting.

Energy Policy Act of 1992 (EPAcT) - This act provides a number of incentives for the development of renewable energy and energy efficiency technologies. It promotes increases in the production and utilization of renewable energy resources, further advances of renewable energy technologies, and exports of United States renewable energy technologies and services.

Permanent Extension of Energy Investment Credit for Geothermal Property - Section 1916 of EPAcT allows for the permanent extension of energy investment credits for 10 percent of the cost of qualified geothermal property. For geothermal property, the credit applies to tangible, depreciable, new property. Property including well casings are eligible for the credit, but power transmission and connection systems are not.

Renewable Demonstration and Commercial Application Projects - Section 1202 of EPAcT promotes the commercialization of renewable energy and energy efficiency technologies through a five year program of Government assistance. Demonstration and commercial application projects are eligible for various forms of assistance such as grants, joint-ventures, cooperative R&D agreements, and interest rate "buydowns." Eligible projects must include at least one for-profit business and require 20% cost-sharing for R&D projects (unless of a basic nature) and 50% cost-sharing for demonstration and commercial application projects.

Renewable Energy Export Technology Training - Section 1203 of EPAcT authorizes the establishment of a renewable

energy and energy efficiency technologies training program, in conjunction with the U.S. Agency for International Development. The program will oversee the training of individuals from developing countries in the system design, operation, and maintenance of renewable and energy efficiency technologies including training in the use of U.S.-manufactured equipment for applications such as water pumping, heating and purification, and the production of electric power in remote areas.

Renewable Energy Advancement Awards - Section 1204 of EPAct authorizes the Department of Energy to make annual renewable energy advancement awards, \$50,000 per year for fiscal years 1994 to 1996, in consultation with an advisory committee. Honorary awards can be made in lieu of financial awards if sufficient funds are not available. Eligible projects should advance the practical application of renewable technologies in utility, industrial, or consumer sectors. Selection criteria include: 1) how the project advances the use of renewable energy; 2) the significance of the impact on people or cost savings; 3) ingenuity; 4) export potential; and 5) environmental soundness.

Innovative Renewable Energy Technology Transfer Program - Section 1211 of EPAct authorizes financial assistance, via the U.S. Agency for International Development, to U.S. firms to promote exports of renewable energy technology and services. In choosing projects, priority will be given to those that obtain cooperation and financial assistance from a host country, use equipment designed and manufactured in the U.S., and offer long-term potential and enhance future competitiveness of U.S. firms in exporting the technology.

Rural Renewable Energy - Section 141 of EPAct authorizes grants of up to \$1 million per State into a revolving fund to finance energy efficiency improvements, including prefeasibility and feasibility studies of projects using renewable energy technology.

Renewable Energy Production Incentives - Section 1212 of EPAct provides for a production incentive payment equal to 1.5 cents/kWh (adjusted for inflation) for energy generated by qualified renewable energy facilities and sold by a state or political subdivision of a state (e.g., a city), and by any corporation or association that is owned by a State (e.g., a publicly-owned utility), or by a non-profit electric cooperative. Qualified renewable energy projects would be eligible for the payment for a ten-year period.

Other Tax-Related Incentives - Current U.S. law permits expensing of Intangible Drilling Costs (IDC's) for geothermal resource development. The expensing of such costs from

project gross income in the project's first and subsequent taxable years, as opposed to capitalizing and depreciating such costs over the project's useful life, provides a tax benefit due to the timing difference of IDC cost recovery. Intangible assets have no salvage value but are necessary for drilling and preparation of wells. Such costs include fuel, labor, repairs, site preparation, well drilling supplies, derrick, tank, pipeline construction, etc. up to the point of commencement of production. Not included are tangible assets with salvage value such as tools, pipes, and well casings.

Current law also permits geothermal projects to determine depletion costs using either percentage depletion or cost depletion methodologies. Under cost depletion, the annual deduction equals the reduction in the remaining value of the resource that results from the current year's additional production. Under percentage depletion, taxpayers deduct a fixed percentage of gross income from resource production, which for geothermal projects is 15 percent. Since percentage depletion is based on gross income rather than on the cost of the underlying assets, the resultant allowances can exceed the actual acquisition and development costs for the property from which the resource is extracted. Annual percentage depletion amounts for geothermal projects are limited to 15 percent of project gross income, and cannot exceed 65 percent of project net income.

The International Scene

This section describes geothermal development activities in many nations near the end of 1994.

Canada

The first Canadian geothermal electricity project is currently underway in the Meager Creek area, 257 km north of Vancouver, B.C. Meager Creek is located in the Coast Mountains, within one of the most geothermally promising parts of the Cascades mountain range. The Meager Creek resource appears to have the potential for supplying about 250 MWe, though the regional potential may be considerably greater. Full Meager Creek development is expected to take approximately seven years, with electricity from the first phase to be on-line by 1995.

China

China is reported to have about 2,500 geothermal manifestations within 30 provinces and autonomous regions. Most of this vast resource contains low-temperature fluids suitable for direct-use applications. Currently, there are over 40 sites at which geothermal direct-use projects have been commercialized. Three examples of these are: cloth dyeing in Tianjin, tannin extraction in Hubei, and hides processing in Hebei. The largest electric power application is in Yangbajing, Tibet, where 19 MWe of China's current 31 MWe is installed. Many of China's plants are small (<1 MWe) flash and binary facilities.

Costa Rica

A 30,000-km², nationwide geothermal survey began in 1987 using geologic, geochemical, and satellite imagery techniques. The first prospect identified by this survey is at Miravalles volcano. The first 55-MWe power plant began operating at Miravalles in early 1994. A second 55-MWe plant is planned for start-up in 1996.

El Salvador

El Salvador was a relatively early geothermal power generator with electricity first produced at Ahuachapan in 1971. Geothermal electricity generation has been given a high priority due to its economic advantages and the relative abundance of resources. In 1992, two 5-MWe wellhead units were installed at the Berlin field; four more units of the same type and capacity are now planned for Berlin and Chipilapa. By mid-1994, El Salvador had 105 MWe of geothermal power on-line.

Ethiopia

Ethiopia has significant geothermal resources in the Ethiopian rift valley and the Afar depression, both of which are part of the great East African rift system. Regional assessments were conducted at ten geothermal localities and pre-feasibility studies were done for three sites. Exploratory drilling has commenced in the Tendaho area of the northern Afar depression. A 5-MWe power plant is also expected in the rift valley at Aluto-Langano within the next two to four years.

France

France has become a significant user of geothermal heat for district heating. In several Paris suburbs and in the Bordeaux region, geothermal waters from limestones at depths in excess of 3 km are being used to heat residences and commercial buildings. Other direct uses include greenhousing, aquaculture, and balneology. In addition, a 4.2-MWe geothermal power plant operates on the French island of Guadeloupe in the Caribbean. Exploration for commercially usable geothermal resources is also in progress on the French island of Reunion in the Indian Ocean.

Greece

High-temperature geothermal resources have been found on the islands of Milos, Nisyros, and Lesvos. A 2-MWe, single-flash, pilot unit was installed at Milos in 1985, generating electricity from high-salinity geothermal brine. A 10-MWe power plant is now planned for Nisyros.

Guatemala

Guatemala is favorably located with respect to geothermal potential because it is the site of a "triple junction" of crustal plates. Pre-feasibility studies were done for the Moyuta and Tecuamburro areas in the southeast of the country, Amatitlan in the central region, and San Marcos in the west. Feasibility studies are completed for the Zunil I field, where fluids from exploration wells provide heat for a vegetable dehydration plant. Feasibility studies are underway for the Zunil II field. There are plans to install 20 MWe by the year 2000.

Hungary

Hungary's low-temperature geothermal resources are mostly located within the Pannonian Basin, where thermal waters with temperatures 30°C and above are used for direct-use applications including production of drinking water, space and water heating, greenhouse heating, and soil heating. Hungary has the largest area of geothermally heated greenhouses in Europe, and has accumulated over thirty years of experience in the design and innovative use of geothermally heated greenhouses.

Indonesia

The first geothermal power plant, installed at Kamojang in West Java, came on-line in 1983 with a capacity of 30 MWe. The plant has since been expanded and has a current capacity of 140 MWe, generating three percent of the electric power in Java. Two small plants at Dieng and Lahendong have capacities of 2 MWe and 2.5 MWe. Two 55-MWe units were completed south of Jakarta, at the Gunung Salak geothermal field in 1994, and funds have been committed to install another 127.5 MWe by 1997. U.S. firms recently signed contracts to develop an additional 900 MWe.

Storage tanks for the Reykjavik, Iceland, geothermal district heating system.

Iceland

Geothermal district heating systems provide heat to approximately 80 percent of all homes in Iceland, with approximately half the population served by the Reykjavik District-Heating Service. Geothermal heat is also used in fish farms; greenhouses; drying of diatomaceous earth, seaweeds, and fish meals; extraction of salts; drying and curing of light aggregate cement slabs; washing and drying of wool; mushroom growing; soil warming; heating swimming pools; and deicing. High-temperature resources at Krafla fuel a 30-MWe power plant. Another 20 MWe is installed as smaller units at Namafjall and Svartsengi.

Italy

With the installation of the first dry-steam geothermal power plant in the world in 1913 at Larderello, Italy became the pioneer of the international geothermal-electric community. The geothermal electric capacity in Italy is now 637 MWe with another 270 MWe planned to be on-line by 2000. Major power plant development is centered in the Larderello, Travale/Radicondoli, and Monte Amiata areas. Direct-use applications have also been increasing, especially for greenhouses and district heating.

Japan

Japan's nationwide geothermal reconnaissance and exploration effort, begun in 1980, continues. Emphasis has shifted to potential electricity production

from reservoirs deeper than those from which hot springs and spas are fed. A new 55-MWe unit was recently installed at the Hatchobaru plant, making it the largest geothermal power station in Japan, with a capacity of 110 MWe. Eight other geothermal power plants accounting for 160 MWe are also in operation. The technologies employed include dry-steam, single-flash, and double-flash. U.S. firms and universities were employed for resource surveys and field development services. Seven new plants are planned or in construction; by 2000 they will add 270 MWe of capacity.

In Japan, many lower-temperature geothermal sources are used commercially for hot baths in resort areas. One notable application of warm waters is in a unique botanical garden featuring tropical plants, crocodiles, and alligators.

The 45-MWe Olkaria geothermal power plant in Kenya.

Kenya

The Olkaria geothermal plant, with three operational units, has 45 MWe of generation capacity. Exploratory and confirmation drilling were carried out at Eburru, and exploration is continuing in several areas of the Rift Valley to inventory resources for future development. Funds are committed for the installation of another 60 MWe.

Mexico

With 752 MWe of operational capacity, Mexico has moved to third place in geothermal development behind the U.S. and the Philippines. The Cerro Prieto field has 620 MWe installed. Los Azufres has 97 MWe and Los Hornos has 35. Most of the units at Los Azufres and Los Hornos are small 5-MWe units. These small power plants will aid in evaluating the resource in those areas, and in planning future power development. U.S. consultants are actively involved in the reservoir engineering at Cerro Prieto and several other sites.

New Zealand

Wairakei, New Zealand, is the site of the world's first geothermal power plant using liquid-dominated resources and

now has 157 MWe of installed capacity. The Ohaaki (Broadlands) plant has been on-line since 1989 with 116 MWe, and a 2-MWe binary unit is operational in the Bay of Plenty area. This puts the total installed capacity at 293 MWe, including 20 MWe privately operated by the Tasman Paper & Pulp mill at Kawerau. Low-temperature waters are used for geothermal space heating and cooling at Rotorua.

Nicaragua

The first geothermal power plant in Nicaragua, a 35-MWe single-flash plant at Momotombo, began operation in 1983. A second 35-MWe unit was installed in the late 1980s. Additional high- and low-temperature geothermal resources are available to fill needs such as power generation, desalting, commercial and industrial air conditioning, refrigeration for fish, and timber drying.

Philippines

With 888 MWe of geothermal power on-line, the Philippines rank second only to the U.S. in geothermal electricity production. A 110-MWe plant is under construction in Bacon-Manito, and the size of this project is expected to double within one or two years after installation of the first

One of the Cerro Prieto geothermal plants in Baja California, Mexico.

plant. A U.S. resource development firm is supplier of all the steam produced from the Tiwi and Makiling-Banahao geothermal fields. The two other fields currently being exploited are Tongonan and Palimpinon. The Philippine National Oil Company (PNOC) and the National Power Corporation (NPC) are collaborating with U.S. firms on the exploration and development of up to six new fields located from Northern Luzon to the southernmost island of Mindanao. Project sizes vary, with up to 400 MWe planned on the island of Leyte alone. Reportedly, Philippine Geothermal Inc. (a UNOCAL subsidiary) has an agreement with PNOC to develop up to 1000 MWe of capacity on a private basis. California Energy Company and Magma Power Company also have active major contracts.

Portugal (Azores)

Most of Portugal's geothermal resource temperatures are below 100°C, confining the potential for geothermal energy to direct use of low-temperature fluids. However, higher resource temperatures are found on the Island of San Miguel in the Azores, where a 3-MWe single-flash power generation unit is in operation.

Russia

The Pauzhetka geothermal power plant on the Kamchatka peninsula is the only operating plant in Russia, with an installed capacity of 11 MWe. Currently, construction is underway for a 50-MWe plant in Mutnovka. Direct-use applications include district heating of seven towns serving a population of 125,000 and the heating of 850,000 m² of greenhouses.

Saint Lucia

Saint Lucia is in the Lesser Antilles, a volcanic chain of islands located above the zone where the western Atlantic crustal plate is subducting beneath the eastern margin of the Caribbean Plate. Exploration for geothermal resources on Saint Lucia started in the early 1950s and two deep exploratory wells

have been drilled to date. Well testing activities are complete but further drilling and testing will be required to accurately characterize the resource and determine whether it can be economically developed.

Turkey

Turkey has substantial high- and low-temperature geothermal resources. A power plant at Kizildere is operational with 20 MWe of installed capacity. Numerous other direct-use projects, mainly for space heating and greenhouses, are also in operation.

Information Sources

Department of Energy Geothermal Program

The goal of the U.S. Department of Energy's Geothermal Program is to establish a scientific and technology base that assists the U.S. geothermal industry in developing specific processes and products at competitive costs in response to increasing energy needs. This goal is being achieved in collaboration with the U.S. geothermal industry. The program strategy is to support research and development that will 1) help the geothermal industry meet critical near-term needs, and 2) provide a technology base through longer-range research for the continued growth of geothermal energy use.

The following major activities are examples of U.S.-Government-funded research being conducted in accordance with the program strategy.

- Advanced techniques to detect and delineate hidden geothermal resources are being developed, including remote sensing techniques and improvements of various electric and acoustic methods.
- Slim-hole drilling/coring, a cost-effective option for exploratory drilling, continues to be investigated. According to preliminary estimates, the cost of exploratory drilling can be reduced by as much as 50 percent if the acquisition of reliable resource data from slim holes proves to be technically feasible. This research includes developing slim-hole reservoir engineering techniques and logging tools.
- Improved materials able to withstand the high temperature and corrosive nature of geothermal brines are being developed.
- Methods to increase the net brine effectiveness of geothermal power plants are being pursued, as are ways to reduce power plant costs.
- Experiments to determine the commercial feasibility of harnessing heat from the hot dry rock reservoir at Fenton Hill, New Mexico.

Government-funded research in geothermal technology is designed to interact with industry's field experience. This cooperation between government and industry improves the probability that geothermally generated electricity will be competitively priced. As technology advances, the geothermal "accessible resource base" will grow, increasing the potential for more power and direct use, and significantly contributing to the world's energy supply mix.

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Geothermal Resources Council (GRC)

The GRC is a non-profit educational association whose purpose is to encourage research, exploration, and development for all forms of geothermal energy. International in scope, it has members in approximately 25 countries, and international members are seated on its Board of Directors. It publishes the *GRC Bulletin*, a monthly magazine of technical and project status information, the *GRC Transactions*, a volume of technical articles presented at the annual meeting of the GRC, and special reports on topics of interest to the industry. It conducts frequent specialized topical workshops on technical, permitting, and financial matters. It publishes an annual Directory of its members. The Directory includes a detailed annotated Registry of U.S. firms that supply geothermal goods and services. *A copy of the Registry is available on request.*

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Geothermal Energy Association (GEA)

The GEA is a non-profit trade association that is open to any company incorporated and 51 percent or more owned in the U.S. The purpose of the GEA is to improve business conditions in the geothermal community and to foster and promote the development and utilization of geothermal resources. The interests of the GEA are international in scope. The GEA publishes statistical information to improve efficiency in the industry and to encourage research and development. It presents industry views to governmental agencies and provides a forum for the industry to discuss industrial problems.

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U.S. Geothermal Industries Corporation (USGIC)

USGIC is a consortium of American geothermal technical service, project development, and equipment manufacturing firms that have organized to provide integrated geothermal project development services internationally. Its shareholders are all firms that have received Certificates of Review from the U.S. Departments of Justice and Commerce that confer substantial antitrust immunity with respect to their coordinated activities offshore. The member companies combine their strengths as geothermal project developers and their opportunities for utilizing several forms of financial incentives for such projects from U.S. Government agencies. USGIC is able to conduct all essential geothermal system development-related activities including: resource exploration (geological, geochemical, geophysical), environmental assessment, permit acquisition, drilling and completion, well testing, reservoir engineering, field design, gathering system design and construction, customized control system design and installation, and power plant and transmission line design, construction, operation, and maintenance.

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3	Geothermal Resources Council (top); California Energy Company, Inc. (bottom)
5	Ormat, Inc.
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Appendix

Glossary of Geothermal Terms

ANOMALY	In geology, a local feature distinguishable through a geological, geophysical, geochemical, or geobotanical measurement over a larger area in which it is contained. Also, a feature that is or has the potential of producing commercially valuable resources.
BALNEOLOGY	Science of the healing qualities of baths, especially natural mineral waters; the therapeutic use of naturally warm mineral waters; the study of hot water bathing.
BASELOAD POWER	Electric generating units that are operated to meet the constant or minimum load on the system. The cost of energy from such units is usually the lowest available to the system.
BINARY-CYCLE PLANT	Fluids are circulated through a heat exchanger to transfer heat to a low-boiling-point hydrocarbon propane. The hydrocarbon vaporizes and forces a turbine to spin and generate electricity.
CASCADING HEAT	A direct-use utilization process that uses a stream of hot water to perform successive tasks requiring lower and lower temperatures.
CASING	A heavy pipe or tubing of varying diameter which is lowered or driven and usually cemented into a borehole during or after the drilling of a well. It supports the sides and prevents caving, loss of fluids, and the contamination of near-surface potable water. It also prevents unwanted gas or water from entering the hole from other than the desired aquifer.
CONDENSER	Equipment that condenses turbine exhaust vapor into condensate.
COOLING TOWER	Structure in which heat is removed from hot power plant (condenser) cooling water.
CORROSION	A complex interaction between a geothermal fluid (its chemistry, temperature, velocity and pressure) and materials in a geothermal energy conversion system. Corrosion includes uniform removal of material along with crevice corrosion, hydrogen blistering, and stress-corrosion cracking.
CRUST	The outermost layer of the earth, composed of relatively cool, brittle, low-density rocks (compared with the mantle), and ranging in thickness from 5 kilometers (beneath the oceans) to over 50 kilometers (continents).
CRUSTAL PLATES	Huge regions of the earth's crust that are in a state of continual relative motion averaging a few centimeters per year. There are six major crustal plates and a few smaller ones (see Plate Tectonics).
DEMAND-SIDE MANAGEMENT	Management practices by electric utilities to reduce the need for new power plant capacity by helping customers reduce consumption of electricity. Energy efficient equipment and improved behavioral practices are emphasized through education and direct subsidies to consumers. To encourage such practices, regulated utility firms are often allowed to earn profits from such conservation activities.
DIRECT USE	Sometimes referred to as non-electric use or direct-use applications, refers to the use of heat energy rather than to its conversion to electrical energy. Primary direct uses include bathing, balneology, space heating and cooling, agriculture, aquaculture, and industrial processing.

DISTRICT HEATING	A utility system serving multiple users with some form of heat energy or geothermal hot water from a central plant or well field. A single-pipe (open-ended) distribution network or a two-pipe system for recirculation of the fluid can be used. Heat exchangers may be used to separate corrosive fluids from the individual user systems. Heat pumps and fossil fuel peaking and storage tanks may be part of the system.
DRILLING MUD	A suspension, generally water based, used in rotary drilling. It is pumped downward through the drillpipe and returns upward outside the drillpipe to seal off porous zones and to counter-balance excessive pressures in production zones. It also serves to cool the drilling bit and to carry rock cuttings to the surface.
DRY STEAM	Superheated steam, i.e., pure vapor with no liquid.
EFFICIENCY	The ratio of the useful energy output of a machine or other energy-converting plant to the energy input is called the First Law efficiency. The ratio of the useful output to the available work in the energy supplied is called the Second Law efficiency.
ELASTOMERS	Flexible lining materials, used in tanks and pipings, with the ability to bond to steel.
FAULT	A fracture or fracture zone in the earth's crust along which slippage of adjacent rock or sediment has occurred at some time in the past.
FLASHING	Conversion of a portion of a hydrothermal liquid to steam by decreasing the pressure on the liquid.
FRACTURE POROSITY	Porosity resulting from the presence of openings produced by the breaking or shattering of a pervious rock unit.
FUMAROLE	A vent at the earth's surface which emits steam or gaseous vapor, usually found in volcanic areas.
GEOCHEMISTRY	Chemistry of the earth; applied in geothermal exploration and production to measure resource potential and chemical changes during production.
GEOLOGIC MAP	A map showing surface distribution of rock types, age relationships, and structural features.
GEOLOGY	A study of the planet Earth; its composition, structure, natural processes and history.
GEOPHYSICS	Physics of the earth; applied geophysics uses various methods to detect physical characteristics of the rock within the earth to delineate geologic features or locate usable resources.
GEOTHERMAL ENERGY	The internal energy of the earth, available to man as heat from heated rocks or water.
GEOTHERMAL HEAT PUMPS	Devices which take advantage of the relatively constant temperature of the earth's interior using it as a source and sink of heat. These devices are used for both heating and cooling purposes. When cooling is needed, heat is dissipated into the earth. Conversely, when heating is needed, heat is extracted from the earth.
HEAT EXCHANGER	Device used to transfer thermal energy from a fluid flowing on one side of a barrier to a fluid flowing on the other side, e.g., an automobile radiator.

HEAT FLOW	Movement of heat from within the earth to the surface where it is dissipated into the atmosphere, surface water, and space by radiation. The average heat flow is about 60 milliwatts/cm ² .
HEAT PUMP	A device which, while consuming energy, extracts heat from one medium and causes heat to be enhanced in a second medium. In conventional usage, the term is usually limited to a device whose useful output is heat.
HOT DRY ROCK (HDR)	Subsurface geologic formations of abnormally high heat content containing little or no permeability, and therefore, no natural fluid.
HYDROGEN SULFIDE	A poisonous, flammable gas of disagreeable odor frequently found dissolved in geothermal waters in small amounts.
HYDROSTATIC	The force per unit area acted upon a body of liquid in static equilibrium.
HYDROTHERMAL	An adjective applied to hot aqueous liquid or vapor, to the processes in which they are involved and to the rocks, ore deposits and alteration products produced by them. Hydrothermal solutions are of diverse sources, including magmatic, meteoric and connate waters.
INJECTION	Process of returning spent geothermal fluids to the subsurface, sometimes written as reinjection when water is actually being circulated.
KILOWATT	1,000 watts -- a unit of power.
KILOWATT-HOUR (kWh)	The energy represented by one kilowatt of power consumed for a period of one hour, equals 3,413 Btu.
MEGAWATT	1,000 kilowatts, a measure of generating capacity. MW_t = thermal power in megawatts, MW_e = electrical output in megawatts (roughly one-tenth of the MW_t after conversion).
NON-CONDENSIBLE GASES	Gases usually contained in geothermal steam or water which do not condense in a powerplant system, e.g., CO ₂ (carbon dioxide), H ₂ S (hydrogen sulfide), CH ₄ (methane), etc.
PEAKING PLANTS	Electric generating plants that are operated to meet the peak or maximum load on the system. The cost of energy from such plants is usually high.
PERMEABILITY	The capacity of a substance to transmit a fluid. Degree of permeability depends upon the size and shape of the pores and/or fractures and their interconnections and the extent of the latter. It is measured by the time it takes for a fluid of standard viscosity to move a given distance. The unit of permeability is the Darcy.
PLATE TECTONICS	A theory of global-scale dynamics involving the movement of many rigid plates of the earth's crust. Considerable tectonic activity occurs along the margins of the plates where buckling, grinding, faulting, and volcanism occurs as the plates are propelled by the forces of deep-seated mantle convection currents. This has resulted in continental drift and changes in shape and size of oceanic basins and continents.
POROSITY	The ratio of the aggregate volume of pore spaces in rock or soil to its total volume; usually stated as a percent.

RECONNAISSANCE	The initial geologic and economic investigation of a large area in order to locate potential geothermal prospects and drilling targets.
RESERVOIR	A natural underground void containing liquids, such as water or steam. In general, geothermal reservoirs are formed by local deformation and faulting of strata causing fractures and, therefore, changes in porosity and permeability.
RESISTIVITY	A fundamental electrical property of materials indicating how well the material conducts electricity; this varies widely with rock type, porosity, temperature, and salinity, usually expressed in ohm-meters.
RESISTIVITY METHOD	Observation of electric potential and current distribution at the earth's surface, intended to detect subsurface variations in resistivity that may be related to geology, ground water temperature and quality, and porosity.
SCALING (Scale)	Deposition of dissolved solids in pipes or other vessels from cooling geothermal fluids.
SCRUBBERS	Devices used to remove water, contaminants, and other foreign materials from steam.
SHUT-IN WELL	A term used by well operators to describe the status of production wells that are not being produced or vented to the atmosphere.
SPACE HEATING	The process of supplying the required heat for the comfort of human beings or commercial necessities in houses, schools, offices, or industrial buildings. The heat required for a typical domestic dwelling on an average winter day in the U.S. is about 27,000 Btu/hr or 7.8 kW.
SUBSIDENCE	A sinking of an area of the earth's crust due to fluid withdrawal and pressure decline.
TDS (Total Dissolved Solids)	Used to describe the amount of salts dissolved in water usually given in parts per million (ppm) or weight.
TECTONIC	Refers to those processes by which rocks of the crust and upper mantle are deformed (faulted, fractured, folded).
TEMPERATURE-GRADIENT SURVEY	The study of precisely measured temperatures at successive depths in a drill hole in order to determine the rate of temperature increase with depth.
THERMAL GRADIENT	Pertains to the rate of increase or decrease in temperature with depth.
THERMAL SPRING	A spring issuing waters significantly higher than the mean annual temperature for that area (20°C higher than ambient -- U.S. Geological Survey designation).
TURBINE	A bladed, rotating engine activated by the reaction or impulse, or both, of a directed current of fluid.
VAPOR DOMINATED	A geothermal reservoir system in which subsurface pressures are controlled by vapor rather than by liquid. This type of occurrence is sometimes referred to as a "dry-steam" reservoir.
WATT	A unit of "power" (energy per unit time) equal to 3.4 Btu/hr.
WELL LOGGING	Assessing the geologic, engineering, and physical properties (resistivity, velocity, density, etc.) and characteristics of geothermal reservoirs by physical or electrical instrumentation deployed in a borehole.