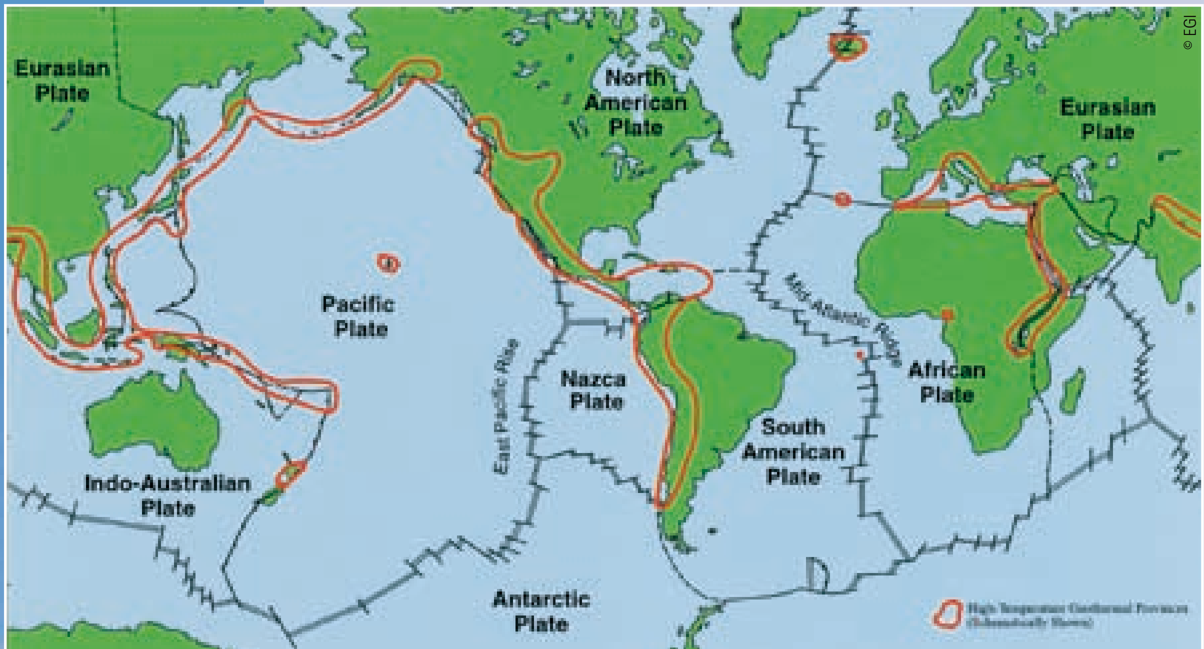
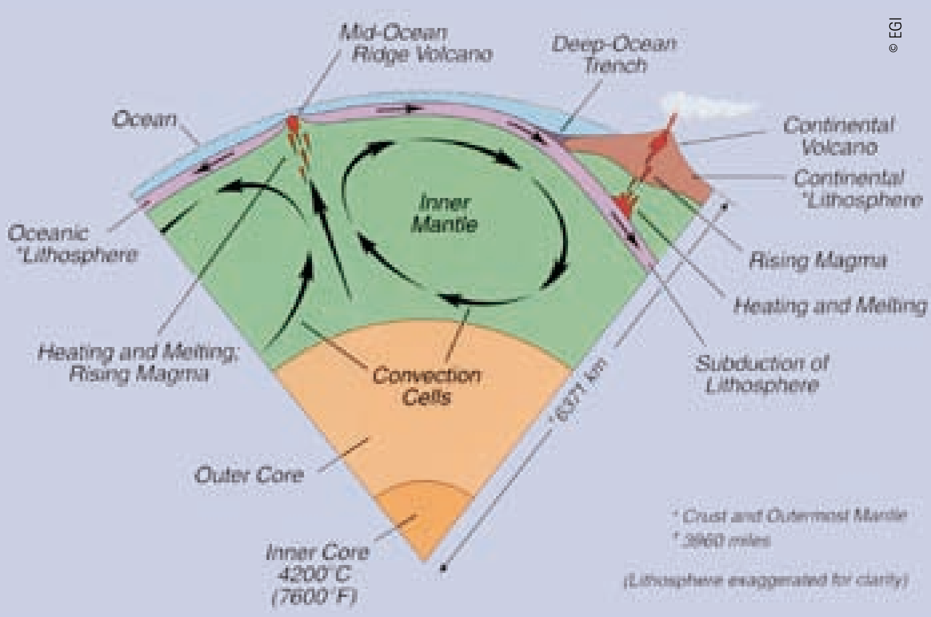
A Bright Future for Geothermal Energy

Geothermal energy is a clean, readily available, and renewable natural resource. Yet the near limitless potential remains largely untapped accounting for only a very small percentage of the total amount of energy we use today.

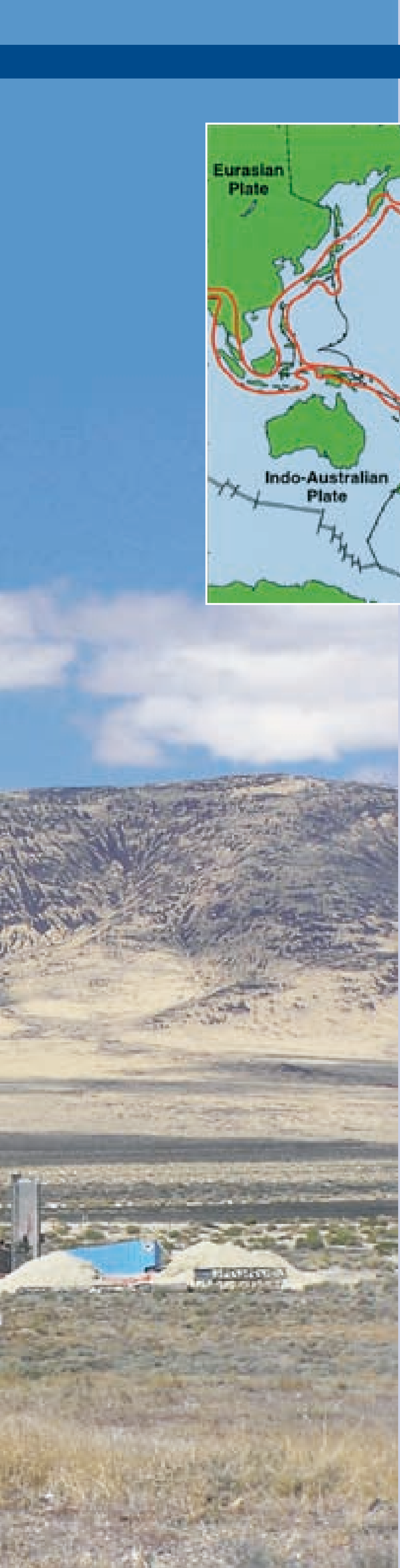
© Tom Smith



The world's geothermal provinces and plate boundaries indicates areas of high temperature resource potential (outlined in red).



Dynamics of the earth's convection cells and areas of rising magma where heat flows are the highest.



Geothermal energy can be seen rising in the form of steam in front of this well being drilled at the Brady's geothermal field in northern Nevada, 70 km northeast of Reno.

Thomas Smith, Associate Editor

Surface geothermal waters in the form of hot springs and thermal pools are familiar indicators of shallow heat anomalies. For centuries, man has used these for bathing, cooking, medicine, and heating (GEO ExPro Vol. 2, No 1, 2005).

The first geothermally generated electricity was produced from steam in a tectonically active area in southern Tuscany, Italy, at Larderello, in 1904. Since those first steps, new technologies have been developed that enable wider use of geothermal energy to generate electricity from waters as cool as 74°C. Consequently, there is a growing awareness of the value of geothermal as a clean energy source and the sheer magnitude of its potential.

Currently 21 countries generate electricity from geothermal sources. Large and small private energy companies (including Calpine, Chevron, INEL, Ormat), and national utilities are actively searching and developing geothermal energy. In fact, Chevron, a major oil company, is the world's largest producer of geothermal electricity with operations in the U.S., Indonesia, and the Philippines. Over 25% of Iceland's electrical needs are generated with geothermal energy. All these areas lay near plate boundaries (see world geothermal provinces map below).

Heat from Within

Heat inside the earth is generated primarily from the decay of radioactive isotopes with some heat left over from the fiery formation of the planet. The temperature gradually increases from the surface down to the 4200°C in the earth's inner core. This heat moves upward to the surface and is continually radiated into space. The average geothermal gradient for the earth is about 25ºC/km. It is highest in volcanically active areas like island arcs where the temperature increases by about 30-50°C/km and is lowest in areas such as the ocean's trenches where the temperature increases only 5-10°C/km.

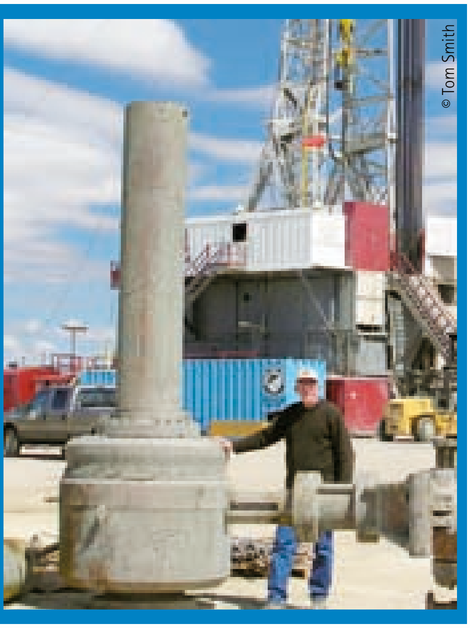
Enormous thermal-convection cells slowly circulating in the earth's asthenosphere (the hot, soft, easily deformable portion of the mantle) have caused the planet's thin, rigid lithosphere (the uppermost mantle and the overlying crust on which we live) to break into vast tectonic plates. Most of the world's high-temperature geothermal provinces are located along **plate boundaries**.

Other areas of higher heat flow originate from **hotspots** above isolated, enigmatic asthenosheric plumes, such as those rising beneath the Big Island of Hawaii and Yellowstone National Park in the state of Wyoming. Along the plate boundaries and under the world's hot spots, rising magma ▶

Geothermal Energy

The word geothermal comes from the Greek words geo (earth) and therme (heat). By geothermal energy we mean heat from within the earth. Geothermal energy is a renewable energy source because heat is continuously produced inside the earth.

The technology for drilling and developing geothermal energy has to a large extent been borrowed from the oil and gas industry. However, in order to achieve the large flows required from geothermal wells, production wells are completed differently than oil and gas wells, typically with 9 inch or larger casing diameters.



© Tom Smith

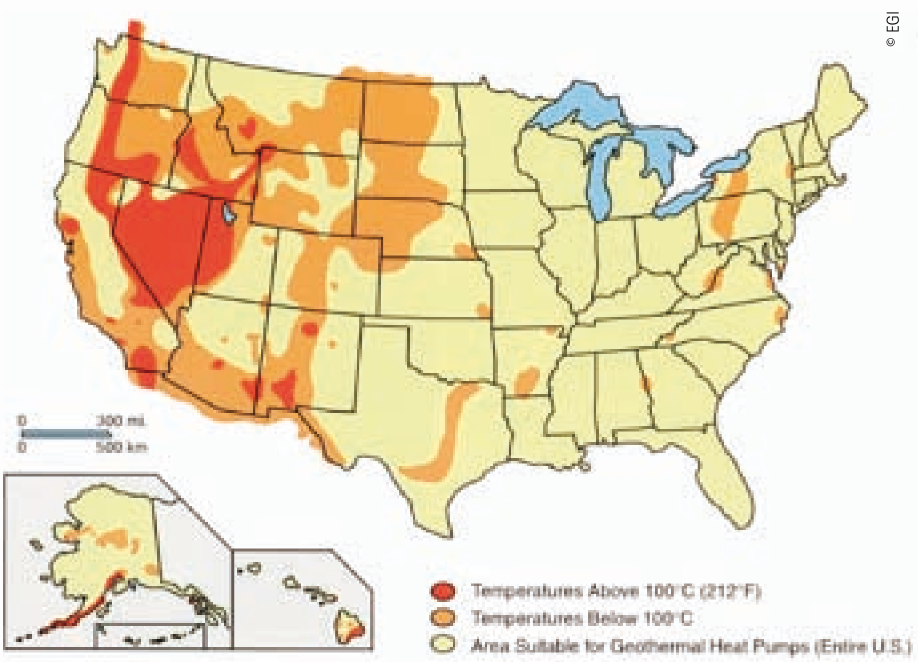
Temperature is the decisive factor

Geothermal energy can be utilized just about anywhere in the world. The resource temperature dictates the type and efficiency of use.

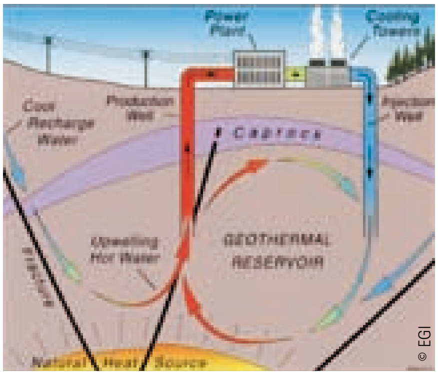
Geothermal heat pumps, which exploit **low-temperature** ground heat, can be widely used to efficiently heat and condition the workplace, schools, and homes.

In higher heat flow areas, **thermal waters** (35 to 150°C) are piped directly from the ground to support municipal heating systems, aquaculture, and greenhouses.

The hottest systems (generally greater than 150°C) use **geothermal steam and hot water** to generate electric power. This source now accounts for 5% of California's electrical generation and 10% for northern Nevada.



Areas of highest heat flow are concentrated in the western states.



Typical high-temperature geothermal system used to generate electricity. Heated at depth, groundwater becomes less dense than the surrounding water and rises through the fractures until encountering the cap rock. This hot water is tapped by production wells. Some of the fluid may leak through the cap rock to form hot springs, fumaroles, and geysers, or reach depths shallow enough to be encountered in water wells and mineral exploration holes. As the water beneath the cap rock moves laterally away from the upwelling center and cools, its density increases. Cooled produced water is also injected back into the system This cooler water descends along the margin of the system where it is be reheated, beginning another cycle. The resulting hydrothermal convection cell can be very stable, lasting for tens to hundreds of thousands of years or more.

ascends through the upper mantle and into the lithosphere sometimes resulting in volcanic activity at the surface. This rising magma creates areas where shallow geothermal systems can be harnessed for their energy.

High-temperature convective geothermal systems, concentrated along the tectonic active areas near plate boundaries, are the most valuable and sought after commodities for geothermal electric power generation. To be viable in this regard, these systems require: 1) heat, which can be supplied by shallow magma bodies or deep circulation of fluids in areas of high geothermal gradients; 2) a supply of water, usually ground water; 3) adequate permeability through interconnected fractures; and 4) a seal or cap rock that confines the thermal fluids.

Exploration

"Geothermal exploration has not appreciably changed since we started exploiting this resource," says Dr. Joseph Moore a geothermal researcher at the Energy and Geoscience Institute (EGI) at the University of Utah. "We rely on surface indicators of rising heat such as steam vents, hot springs, and volcanic activity much like the oil industry used oil seeps to locate prospects around the turn of the century."

Jeff Hulen and David Langton examine core from geothermal drilling. Located in the heart of Salt Lake City, Utah, the EGI Geothermal Sample Laboratory contains over 520,000 kg of geothermal drill cores as well as drill cuttings. These represent several hundred kilometers of deep geothermal drilling completed around the globe at a cost in excess of 2 billion U.S. dollars. Research on these invaluable subsurface samples has enabled important scientific breakthroughs in the understanding of volcanoes and high-temperature magmatic-geothermal systems.

Some of the information for **Exploration**, **Zeroing in** and **Testing the Prospect** is from "Exploration Strategy for High-Temperature Hydrothermal Systems in Basin and Range Province", Ward and others, AAPG Bull. January, 1981. The paper was prepared at the University of Utah Research Institute. Dr. Moore was one of the reviewers and still considers this paper to be one of the best to define geothermal exploration.

In fact, most potential areas have been inventoried for the locations and descriptions of surface geothermal activity as well as any wells that have encountered heat anomalies. Many of the current systems in operation have such surface expressions of geothermal activity.

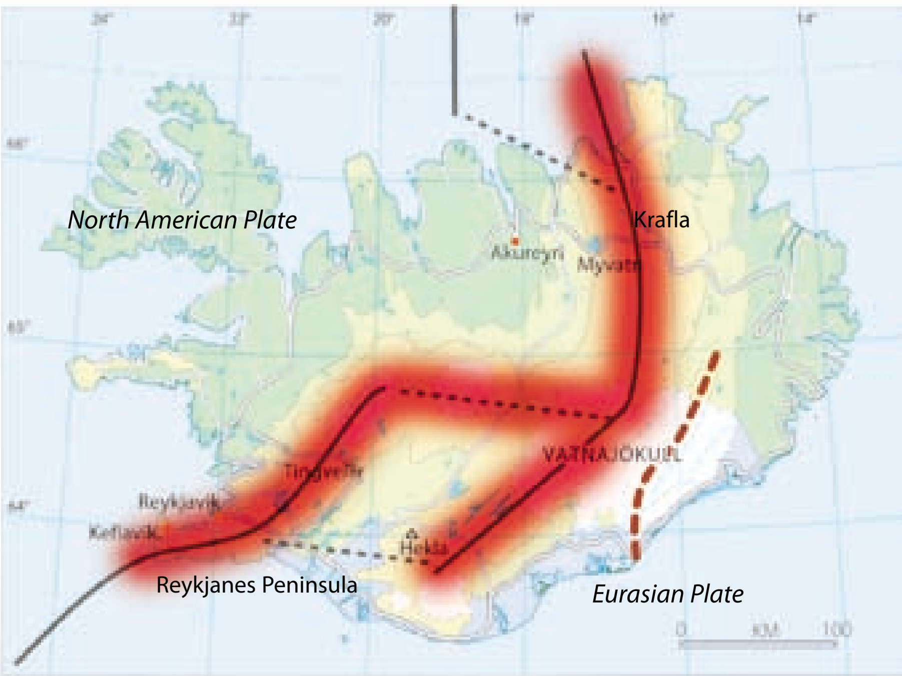
"Evidence of thermal activity at the surface thus remains the first line of exploration", Moore says.

However, many areas have little or no surface expression. **"The geoscientist is the most important tool in exploring for geothermal prospects,"** according to Jeff Hulen. "Once potential areas of higher heat flow are identified, the geologist obtains and analyzes satellite imagery and available geologic maps, then completes additional, much more detailed mapping to delineate fault and fracture trends that could be key controls for underlying, concealed geothermal systems."

"A variety of geophysical and geochemical techniques then can be applied for more confident characterization of the resource in advance of actual exploration drilling. Curiously, in the State of Nevada, geothermal prospecting has much in com-

Surface indicators of geothermal activity include fumaroles, hot springs, and geysers. Some potential geothermal prospects are found by accident. At Soda Springs, Idaho, hot water was found while drilling a water well to supply a municipal swimming pool.

The map shows the rift that transects Iceland with the North American Plate to the left and the European Plate to the right. In Iceland, geothermal energy is coming from both low temperature areas, outside the rift zone, and high temperature areas, inside the rift zone (colored red). The high temperature zone is also associated with volcanism.



The geothermal power plant in Krafla, Iceland, is using hot steam and has been operating since 1977. Altogether 33 wells have been drilled in the area to get sufficient energy. Attempts are now being made to multiply the output by drilling into superheated water with temperatures in the range of 450-600 °C.

© Tom Smith

Geologists Jeff Hulen, formerly with EGI, now a consultant, and Stu Johnson of Ormat, a major developer of geothermally generated electricity. Both have many years of experience in geothermal exploration and research. "There are many prospects yet to be found," claim both Jeff and Stu, "many without distinct surface indicators. A lot of detailed geologic work goes into finding these "blind" prospects".

mon with the search for gold deposits, which in essence are nothing more than fossilized geothermal systems."

Many of the techniques in oil and gas exploration are also used to locate geothermal systems. Of particular importance are chemical analyses of hot springs and fumaroles, which help to estimate subsurface reservoir temperatures, and electrical resistivity surfaces, which can be used to locate areas of subsurface alteration and hot fluids. Gravity, magnetic, and seismic surveys can help delineate faults.

Zeroing In

Once high priority prospects have been identified, shallow, generally less than 1000 m, thermal-gradient wells are drilled. Temperature measurements are the primary product of the drilling. Other studies of the drill holes include thermal conductivity measurements on rock samples that permit gradient measurements to be converted to heat flow. Lithologic and alteration logging of cuttings yield information on rock types, fracturing, and hydrothermal alteration that can be tied to the results of surface mapping. This technique is used to gain an improved understanding of the targeted geothermal resource at depth.

A conceptual model is now made to integrate the prospect-specific geologic mapping, geochemical, alteration, and thermal-gradient information with the regional database. The geoscientist can estimate the lateral extent, depth, heat-source types, and temperature of the prospect. Detailed geologic and heat flow mapping, resistivity, self-potential surveys, and the drilling of slim holes (commonly cored borehole drilled to 300 to 1000 m) can be done to complete the conceptual model at depth.

Testing the Prospect

All exploration work outlined above still does not guarantee success, but must be done to minimize the risk of drilling poorly placed production wells. Drilling the production test well is by far the most expensive and riskiest portion of finding and developing a geothermal field. As drilling progresses, the conceptual model of the resource is refined and the risk decreases.

"To be successful for the purposes of generating electricity, production wells must yield large quantities, about 2,000 gallons (7.6 m^3) per minute (69,000 b/11,000 m^3 per day), of hot water," says Stu Johnson of Ormat.

Once substantial flows are established by test wells, injection wells need to be drilled to continually recharge the convective system. Most of the fields have a ratio of 2 producers for every injection well. All produced water is reinjected to maintain reservoir pressure. Production and injection must be carefully managed so that temperatures and pressures are maintained.

Mud logger, Neil Peterson, of Horizon Well Logging, looks for evidence of hydrothermal alteration in cuttings and monitors the well for loss of circulation, an indicator that the well will be a good producer.

Dr. Joseph Moore shows a typical core and fracture that drillers must hit to get the flows necessary for a successful geothermal well. Dr Moore is recognized worldwide for his research on the hydrothermal alteration, geology, and evolution of geothermal systems. The results of his investigations have been published in numerous international scientific journals and conference proceedings. He currently serves on the Board of Directors of the Geothermal Resources Council and as Associate Editor for the Americas of the journal Geothermics.

Enhanced Geothermal Systems

Naturally occurring geothermal systems are limited, not so much by the heat source, but by the amount of fluid and the number and size of the fractures available for the fluid to circulate and absorb the heat.

According to Dr. Moore "there is still a good inventory of naturally occurring geothermal systems yet to be put into production, but there are far more potential high-temperature sites that lack adequate permeability through a connected fracture network. The future of geothermal electri-

Gathering lines to and from the power plant, both to supply the plant with steam and hot water, and return water back to the injection wells that keep the system charged.

cal power generation may lie in the ability to enhance, or even create, subsurface fracture networks."

Research into the formation of enhanced geothermal is just beginning. Projects in the U.S., Europe, and Australia have demonstrated that it is possible to create permeable fracture networks around injection wells through hydrofracturing and then drilling into these fracture systems to produce hot water. A 2006 MIT study, "The Future of Geothermal Energy" claims that once this technology is developed, enhanced geothermal systems could produce 10 to 20% of the United State's electricity.

Direct Use

Direct use applications for low- to moderate-temperature (35 to 150°C) water has grown considerably since early man's use of hot springs for basic needs. At Boise, Idaho, hot water has been used to heat buildings since 1892 and two of the original wells are still operating. The system is the largest in the U.S. and now serves over 360 buildings in downtown Boise with a cost savings over natural gas of about 30%. Although the cost of drilling wells, installing a heat exchanger, and piping is initially more expensive than traditional furnaces, the difference in cost can be recovered in 4 to 6 years from the energy savings.

Like all geothermal systems, use must be carefully managed. In the 1980's, production of the Boise system was doubled resulting in a 25% decline in water levels. A mathematical model of the aquifer showed that water reinjection would be beneficial and a 1,000 m deep injection well was drilled to recharge the system. As a result, water levels are rising and temperatures are now being sustained.

The list of direct users and uses of geothermal heat is growing dramatically - and for good reasons. For example, the city of Reykjavik, Iceland has the world's largest district heating system. Once very polluted, Reykjavik has become one of the cleanest

Resource Base

Any discussion of the geothermal resource base can be overwhelming by the sheer magnitude of its potential. In fact, the resource numbers are so large they are difficult to comprehend. For instance, just in the United States, magmatic geothermal systems to a depth of 10 km in the crust have nearly 200 times the energy equivalent of the known U.S. oil reserves and crustal heat down to 10 km has 2,500 times that amount of energy. Worldwide figures are equally impressive, but what represents reality?

The Idaho State Capitol building, one of over 360 buildings heated by geothermal water in Boise, Idaho, is the only state capitol building so heated in the U.S.

cities in the world by using geothermal energy as the main source of heat.

The potential to directly use geothermal energy does not end in Boise or Reykjavik. Many other cities in the U.S., and around the world, can reap similar benefits. The U.S. Department of Energy has inventoried 1,277 geothermal sites within 5 miles of 373 cities in just 8 western states. Japan is the world's largest user of direct geothermal heat. Any country lying near plate boundaries, like the Philippines, Mexico, Italy, Greece, are all using and expanding the their use of geothermal heat.

Geothermal Heat Pumps

For areas without higher heat flows, low-temperature ground heat can be utilized with efficient ground-source geothermal heat pumps (GHP). Their use can reduce energy consumption by 30 to 60%. GHP's circulate water or other liquids through pipes buried in a continuous loop. Working similar to a refrigerator (a one-way heat pump), the GHP can extract heat from the ground in the winter for delivery to the building or home and remove heat in the summer. Electric power is required to move the heat but not produce it, delivering 3 to 4 times the energy it consumes.

An interesting example of the wide use of GHP technology will be implemented at the 2008 Bejing Olympics. There will be 160 geothermal wells completed in the city by 2008. The construction of a geothermal heating project in Olympic Garden will provide space heating for most of the stadiums and gymnasiums there.

Its Time Has Come

Could the western United States become the Saudi Arabia of geothermal energy? "The potential is there," Dr. Moore says. "I am very encouraged of what has happened over the past few years in the progress companies and local governments have made toward the development of this clean and valuable resource."

"It has been very hard for geothermal, or any other viable alternative resource, to compete with conventional coal and gas in generating electricity. Now, local and state governments are seeing the need for clean energy alternatives to help meet growing energy demands, lessen our dependence on foreign oil, and address environmental concerns. Geothermal development is progressing even faster overseas. In many countries, private companies are working closely with national utilities to expand production and develop new conventional hydrothermal and enhanced geothermal system resources."

"We can expect a significant increase in the generation of electricity from geothermal systems worldwide over the next few years," Dr. Joseph Moore, research scientist at the Energy and Geoscience Institute (EGI) at the University of Utah, concludes.

"If only a small fraction of this potential is captured, geothermal energy could help meet the world's growing needs.

Most experts agree that the geothermal resource base is huge and we have barely scratched the surface in the utilization of this energy source. If only a small fraction of this potential is captured, geothermal energy could help meet the world's growing needs. How much will depend on economics and developing technologies to exploit this resource. Now, with very rare exceptions, only high-temperature (>150ºC) geothermal systems have been harnessed for the production of electrical energy.

"Geothermal companies have a large inventory of these higher temperature geothermal systems awaiting development, in some cases pending only enactment of appropriate tax incentives. Enhanced systems will bring even more of this potential into the energy equation," Says Dr. Moore.

Geothermal energy is considered by most a renewable resource. Magmatically-heated systems are driven by hot igneous intrusions, some still partially molten, that gradually cool over hundreds of thousands of years. Italy's Larderello field has been in production since 1904 and not a single geothermal field has been exhausted to date.

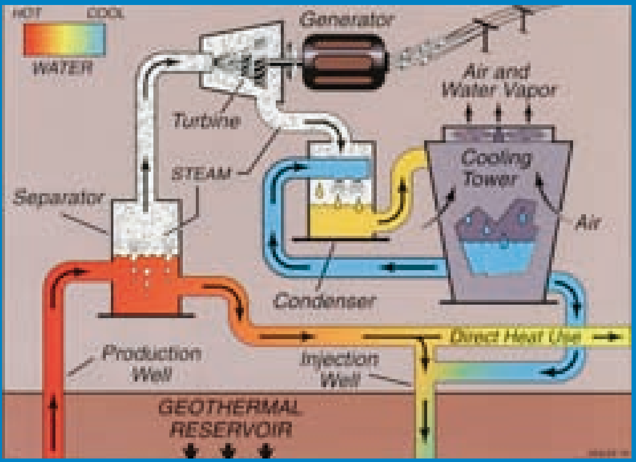
"Carefully managed geothermal systems can be sustained indefinitely to provide baseload power," says Dr. Moore.

Generating Electricity

The fluid in most geothermal reservoirs is liquid water. As the water is brought to the surface from depths of up to 4 km, and the pressure is reduced, the water flashes or explosively boils. The steam is piped to turbines and electricity is produced. The remaining unflashed liquid is reinjected. At some plants, this water may be flashed again at lower pressure, or used to heat another fluid that vaporizes at a lower temperature than water in a binary plant and generate additional electricity. Binary power plants can generate electricity over a broader range of temperatures than "flash plants". Flash and binary-cycle plants can be combined for efficient use of all the geothermal water produced. Using binary technology, waste water from oil and gas wells in many areas can used to generate electricity.

The plant at Chena Hot Springs, Alaska, operates at 74ºC, the lowest temperature geothermal source currently used for commercial power production in the world. Unlike these liquid-dominated systems, wells in a few high temperature reservoirs like The Geysers, California and Larderello Italy produce only dry steam.

Power plants are modular so that as a geothermal system is developed, more generating capacity can be installed as needed. Systems can be small requiring only 1 or 2 wells to operate. Large systems, such as with the Steamboat Hills 100 MW geothermal complex, will supply Reno, Nevada with its entire domestic electricity needs about 70,000 homes.



Flash-steam power plant. are passed through a heat exchanger to heat a secondary fluid that vaporizes at a lower temperature than water. In a closed loop, the secondary fluid vapor spins the turbine-generating unit, is condensed back and revaporized.