AUTHOR QUERY FORM

ELSEVIER	**Book:** SIGURDSSON-9780123859389 **Chapter:** 71	**Please e-mail your responses and any corrections to:** **E-mail:** **Chandramohan@elsevier.com**

Dear Author,

Any queries or remarks that have arisen during the processing of your manuscript are listed below and are highlighted by flags in the proof. (AU indicates author queries; ED indicates editor queries; and TS/TY indicates typesetter queries.) Please check your proof carefully and answer all AU queries. Mark all corrections and query answers at the appropriate place in the proof using on-screen annotation in the PDF file. For a written tutorial on how to annotate PDFs, click http://www.elsevier.com/__data/assets/pdf_file/0016/203560/Annotating-PDFs-Adobe-Reader-9-X-or-XI.pdf. A video tutorial is also available at http://www.screencast.com/t/9OIDFhihgE9a. Alternatively, you may compile them in a separate list and tick off below to indicate that you have answered the query.

Please return your input as instructed by the project manager.

Location in Chapter	**Query / Remark**	
AU:1, page 1	Please provide the abstract and keywords.	☐

Chapter 71

Utilization of Geothermal Resources

c0071

Stefán Arnórsson
Institute of Earth Sciences, University of Iceland, Reykjavık, Iceland

Sverrir Thórhallsson
Iceland GeoSurvey, Reykjavık, Iceland

Andri Stefánsson
Institute of Earth Sciences, University of Iceland, Reykjavık, Iceland

Chapter Outline

GLOSSARY

[AU1]

appraisal well A well drilled in a prospective wellfield within a geothermal field that has been roughly delineated by step-out wells with the purpose of quantifying its production characteristics and proving hot fluid.

direct use (of geothermal heat) Extraction of heat from hot fluid to heat buildings, dry vegetables, etc.

earth energy sources There are only five sources of energy on the Earth: energy generated by (1) nuclear fusion, (2) nuclear fission, (3) pull of gravity, (4) energy stored in chemical bonds (fossil fuel, biomass), and (5) primordial heat. About half of this heat still remains in the Earth.

energy resource Something that can be used to do work, such as moving vehicles, and produce heat or electricity with present-day technology.

enhanced geothermal system Geothermal system in hot-dry (impermeable) rock, where permeability is artificially created by fracturing the rock at depth.

geothermal energy Energy stored in the form of heat below the surface of the solid Earth.

geothermal exploration well A well drilled for the purpose of discovering a prospective wellfield within a hydrothermal system.

geothermal field (area) An area with finite boundaries, usually defined by the distribution of hot springs and/or fumaroles.

geothermal fluid Hot water and/or steam hosted in a hydrothermal system. Geothermal fluids contain dissolved gases and solids.

geothermal system Any body of hot rock with or without hot fluid in the uppermost part of the Earth's crust. Some geothermal systems are hydrothermal systems but others are not.

heat pump A device to transfer energy in the form of heat from a cooler body to a warmer one.

hot-dry rock Geothermal system characterized by impermeable rock.

hydrothermal field See geothermal field.

hydrothermal reservoir A body of permeable hot rock in the uppermost part of the Earth's crust that contains hot fluid, which can be extracted from the reservoir and brought to the surface through drillholes.

hydrothermal system A body of permeable hot rock with hot fluid that underlies a hydrothermal field. See also geothermal field.

The Encyclopedia of Volcanoes. http://dx.doi.org/10.1016/B978-0-12-385938-9.00071-7

injection well A well used for disposing of spent hydrothermal fluid from production wells/power plants.

production well Any well that produces steam/hot water.

renewable energy resource An energy resource that is replenished at a rate equal to or higher than it is consumed. They cannot be exhausted. Examples: direct sun energy, wind, and hydropower.

resistance heating Use of electricity for house heating that involves passing electric current through radiators. When there is resistance to the flow of this current through the radiator, the electric energy is converted into heat energy, hence resistance heating.

scaling Formation of mineral deposits in wells and surface equipment by precipitation of solids from the flowing fluid.

step-out well Well drilled in the vicinity (~1 km) of a successful exploration well with the purpose of delineating the size of the anomaly discovered by the exploration well.

s0010 1. INTRODUCTION

p0115 **Geothermal energy** is defined as energy in the form of heat below the Earth's solid surface. **Geothermal systems** represent bodies of hot rock with or without hot fluid in the upper part of the Earth's crust. Many classifications have been proposed for such systems. The one used here is that of Goff and Stimac (see Chapter 46), which is based on the geological environment in which these systems occur. The most important types are systems in young igneous settings, tectonic systems, sedimentary basins, and impermeable **hot-dry rock** (also called **enhanced geothermal systems** (EGS)). The first three types have also been termed **hydrothermal systems**, and this terminology is used here. Their development has been proved to be technically and economically feasible. Thus, they represent an **energy resource**. The heat stored in hot-dry rock within drillable depths in the Earth's crust could also be classified as an energy resource if the current technology can be refined to extract heat economically from such rock.

p0120 Examples of exploited fields in young igneous settings include Wairakei in New Zealand and Palinpinon in Philippines. Laugarnes and Laugarland in Reykjavík and Akureyri, respectively, in Iceland represent tectonic systems. The former is an old high-temperature system of > 250 °C as indicated by the hydrothermal alteration mineralogy, but at present reservoir temperatures are 130−140 °C. Szentes in the south Hungarian plains provides an example of a sedimentary basin hydrothermal system. The hot-dry rock of the Cooper basin in Australia represents an EGS, where a 25 $\mathrm{MW_e}$ demonstration plant is being developed.

p0125 Globally, geothermal energy is not an important energy resource. Today, it accounts for only about 0.22%, ~11 GW (gigawatts), of the total installed electric power capacity worldwide (~5000 GW). Despite this, it is very important for many countries with abundant hydrothermal activity. For example, within a few years, almost half of Kenya's electric power will be generated by geothermal steam.

p0130 The heat transported from the Earth's interior through its surface is ~50,000 GW. Accordingly, the heat flowing through every meter square of the Earth's surface is around 100 mW (milliwatts). In comparison, the radiation from the Sun that reaches the Earth is 342 $\mathrm{W/m^2}$ or 3420 times larger than the energy flow from inside the Earth. The heat flow passing through ice-free dry land areas is only about twice the installed electric power. By looking at all the above numbers, it should be evident that the future source of renewable energy for mankind is the Sun. Further, it also seems impossible to make any significant use of the renewable conductive heat current from the Earth's interior.

p0135 The amount of energy stored within the Earth in the form of heat, 10^{31} J, is enormous. So far, however, use of this energy has been technically possible and economically feasible only where geological and hydrological conditions are favorable for the formation of hydrothermal systems. Volcanic and tectonic systems are most important. They are characterized by high permeability allowing groundwater circulation to depths of a few kilometers, where it heats up by contact with hot rock. Subsequently, it ascends due to buoyancy. Use of geothermal water in sedimentary basin has also proved to be economic. Their water may be connate, at least in part, i.e., of the same age as the host sediments, and fluid convection is not significant. Heat is recovered from hydrothermal systems by drilling, thus bringing the hot fluid to the surface.

p0140 Several attempts have been made to extract heat from hot-dry rock. They involve drilling of "injection" and **production wells**, and hydrofracturing of the rock to create permeability. Subsequent production consists of pumping cold water into the **injection well** and extracting this water from the production well. As the water flows between the two wells through the artificially created fractures, it gains heat from the rock. So far, this technology has not resulted in projects of economic importance. If current technology can be improved, it may become feasible to extract heat from such impermeable rocks in which case an enormous mine of heat has become a resource.

p0145 Geothermal energy is sometimes classified among the **renewable energy resources**. However, renewability of the different types of geothermal systems is highly variable. It is a good approximation to regard tectonic systems, sedimentary basins, and hot-dry rock as nonrenewable resources (see O'Sullivan et al., 2010). The renewability of systems in young volcanic settings is variable, uncertain, and affected by the extent of heat withdrawal by the exploitation relative to the natural heat output (see Sanyal, 2005).

p0150 In the present chapter, the main focus is on the development and use of hydrothermal systems and the rapid growth in **heat pump** usage. Hot-dry rock systems are not discussed further.

s0015 2. USE OF HYDROTHERMAL FLUIDS

s0020 2.1. Energy Usage

p0155 Modern usage of geothermal energy started at Larderello, Italy. On 4 July 1904, geothermal steam was used for the first time to generate electric power. In 1912, this was followed by the installation of the first turbine generator unit powered by underground steam. By 1944, the installed power had increased to 127 MW. In the 1920s, hydrothermal power explorations were carried out in California and Japan but at the time did not result in power developments. Since the 1960s, many countries have been active in developing hydrothermal resources for various types of direct uses of the heat stored in the **geothermal fluid** such as house heating and greenhouse farming in addition to power production. During the 2000–2010 period, the direct use of geothermal energy increased much, by 23,300 TJ annually (12.2%). The most striking feature is in the rapid increase in the use of geothermal heat pumps, which rose on average by 76% annually in the 2000–2010 period. The increase in installed capacity for electric power generation has been slower over the same period, 9.2% annually corresponding to a total of 2743 MW_e. Direct use of geothermal energy in the form of heat utilization is summarized in Table 71.1. Figure 71.1 shows installed power capacity in 2010 and planned capacity by 2015. In the past, however, similar plans for capacity increases have been made but not realized.

p0160 Power generation by geothermal steam involves passing it through a turbine in much the same manner as steam produced by burning coal. Geothermal steam is produced from high-temperature hydrothermal systems ($T > 200$ °C). Direct use of heat in geothermal fluids is generally based on exploiting geothermal systems with lower temperatures (50–150 °C) and even lower in the case of swimming pools and heat pumps. The growth of the heat pump technology has occurred mostly in countries, or in areas within countries, with very limited or no hydrothermal activity, such as Sweden, Germany, France, the Netherlands, and Norway, and is a reflection of energy policies. They make more efficient the use of electricity for space heating than direct use of the electricity, i.e., **resistance heating**.

p0165 Hydrothermal resources account for only a very small fraction of the world's total installed electric capacity, or ∼11 GW, out of the total estimate of ∼5000 GW for 2009, i.e., 0.22%. The annual production of electric energy from geothermal plants is, however, most likely higher than these numbers indicate because they have higher load factor than fossil fuel plants and most hydropower plants. A load factor of 100% means that the power plant is running at full capacity all year round.

2.2. Extraction of Chemicals s0025

Hydrothermal fluids have been utilized on a small scale as a source of various chemicals. At Larderello, Italy, boron was extracted from geothermal steam before electric power generation started. In Japan, cesium has been extracted from hot spring waters and mercury from hot spring deposits at Sulfur Bank in California. Production of various metals from the hot brine in the Salton Sea area in California (e.g., lithium) has been tested and a new plant is under construction. Many hydrothermal fluids are rich in lithium, which could be extracted by the use of ion exchange resins if the silica in the fluid could be removed. In New Zealand, a technique was developed to extract silica from the waste brine of the Wairakei geothermal power plant by coprecipitating it with lime to form a useful calcium silicate for the building industry. Extensive research has been carried out that may lead to production of high-purity silica polymers from geothermal brines. Common salt was for a time produced in a factory on Reykjanes, Iceland, from geothermal seawater and the steam used in the evaporation process. Carbon dioxide originating from geothermal steam is liquefied or turned into dry ice in factories in Turkey and Iceland. p0170

2.3. Factors Affecting Energy Usage s0030

The principal factors that determine potential use and economics of hydrothermal resources are reservoir temperature, reservoir size, formation permeability, and the chemical composition of the fluid. The location of the resource in relation to the market is also of importance, at least when using the heat in hot water or steam directly, i.e., for greenhouses. For financial and technical reasons, transport of hot fluid over long distances is not possible. In this respect, the value of geothermal energy is inferior to fossil fuel, but for power production it is on pair with hydropower. p0175

Baldur Líndal, an Icelandic chemical engineer, assessed the potential use of geothermal water and steam on the basis of their temperature (Figure 71.2). From this figure, it is clear that thermal water with temperatures as low as 20–30 °C constitutes a useful energy resource. Sites with temperatures even lower than this are still a viable resource in the case of heat pumps. p0180

The chemical composition of hydrothermal fluids is highly variable with respect to gases and dissolved solids ranging from very dilute to hypersaline brines. The chemical composition can significantly affect the economy of resource exploitation by causing operational problems, such as deposition of solids from the flowing fluid in wellbores and surface equipment (**scaling**), and corrosion. High gas content in the steam may affect its quality for power generation. Disposal of spent brine and condensed p0185 t0010

TABLE 71.1 Direct Use of Geothermal Heat in 2010 by Country

Country	Installed Capacity (MW$_t$)	Annual Energy Usage (TJ)	Load Factor
Albania	11	40	0.11
Algeria	67	2099	1.00
Argentina	307	3907	0.40
Australia	33	235	0.22
Austria	663	3728	0.18
Belarus	4.5	44	0.31
Belgium	118	547	0.15
Bosnia and Herzegovina	22	255	0.37
Brazil	360	6622	0.58
Bulgaria	98	1370	0.44
Canada	1126	8873	0.25
China	8898	75,348	0.27
Columbia	14	287	0.63
Croatia	67	469	0.22
Czech Republic	216	1290	0.19
Denmark	200	2500	0.40
Estonia	63	356	0.18
Finland	994	7966	0.25
France	1345	12,929	0.30
Georgia	27	689	0.82
Germany	2485	12,764	0.16
Greece	135	938	0.22
Hungary	655	9767	0.47
Iceland	1826	24,361	0.42
India	265	2545	0.30
Iran	42	1064	0.81
Ireland	138	692	0.16
Israel	82	2193	0.84
Italy	867	9941	0.36
Japan	2100	25,698	0.39
Jordan	153	1540	0.32
Kenya	16	127	0.25
Korea (South)	229	1955	0.27
Lithuania	48	412	0.27
Macedonia	47	601	0.40
Mexico	156	4023	0.82
The Netherlands	1410	10,699	0.24

TABLE 71.1 Direct Use of Geothermal Heat in 2010 by Country—cont'd

Country	Installed Capacity (MW_t)	Annual Energy Usage (TJ)	Load Factor
New Zealand	393	9552	0.77
Norway	1000	10,800	0.34
Poland	281	1501	0.17
Portugal	28	386	0.44
Romania	153	1265	0.26
Russia	308	6144	0.63
Serbia	101	1410	0.44
Slovak Republic	132	3067	0.74
Slovenia	116	1015	0.28
Spain	141	684	0.15
Sweden	4460	45,301	0.32
Switzerland	1061	7715	0.23
Tunisia	44	364	0.26
Turkey	2084	36,886	0.56
Ukraine	11	119	0.35
The United Kingdom	187	850	0.14
The United States	12,611	56,552	0.14
Vietnam	31	92	0.09
Other countries (22)[1]	93	1344	0.38[2]
Total	48,523	423,374	

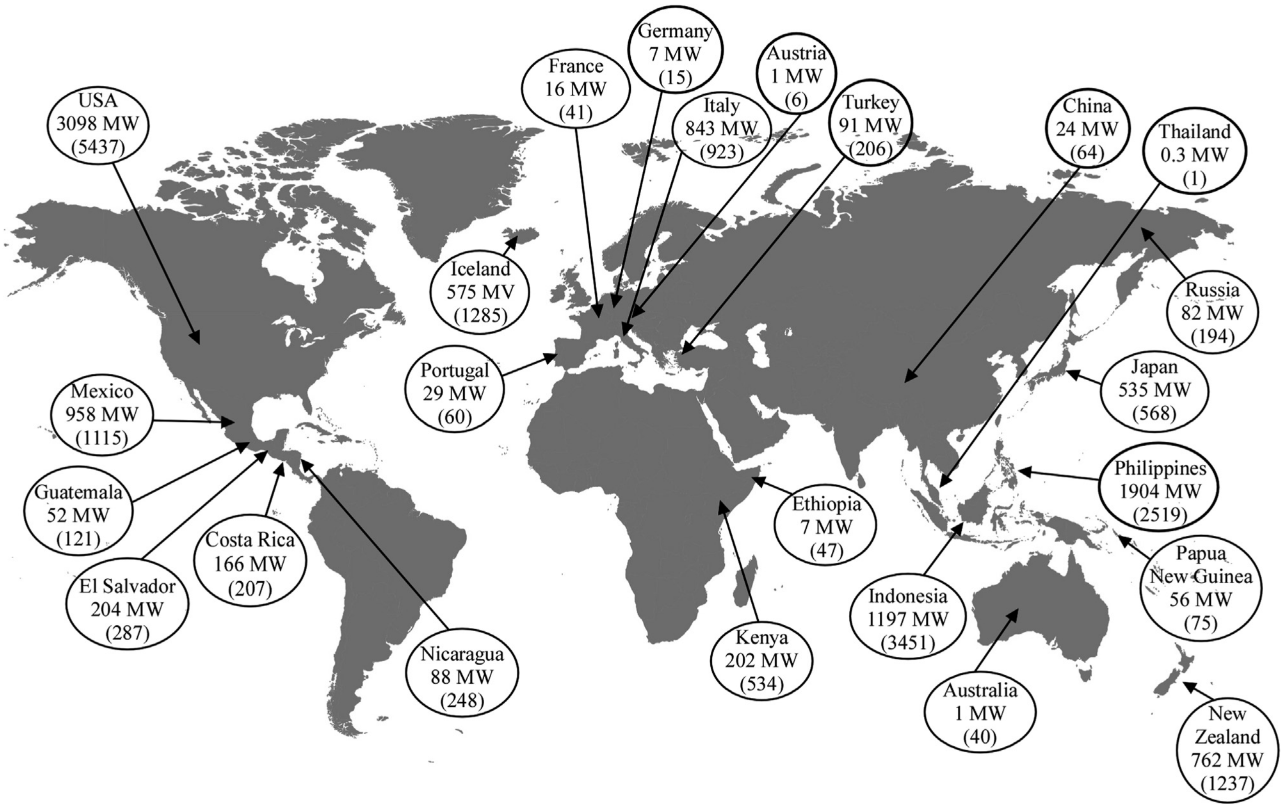
[1] *Armenia, Caribbean Islands, Chile, Costa Rica, Ecuador, Egypt, El Salvador, Ethiopia, Guatemala, Honduras, Indonesia, Latvia, Mongolia, Morocco, Nepal, Papua New Guinea, Peru, Philippines, South Africa, Tajikistan, Thailand, Venezuela, Yemen, all with <10* MW_t.

[2] *Weighed average.*

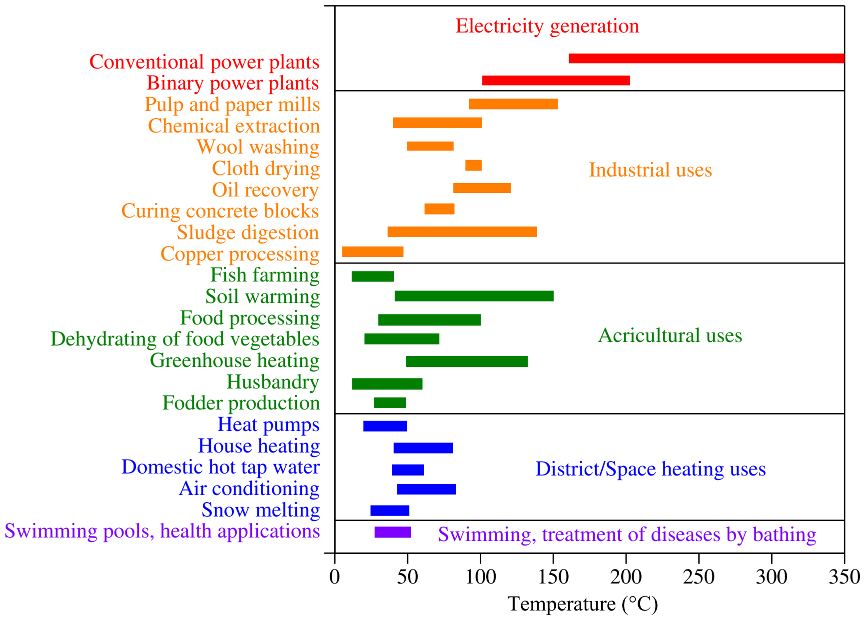
steam into drillholes is practiced in many geothermal fields worldwide in order to minimize the environmental impact of utilization. The geochemical environment and fluid temperatures mostly control fluid composition in each type of hydrothermal systems. The most common features that have delayed and, in some cases, even inhibited the development of drilled hydrothermal systems are inadequate permeability and foreseen operational/environmental problems as determined by the chemical characteristics of the hydrothermal fluid.

s0035 2.4. Power Generation, Direct and Multiple Uses

p0190 Although geothermal steam is principally used in the same way to generate electric power as is steam formed in boilers using fossil fuel or nuclear energy, there is one major difference. In the case of fossil fuel and nuclear energy, the steam inlet pressure for the turbines can be chosen to maximize efficiency. For geothermal steam, the characteristics of the reservoir determine, at least to some extent, the optimum turbine inlet pressure, which is usually in the range of 4—11 bar gauge. The efficiency of geothermal steam for electric power generation is poor. Only about 20% of the thermal power of the flowing steam can be converted into electricity, depending on turbine inlet pressure and efficiency. The efficiency is even less relative to the total thermal power (steam and water) of wells. As an example, consider a reservoir with liquid water at 260 °C and a steam separation pressure of 6 bar abs. (this is equal to a temperature of 159 °C for saturated steam). Boiling by a pressure drop from 260 to 159 °C will cause 22% (steam fraction by weight) of the reservoir water to be converted



f0010 **FIGURE 71.1** Installed geothermal power by country in 2010 and planned increase by 2015 (in parenthesis). Twenty-two countries that did not produce electricity from geothermal fluids in 2010 plan to have an installed capacity of 1120 MW_e by 2015.



f0015 **FIGURE 71.2** The Líndal diagram. This diagram is named after an Icelandic chemical engineer, Baldur Líndal. It depicts potential uses of steam and hot water depending on their temperature. The present figure is a shortened version of the initial diagram.

into steam. Only the steam fraction can be utilized to generate power, while the remaining 78% of the produced mass is injected back into the reservoir, so the heat is not totally lost. The wastewater contains 46% of the total heat coming from such a well. Assuming that the wastewater could be utilized by cooling it further to 35 °C, the remaining heat of 46% is reduced to 10%. A steam flow of 1.7–2.0 kg/s is required to generate 1 MW of electric power in a geothermal turbine.

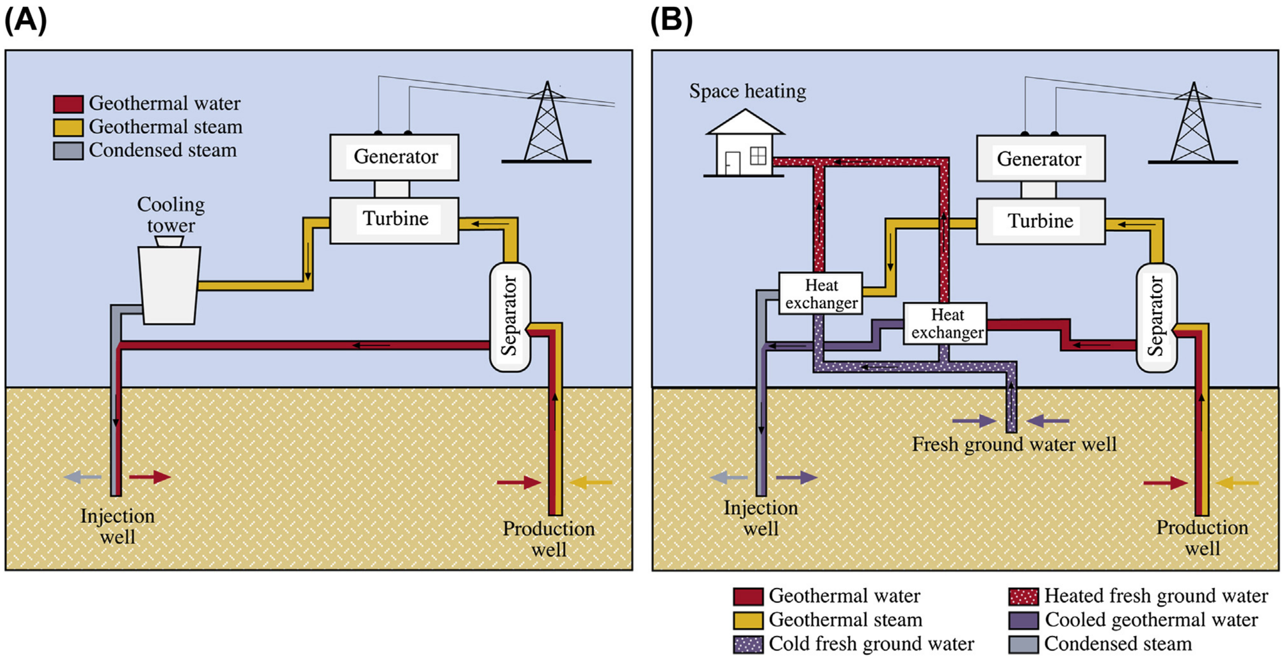
p0195 Direct use of hot water/steam for heating is much more efficient than the use of steam only for power generation. For space heating, heat can easily be extracted in radiators by cooling it down to 35 °C and even lower in floor-heating systems. As an example, for an initial hot-water temperature of 80 °C and assuming useful heat as that in excess of 35 °C (20 °C) gives an efficiency factor of 56% (75%).

p0200 The poor utilization of heat in hydrothermal fluids by conventional electric power generation has led to technological improvements. Two methods have mainly been pursued. One involves a so-called binary cycle (bottoming cycle) and the other utilizes for multiple purposes from the same field such as power generation, house heating, bathing, etc. (Figures 71.2 and 71.3). Multiple utilization of this kind may also involve extraction of useful chemicals from geothermal fluids. The binary cycle involves heating a low-boiling point secondary fluid in a closed loop of a heat exchanger. That fluid is then used to drive the turbines or expanders. Heat recovered from turbine condensers is then used as the first stage in the heating of freshwater, e.g., for space heating. The water separated from the steam in steam separators provides additional heating in heat exchangers to the final temperature. In this way, the geothermal resource can be more effectively utilized (Figure 71.3(B)). Problems with efficient use of high-temperature geothermal fluids may arise as they become supersaturated with minerals at low temperatures. Cooling of the fluid sometimes leads to amorphous silica scaling in production wells and surface equipment, and scaling of calcium carbonate and anhydrite in injection wells. Such scaling can impede smooth operation of a geothermal installation by clogging pipelines and reducing heat transfer in exchangers, thus increasing the operational costs. The possibilities of multiple uses of hydrothermal fluids depend on the availability of a local market for the heated freshwater.

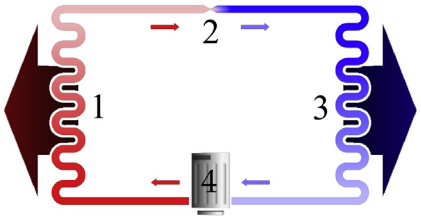
2.5. Heat Pumps s0040

As already mentioned, the use of heat pumps has grown rapidly during the last two decades or so. In principle, a heat pump is used to extract heat from a cooler body and transfer it to a warmer body. Heat pumps can be switched between operating in a heating mode or as air conditioners. p0205

There are basically two configurations for heat pumps, one that extracts heat from air (air-source heat pumps) and other from the ground (ground-source heat pumps). In the latter case, the heat may be extracted either from the soil directly or from deeper strata in the ground using drillholes. The latter are geothermal heat pumps. The ultimate source of heat utilized by a heat pump that uses air and soil is solar. Geothermal heat pumps may also use some solar heat if p0210



f0020 **FIGURE 71.3** (A) Conventional power generation. (B) Power generation combined with space heating.



f0025 **FIGURE 71.4** Simplified illustration of how heat pumps work. (1) Flow of heat from warm liquid in red loop into house. (2) Expansion valve. Liquid vaporizes here and cools extensively. (3) Cooled gaseous fluid picks up heat from surroundings. (4) Compressor. Gaseous fluid becomes liquid and warm.

they extract heat from downward-percolating groundwater and also when they are used for cooling buildings in summer time and the heated water warms up rock around drillholes.

p0215 Heat pumps are based on the so-called Joule—Thompson or Joule—Kelvin effect, discovered in 1852 (William Thompson later became 1st Baron Kelvin). This effect describes that all gases except hydrogen and helium cool upon rapid expansion. The development of the first heat pump is attributed to an Austrian, Peter von Rittinger (1811—1872). Essentially, a heat pump consists of a fluid that circulates in a closed loop, which includes a compressor and an expansion valve (a pressure-lowering device) (Figure 71.4). When fluid passes through the expansion valve, it is extensively depressurized, leading to severe cooling (from 20 to 30 °C). The cooled fluid gains heat from the environment (air, ground) by conduction. When the gaseous fluid reaches the compressor, it is compressed into liquid, which is warmer than the liquid that entered the expansion valve. The compressor uses only one-fourth to one-third of the electricity needed for direct (conventional) heating compared with resistance heating in radiators.

s0045 3. HYDROTHERMAL SYSTEMS AND THEIR ROOTS

p0220 Their volume but also many other factors, including temperature, porosity, permeability, and the chemical quality of the fluid, affect the generating capacity of individual hydrothermal systems, both for power production and for direct use. Most of these characteristics can be reasonably well quantified by drillings into the geothermal reservoir. This is, however, not so when it comes to system volume because the base of fluid convection is not known.

p0225 In order to account for the high natural heat output of many high-temperature hydrothermal systems, it is necessary to assume that the heat source is very hot and that temperature gradient from this heat source to the base of the convecting fluid must be very high, 10 °C/m, even more in the case of magma or very hot rock that represents recently consolidated magma. Modeling studies indicate that fluid convection over very hot heat sources may be one-dimensional, at least if permeability above it is sufficiently high. One-dimensional convection involves descent of liquid water through very small pores in the rock and along mineral grain surface and rise of vapor along more permeable fractures, both occurring right above the heat source. The ascending vapor may form by complete evaporation of the descending liquid water. The rising steam may condense partly or completely in shallower groundwater, heating it in the process.

After fluid convection has started in a newly born hydrothermal system, the ascending hot fluid will gradually heat the rock above the heat source and probably also to the sides by lateral hot-water flow. When the system has matured, considerably greater proportion of the heat in the system will be stored in the rock rather than in the hot fluid depending on rock porosity of course. Exploitation of such fields will involve enhanced natural recharge of groundwater that ultimately was mostly if not solely nonthermal (meteoric water or seawater). This recharge makes it possible to extract heat from the hot rock of the system, its effectiveness depending on its porosity and the spacing of permeable fractures in the reservoir. p0230

In recent years, holes drilled into volcanic systems have penetrated magma, in Hawaii in 2005, two times at Krafla in Iceland in 2008—2009, and very likely at Menengai in Kenya in 2011. At Krafla and Menengai, a zone of superheated steam overlies the magma body but underlies a two-phase (water + steam) reservoir. At Alto Peak in the Philippines, it is known from drillings that a vapor zone underlies a two-phase reservoir although drillholes have not penetrated magma. It remains to be verified by deeper drillings in new areas whether or not two-phase **hydrothermal reservoirs** are typically separated from their magma heat source by a vapor zone. At Krafla and Menengai, the magma bodies were as shallow as ∼2 km. This sets an upper limit to the thickness of usable hydrothermal reservoir to around 1500 m assuming that production will be confined to depths of more than 500 m. It may even be thinner. Magmatic gases, some of which render the fluid acid when they dissolve in it, may cause this fluid to become too corrosive for exploitation. Acid fluids could also be formed by complete evaporation of the recharging liquid water to vapor and its subsequent partial or complete condensation in shallower groundwater. Gradually, water—rock interaction will destroy the acidity of this deep fluid, as many of the rock-forming minerals in common rock types act as bases when they dissolve in water, i.e., their dissolution involves consumption of protons. If superheated steam forms in the roots of volcanic hydrothermal systems, its depressurization may lead to intense silica scaling. The solubility of silica in steam can be considerable at high pressure, but upon depressurization the solubility decreases strongly and intense deposition sets p0235 in. Such deposits may render the steam unexploitable, at least with respect to present-day technology.

p0240 For environmental purposes, it is common practice to inject spent hydrothermal fluids into the ground. Injection of the spent fluid back into the reservoir has been considered to be beneficial because it will counteract reservoir pressure drawdown. Such injection may, on the other hand, reduce the effective withdrawal of heat from the reservoir rock, at least in the case of high-temperature two-phase systems. Liquid water in micropores may be immobile due to its adhesion onto mineral grain surfaces, but if pressure drawdown in larger permeable fractures causes sufficient cooling of the fluid by depressurization boiling, it may create sufficient temperature difference between fluid and rock to cause the immobile water to boil. The vapor so formed could flow into the larger pores and ultimately into production wells due to its better flowing properties as compared with liquid water.

p0245 In order to explain the relatively large heat output from some tectonic systems in nonvolcanic regions, it must be assumed that their heat source is hot rock in their roots. Mining of heat occurs under natural conditions, and exploitation that involves enhanced fluid withdrawal will enhance this mining of heat from the rock.

p0250 Some hydrothermal system are vapor-dominated, others are liquid-dominated. In the latter, steam forms by depressurization boiling as the liquid water flows through the aquifer and ascends in the well. The quantity of steam that forms depends on the initial temperature of producing aquifers and the magnitude of pressure drop. As an example, 41% of 300 °C liquid water is transferred into vapor by depressurization boiling to 100 °C. It is for this reason that wells drilled into liquid-dominated systems discharge a two-phase mixture of water and steam or steam only if the boiled liquid water is retained completely in the aquifer due to its adhesion onto mineral grain surfaces. Segregation of the two phases in this way is affected by their relative volumes in the flow but also by the surface area between rock and fluid. Due to its properties, liquid water forms a thin layer on mineral surfaces but vapor does not "wet" these surfaces.

s0050 4. RENEWABILITY OF GEOTHERMAL SYSTEMS

p0255 Possibly the best definition of a renewable energy resource is that given by Girardet and Mendonça (2009): "An energy resource is renewable if it cannot be exhausted." It is frequently stated that geothermal energy is a renewable energy resource. Indeed, the European Union and the Department of Energy in the United States classify geothermal energy among renewable energy resources despite the fact that almost all geothermal energy is not renewable, certainly not on a timescale that matters to mankind. The reason is likely political. In their estimates of geothermal potential for power production, the U.S. Geological Survey and the National Energy Authority in Iceland evaluate this potential by referring to 30- and 50 -year production periods, respectively. From this, it may be deduced that both organizations view geothermal resources as mines of heat.

The renewability of geothermal systems depends on the type of their heat source and the extent of exploitation that generally outpaces the natural heat output considerably. Opinion among scientists is divided on to what extent individual geothermal systems are renewable. If the heat that renews the system is by conduction alone from deeper and hotter levels in the Earth's crust, it is, however, clear that it is a good approximation to regard these systems as nonrenewable, as recovery time after 100 years of production may be on the order of 1000–100,000 years or even more depending on heat extraction rates by the exploitation. In some tectonic systems, deep drilling indicates that mining of heat from the rock in the roots of these systems occurs under natural conditions (Figure 71.5) and it is this heat mining that sustains the system. Exploitation will enhance the heat mining and conductive heat transfer from below and possibly also from the sides presents no significant short-term contribution, making these systems a transient phenomenon, hence nonrenewable. p0260

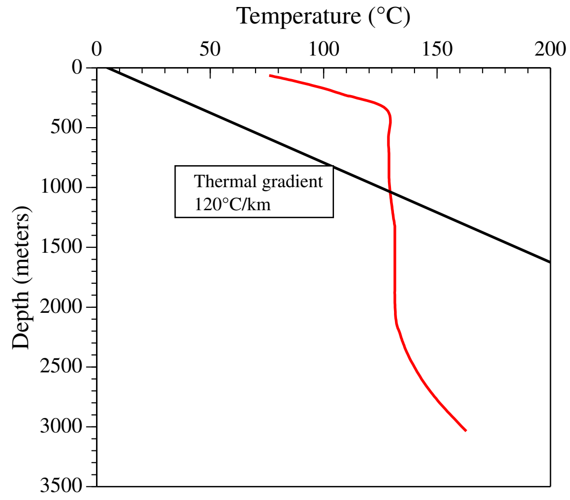
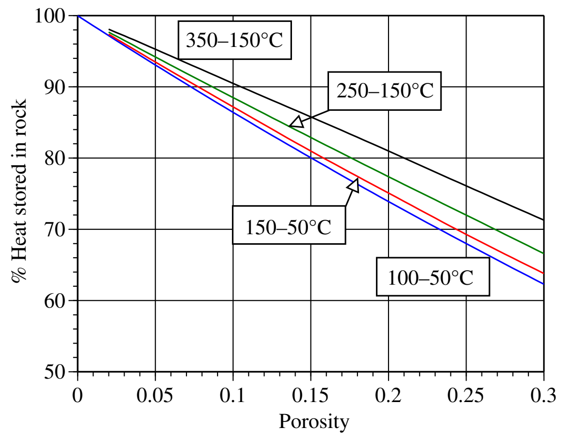


FIGURE 71.5 Temperature profile (red curve) in a deep well at Laugarnes field in Reykjavík, Iceland. The black curve shows temperature gradient in wells outside the geothermal field. Above the point of intersection of the two curves, the temperature is higher within the hydrothermal system than in the rock enveloping it. Below this point, on the other hand, the temperature within the geothermal system is lower at any depth than in the surrounding rock. The temperature distribution in the well is considered to reflect that the convecting water has mined heat from the rock (under natural conditions) in the roots of the system and transported it to shallower depth levels due to its density-driven convection, thus leveling out temperature over a great depth range within the geothermal system. The temperature distribution in the well also indicates that recharge is from above, not from the sides. f0030

p0265 Geothermal systems with a magmatic heat source may have higher renewability than other types of geothermal systems. It is, however, also affected by the extent of exploitation, how frequently magma is intruded into their roots, and to what extent the heat flow from the heat source is lost to the surface after production is halted and how much goes into heating up the rocks that cooled during the production period as a consequence of enhanced cold water recharge. It is not possible to generalize about the renewability of these systems. Data on the flow of new magma into their roots are also lacking, except possibly in a few cases. To be able to estimate the renewability of any magmatic hydrothermal system, data are needed that are specific for each system and the outcome may turn out to be no more than a skilled guess.

p0270 Recent publications on the subject of renewability of magmatic hydrothermal systems do not address sufficiently the concept of time. This is, however, important. Such systems are born, develop, cool down, and become extinct. All existing geothermal systems in young igneous settings need not have a magma heat source today although they might have had one earlier in their life. At diverging plate boundaries, like in Iceland, a volcanic hydrothermal system will eventually be displaced from its magma heat source as it drifts out of the volcanic zone at which time it will become practically nonrenewable and it will gradually cool down and become extinct. Some 40 fossil volcanic hydrothermal systems are known in Iceland. A mature hydrothermal system without magma or very hot igneous intrusive body in its roots can have high natural heat output over a long time on the human timescale, at least if permeability is sufficient just as is the case with some tectonic systems.

p0275 The heat stored in a given volume of rock within a hydrothermal system depends largely on its porosity and temperature (Figure 71.6). Measurement of rock porosity in cores from drillholes allows an estimation to be made of the heat stored in a given volume of rock with reasonable accuracy. For example, in a reservoir with a temperature of 250 °C and a porosity of 10%, the heat stored in basaltic rock is 88% of the total heat in excess of 150 °C. To extract this heat from the rock through recharge of 5 °C groundwater, it is necessary to replace the original liquid water 4.5 times. However, extraction of heat from the rock may not be very effective (it has been estimated to be 5–20%) depending on the spacing of permeable fractures.



f0035 **FIGURE 71.6** Percentage of heat stored in basalt as a function of porosity. Four scenarios are shown corresponding with different reservoir temperatures. The numbers on the left in each box represent the reservoir temperature and the ones on the right the lower limit of usable temperature.

5. DRILLING FOR HYDROTHERMAL FLUIDS s0055

Drilling of deep wells is required to reach geothermal reservoirs. They have to be of large diameter to bring economic quantities of geothermal fluids to the surface. The targets for geothermal wells are (1) desired temperature and (2) permeable strata, and both have to be present for a successful well. For low-temperature wells, the temperature target is in the range 50–130 °C; for medium-temperature wells, 130–210 °C; and for high-temperature wells, >210 °C. Low-temperature wells are suitable for direct use of the heat in the geothermal fluid, medium-temperature wells for binary generation, and high-temperature wells for steam power plants. If the temperature is below 210 °C, it is not certain that a high-temperature well can sustain self-flow of the boiling fluid, and thus the last casing string needs to be deep enough to block inflow of colder fluid. The permeability, aquifer pressure, and well diameter dictate the maximum flow rate. For low-temperature wells, it should be 30–90 L/s (∼5–15 MW_t; megawatts thermal for space heating) and for high-temperature wells, around 10 kg/s of steam (40–60 kg/s total flow corresponding to ∼5 MW_e; megawatts electric). This requires drilling of wells to a depth of 1000–3000 m in the case of high-temperature resources. For low- and medium-temperature wells, the range is in depths of 400–6000 m. p0280

The drilling equipment and technology is mainly derived from the petroleum industry with some modifications in the equipment such as mud-cooler and greater mud-pumping capacity. Currently, the number of drilling rigs in the world engaged in geothermal drilling is about 1% of that for petroleum. p0285

Some drilling procedures as well as casing designs have been modified to meet different reservoir conditions. ~~Geothermal wells are mainly in volcanic rocks and most often of high temperature, whereas oil and gas wells are primarily in sediments and sedimentary rocks.~~ The drilling tools and methods are, in general, similar ~~as for~~ petroleum drilling. The drill bits are selected for hard rock, mainly tricone bits with tungsten carbide inserts but also some polycrystalline diamond compact bits and hybrids have p0290 found application. The steel grade in the casings is selected with respect to the presence of H_2S and H_2 and the technical standards are the same.

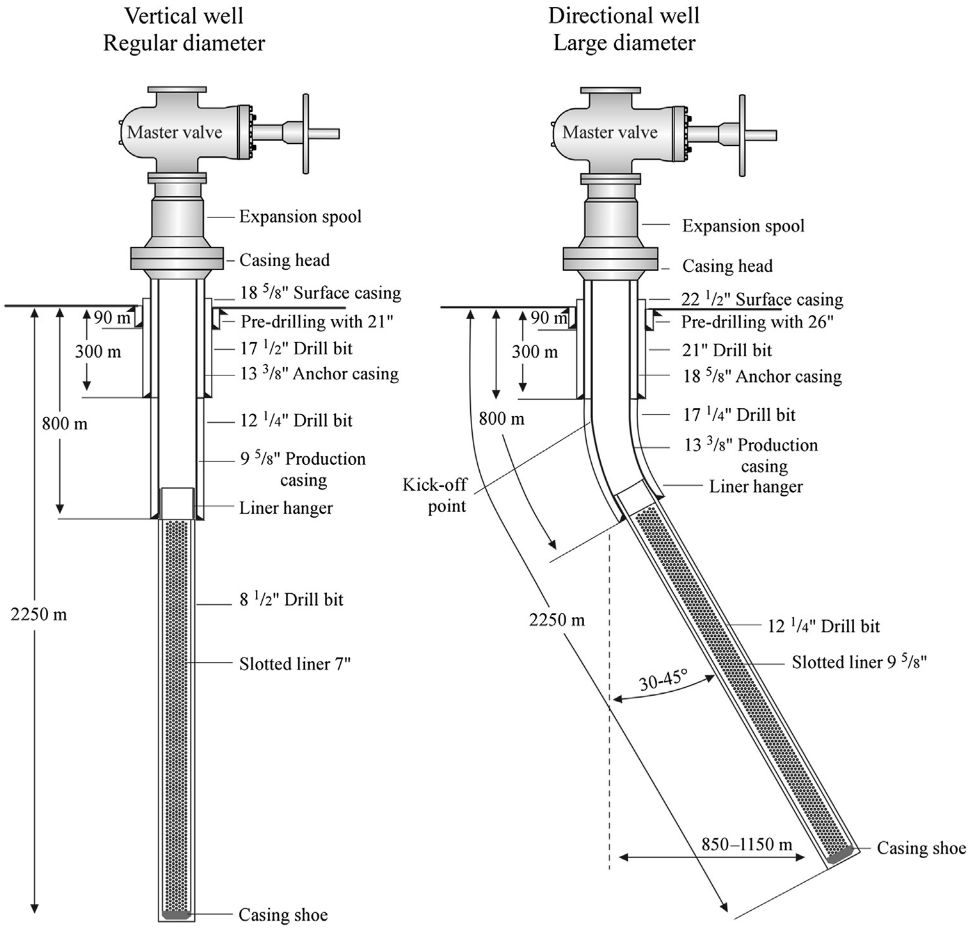
p0295 Nowadays, most geothermal wells are drilled directionally, rather than vertically. The trajectory of the directionally drilled geothermal wells is similar in most fields worldwide. The special directional drilling tools employed are a steerable mud motor just above the drill bit with logging equipment (MWD, measurement while drilling) next to it to relay information to the surface on the angle of inclination and azimuth (direction). The inclination relative to vertical is changed gradually from 1.5 to 3 per 30 m at a depth of 300−400 m until it reaches 30−45° according to the directional plan. The final inclination is reached at 700 to 800 m depth, and continued drilling is usually straight in the desired direction and at fixed inclination until the total depth is reached. Thus, the bottom of a typical directional well is about 1000 m displaced from vertical.

p0300 The drilling fluid is simple for geothermal drilling. While drilling for the casings, the drilling fluid is mainly a low-solid drilling mud (bentonite about 50−60 kg/m^3) with some caustic soda added to stay above pH 9. In the open hole section, the drilling fluid is water only, but often compressed air and drilling soap are added for "pressure balance drilling" after permeable horizons have been intersected. Permeability shows up as loss zones, where the drilling fluid enters the reservoir due the lower pressure in the reservoir than in the fluid-filled well. Large fluid losses often encountered in geothermal wells give rise to drilling problems such as cleaning cuttings from the well and achieving good cementing of the casings. The drill string may also get stuck in the hole because of fluid losses, especially in the case of multiple loss zones. Although fluid losses cause many drilling problems, they are precisely what is required for a productive well. An indication of future well productivity can be obtained with the rig still in place with a step-rate injection test and monitoring of the pressure change downhole at (or near) the main loss zone. For the test, water is pumped into the well in 3 ~~h long~~ steps of 20, 40, and 60 L/s and the downhole pressure is recorded. This usually produces a linear relationship of flow vs pressure and the result is reported as the Injectivity Index in units of (kg/s)/bar. Injectivity Index less than 2 (kg/s)/bar indicates a poor well, around 5 (kg/s)/bar is fine, but values above 10 (kg/s)/bar indicate a very permeable and a good well.

p0305 The drilling equipment for production-size wells is large and heavy, requiring 50−100 truckloads to transport. The drill rigs have a hook load rating of 200−450 tons that have a ~~hoisting~~ capacity to drill to a depth of 3000−7000 m ~~but rarely go below 3000 m.~~ A few smaller truck-mounted rigs exist in the 60 to 100 ton range that drill slimholes to 1500−2000 m for exploration and also small wireline coring rigs for 1000−1500 m used by the mineral exploration industry.

p0310 For high-temperature wells, the casing design usually calls for three cemented casing strings of different diameters that extend to successively greater depths (Figure 71.7). The selection of drill bit and casing diameters usually follows a recommendation by the American Petroleum Institute and three different casing programs presently dominate. The "regular" high-temperature well casing program has a production casing outside diameter of 244.5 mm (9 $^5/_8$″) and ends in a 177.8 mm (7″) liner. This is the most common diameter size selection. The "large" well design has a 339.7 mm (13 $^3/_8$″) production casing that ends in a 244.5 mm (9 $^5/_8$″) liner. In addition, a few slimhole designs have a 193.7 mm (7 $^5/_8$″) production casing and a 114.3 mm (4 ½″) liner. These casing programs are the same for vertical or/and directional drilling. The "regular" well is designed for production, whether drilled for the purpose of exploration or other purposes. In very permeable and productive reservoirs, the well output may be restricted by the casing diameter. Then the "large" casing program, which can produce twice as much, is preferred.

p0315 The surface casing is typically set at a depth of 60−80 m to support the well through the soil and loose overburden, and ~~it contains~~ the first blowout preventer. The blowout preventers are of the same type as for petroleum drilling. They have different sizes depending on the section of the well being drilled. The blowout preventer stack typically consists of a double-gate ram preventer, an annular preventer, and a rotating head preventer. The casing is cemented in place with a high-temperature cement mix that is blended with water to produce a slurry, which is pumped down inside the casing, out of the bottom of the pipe, and back up to the surface via the annulus between the casing and open hole. It is extremely important that all casing strings are fully cemented from top to bottom. The cementing operation is one of the most critical procedures for longevity of the well. The second casing string is the anchor casing, which is landed at a depth of 300−400 m. The innermost casing is the production casing, set to 800−1100 m depth in a typical 2000−2500 m deep well. All of these three casing strings reach back to the surface and are cemented in place along their full length. The "open hole" section of the well is then drilled to the target depth. Finally, a liner with drilled holes is landed in the well, which allows the reservoir fluid to flow into the well (up to 100 holes per meter of liner, each with a diameter of 20 mm). For low-temperature wells in volcanic regions like Iceland that typically reach 1000−2000 m depth, well designs are similar in diameter but the production casing and liner are omitted. In continental settings where the geothermal gradient is near normal, wells may reach 3000−6000 m depth. Such wells require more casing strings and have well screens in the open hole section. All low-temperature wells have downhole pumps installed inside the production casing, either of the shaft-driven type



f0040 **FIGURE 71.7** Schematic layout of high-temperature geothermal wells drilled vertically and directionally. Casing design is the same, but the directional wells require special tools to deviate the well. Logging operations for each well section, as practiced in Iceland, are shown.

or ~~of a~~ submersible pump. Some wells can be so productive that the maximum flow is limited by the diameter of the pump body that can be placed inside the casing.

s0060 6. STRATEGY IN GEOTHERMAL DEVELOPMENT AND USE

s0065 6.1. General

p0320 The presence of hydrothermal reservoirs is generally manifested by hot springs and/or fumaroles and, in some cases, by hydrothermal alteration and sinter deposits. Exploration has, however, revealed hidden reservoirs. Sometimes the distribution and intensity of surface hydrothermal activity and the lateral extent and productivity of the underlying reservoir are not strongly related.

p0325 As with exploitation of the Earth's mineral resources, uncertainty is always involved with the success and economy of developing hydrothermal reservoirs at the time when the decision is made to go ahead with exploration. The uncertainty is due to limited information that is available about the characteristics and size of the anticipated resource. Development, therefore, always requires risk capital. Sometimes, exploration and subsequent development work reveals that utilization of the resource would be uneconomic. The most common causes for this are inadequate permeability and unfavorable reservoir fluid chemical composition.

Due to the uncertainty in predicting the success of developing a hydrothermal resource, it is common to divide exploration and subsequent development into phases. For each phase, the aim is to minimize cost and maximize information. At the end of each phase, a decision is made whether to continue or terminate the project. The phases are as following: p0330

1. Surface exploration
2. Exploration drilling
3. Appraisal drilling
4. Feasibility study and preliminary plant design
5. Additional production drilling to recover the amount of fluid required

p0360 The first four phases listed above correspond to comparable phases used in the exploration and development of subsurface mineral resources. The mining industry calls the different phases as anomaly, indicated deposit, proven deposit, and economic deposit. An environmental impact assessment is part of the early development phases. A more detailed description of the steps involved in geothermal exploration and development is shown in Figure 71.8.

s0070 6.2. Surface Exploration

p0365 Surface exploration is used to locate favorable geothermal fields within a particular region or country and to aid in skillful siting of exploration wells within them. It includes geological studies, geochemical and geophysical surveys, and sometimes hydrological balance assessment also.

p0370 Geological studies focus on mapping geological formations and the distribution and type of thermal manifestations. An attempt should always be made to relate the distribution of thermal manifestations with local structures such as faults and volcanic edifices. Frequently, the overall distribution of geothermal activity can be linked with larger geological structures, such as calderas, in which case, favorable drilling targets might be confined to the caldera, or by fractures/faults with the purpose of intersecting these permeable structures. Calderas, which form in response to rapid emptying of a magma chamber during a major explosive volcanic eruption, define approximately the lateral extent of the underlying magma chamber that was emptied when the caldera formed. New magma is likely to flow along the path of earlier magma that formed the magma chamber. Thus, the lateral extent of the magma heat

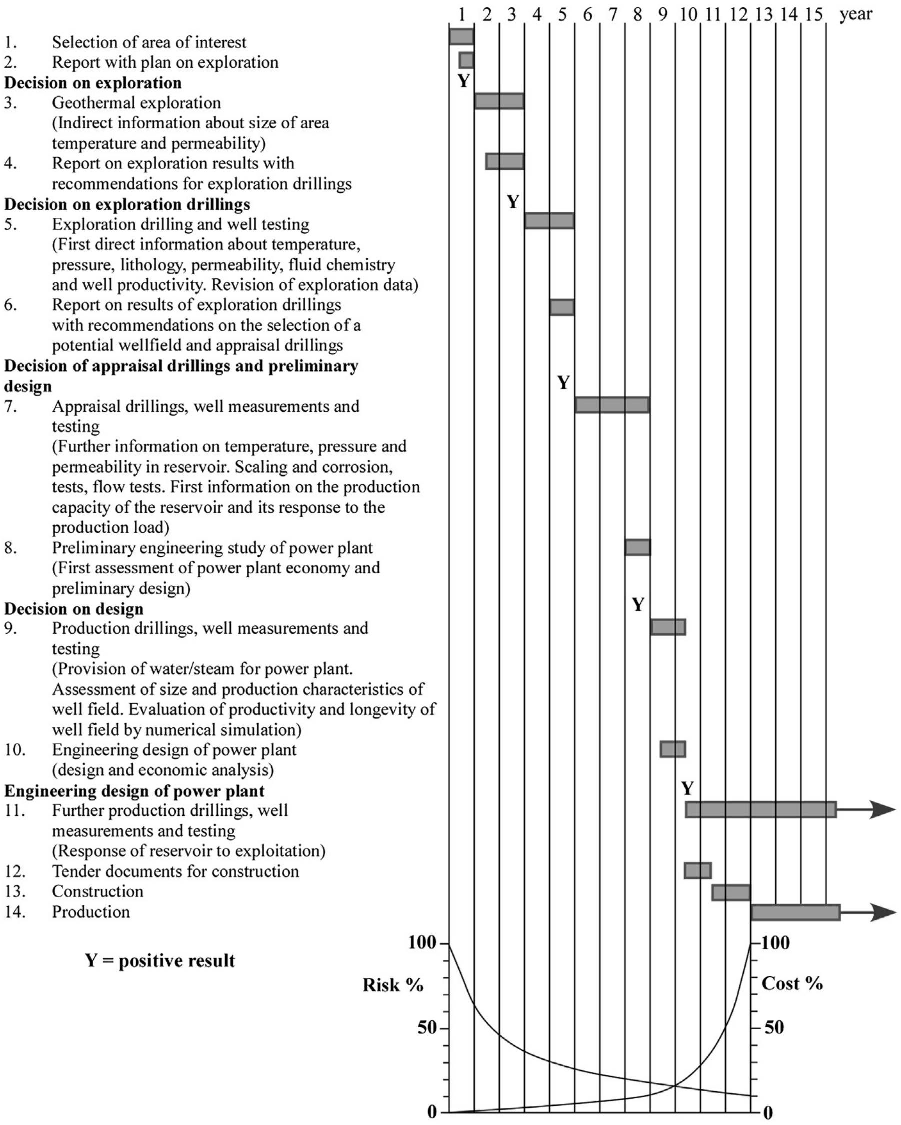


FIGURE 71.8 Strategy in geothermal exploration and development. Work involving environmental impact assessment is not shown. It varies from country to country when this work is carried out during the development work. Likely, this is affected by legislation in each country. f0045

source to the hydrothermal system would not be expected to extend beyond the caldera.

p0375 The principal purpose of geochemical surveys is to estimate temperatures in the underlying hydrothermal system with the aid of geothermometers. Sometimes carbon dioxide and radon are measured in soil gases to locate thermal anomalies. Data on hydrogen and oxygen isotopes in the water provide information on the origin of the hydrothermal fluid and subsurface flow directions. Studies in many geothermal fields have shown that mineral—solution equilibria exist at depth in hydrothermal reservoirs. This is an important observation, as equilibrium greatly constrains fluid compositions, making it possible to predict fluid properties with respect to their scaling tendencies and corrosion. Application of geothermometers assumes that specific mineral—solution equilibria prevail in the reservoir and that chemical reactions in upflow zones insignificantly modify the reservoir fluid composition, making it possible to use the chemical composition of hot-spring waters and fumarole steam to estimate subsurface temperatures.

p0380 Geophysical surveys have been classified into two groups: one providing information on geological structures and another supplying temperature information. The most widely used geophysical exploration tool maps electrical resistivity of bedrock. Hydrothermal systems are typically identified as resistivity lows. Resistivity surveys have proved useful to map the lateral extent of hydrothermal systems. Gravity surveys are sometimes useful in locating faults and intrusive bodies. Magnetic surveys are sometimes employed because hydrothermal alteration can cause decay of magnetite, leading to a negative magnetic anomaly.

p0385 Shallow ground temperature surveys (1 m) and drilling of shallow gradient holes (from few tens to few hundreds of meters deep) have also been used to locate upflow zones in hydrothermal systems. Ascending hot water/steam produces anomalously steep thermal gradient near the surface.

p0390 All data from exploration surveys are synthesized into a first conceptual reservoir model, which shows predicted subsurface temperatures, structural control of fluid flow, lateral extent of the **hydrothermal field**, and possibly other geological features such as caldera structure. If the outcome of the exploration survey is favorable, the report describing the results should include proposed sites for exploration drillholes.

s0075 6.3. Exploration Drilling

p0395 Exploration drilling provides the first direct data about the hydrothermal reservoir. It is much more expensive than the earlier surface exploration. The most important data obtained from exploration drillings include temperature, permeability, fluid chemical composition, and well's thermal output (mass flow and enthalpy). Successful results from exploration drillings lead to the selection of a prospective wellfield within a particular hydrothermal area. Following the drilling of a successful exploration well, drilling of **step-out wells** is usually done as a next step to get preliminary information about the extent of the anomaly (temperature, permeability) discovered by the exploration well.

In a hydrothermal area that is tens of square kilometers in size, it is common to drill several exploration holes in one go. These holes are drilled at possible production wellfields on the basis of the surface exploration results, and the best prospect is selected for drilling step-out wells. p0400

The main purpose of exploration drilling is to locate a promising production wellfield. However, in the case of small fields, it may be justified to drill wells near the anticipated field margins to verify its boundaries, especially when size and capacity are of concern for the intended utilization. As a rule, the principal aim of drilling any deep borehole is to prove hot fluid. New information from exploration drillings and later drilling and well testing requires updating the conceptual reservoir model. p0405

6.4. Appraisal Drilling s0080

Having located a promising production wellfield through exploration and step-out wells, the next development phase involves appraisal drillings to quantify the production characteristics of the identified hydrothermal reservoir. Appraisal drilling provides the necessary information for design and economic analysis of the project and, last but not least, the recovery of fluid for the intended utilization. For that reason, appraisal drilling is often termed as production drilling. However, any productive well is appropriately termed a production well. Having delineated a production wellfield, additional production wells are drilled between the **appraisal wells** to recover the needed amount of fluid for the production. p0410

6.5. Feasibility Study and Plant Design s0085

There are no fixed rules as to how much fluid should be proved (recovered) before a firm decision is made to construct a plant, whether for direct use of heat or for power generation. In a new area, the amount of steam to be proved for a power plant may be as much as 80% of the total steam required. However, if a new production field is being developed within an already exploited hydrothermal area, the number may be considerably lower (~50%) because understanding of the field production characteristics is already likely high based on information and experience from the previous development. p0415

It used to be common practice to discharge all productive wells drilled in a particular wellfield simultaneously over a period of time (several months) to test p0420 interference and measure decline in output with time. For environmental reasons, such tests may be limited to shorter periods and each new well is flow-tested shortly after it has been completed. Through numerical simulation, the flow-test results are used to predict the generating capacity of the reservoir as well as decline in well output and the longevity of the wellfield. When production history is short, the prediction carries considerable uncertainty but becomes more reliable as production history becomes longer.

p0425 Details of the strategy of geothermal exploration and development depend on the size of the plant to be constructed. The scheme described above was drawn up for a 50- to 100-MW electric power plant, which is a common size for such plants.

p0430 The electric power generating capacity per unit area of a wellfield depends on many factors such as temperature, permeability, and porosity. A useful working rule, when information is limited, is to assume a capacity of 15 MW_e/km^2 of wellfield. Thus, for a 75 MW plant, a wellfield of 5 km^2 size would be required plus some reserve area for drilling additional wells to replace the anticipated decline in output from initial production wells. Assuming the thickness for a hydrothermal reservoir of 1.5 km^2, rock porosity of 10%, and average reservoir temperature of 250 °C, the amount of fluid stored in 1.5 km^2 area of rock suffices to generate 15 MW of electric power over a period of 35 years, i.e., a period more than sufficient to depreciate the power plant.

p0435 Geothermal wells are never bonanzas like oil and natural gas wells. Oil wells produce a commodity measured in dollars, whereas wells drilled into hydrothermal systems produce a commodity measured only in cents. For this reason, exploration and development of such system demands a high ratio of successful wells. To generate electric power from geothermal steam in a particular area would be economically very attractive only if the average well yield was ~10 kg/s of steam (equivalent to ~5 MW_e) over a period of at least 10 years or proportionally longer if the yield is lower. The average steam yield per drilled well into volcanic hydrothermal systems worldwide is 4–5 MW_e. The poorest average yield of wells drilled into exploited hydrothermal reservoirs is a little less than 2 MW_e.

s0090 7. MONITORING STUDIES

p0440 During the early days of exploitation of hydrothermal systems, it was considered sufficient to prove the required steam flow rate for the intended use by short-term testing (a few months or even less) of producing wells and extrapolation of the results into the future. Experience, however, has shown that fluid pressures may decline considerably in exploited hydrothermal reservoirs because recharge is less than the rate of fluid extraction. This leads to decreased flow from wells and enhancement of cooler groundwater inflow from the surrounding rock. This necessitates monitoring of the response of hydrothermal reservoirs to the production load. Therefore, geoscientific work is not complete at the time of commission of a power plant.

Overexploitation of hydrothermal reservoirs is not uncommon. It leads to rapid drawdown of reservoir pressure and a corresponding decline in well output and power generation. This happened, for example, at the Geysers vapor-dominated field in California. The reason for rapid pressure drawdown was low porosity of reservoir rock and the correspondingly low quantity of liquid water in the reservoir that would generate steam by its boiling. To counteract pressure decline, water has been injected into the reservoir at the Geysers. p0445

Today, monitoring of the response of hydrothermal reservoirs to the production load has become the general practice worldwide. Data on the long-term response of a hydrothermal reservoir to production are necessary for specifying how the reservoir should be best exploited both economically and environmentally. Data to be collected are both physical and chemical. They involve regular measurement of flow rate and discharge enthalpy of wells and sampling and analysis of well fluid. Reservoir pressure also needs to be monitored at depth on nonproducing wells. The chemical data are useful for assessing any changes in scaling tendencies but more importantly to map cold water recharge into the reservoir that is enhanced by production. Monitoring data are valuable for timing and siting of new wells that need to be drilled to counteract the decline in flow from earlier production wells. The data are further used to update the reservoir production model to improve predictions about the long-term generating capacity of the reservoir. p0450

8. ENVIRONMENTAL ASPECTS s0095

8.1. General s0100

Most often geothermal energy can be regarded as a relatively clean resource and it is so in comparison with fossil fuels. The environmental impact, however, can be considerable. It varies by the fluid's chemical composition, the strength of rock overlying the reservoir and its stress field, and the magnitude of exploitation. Pollution caused by harnessing hydrothermal reservoirs can be (1) visual, (2) thermal, and (3) chemical. Additional adverse environmental impacts include the following: (1) extinction of surface thermal activity, (2) spoiled scenery, (3) noise pollution, (4) soil erosion and damage to vegetation, (5) land subsidence, and (6) induction of or enhancement of seismic activity. Volcanic hydrothermal fields often occur in areas of highly valued scenic beauty and they may, therefore, be of economic value not only as energy resources but also for tourism. p0455

s0105 8.2. Physical Impact and Pollution

p0460 The principal change resulting from exploitation of hydrothermal systems is reservoir pressure drawdown. This may cause hot-water springs to dry out but enhance fumarole activity. Also, pressure drawdown will enhance flow of recharging cold groundwater into the reservoir. The magnitude of these changes depends on the intensity of exploitation, i.e., the rate of fluid withdrawal from the hydrothermal system.

p0465 Power plants, steam supply systems, and roads to individual wells and along the steam pipelines all degrade the scenery and disturb the land surface, particularly in rugged terrain. A combination of heavy rains and steep slopes of incompetent rock can cause landslides and high soil erosion rates. Steam flow from the powerhouse (steam ejectors, cooling towers), steam separators, and wells leads to visual and some thermal pollution. If wastewater is disposed of on the surface, shallow groundwater and streams and other surface waters can become thermally polluted. Noise pollution occurs by wells, steam separators, steam ejectors, and cooling towers.

p0470 If the geological formation on top of geothermal reservoirs is incompetent, as is, e.g., the case at the Wairakei and Ohaaki-Broadlands fields in New Zealand, lowering of the water level in the reservoir causes emptying of fluid from pore spaces. As a consequence, they collapse, leading to land subsidence. This can cause problems in relatively densely populated areas and in flat-lying areas where rivers are flowing. Power production at Wairakei started in 1958, and by 2005, subsidence at Wairakei amounted to as much as 14 m.

p0475 Injection of waste fluid from geothermal power plants into the ground causes the groundwater table around an injection well to rise, thus increasing the hydrostatic head. This may affect the stress field in the rock sufficiently to cause it to fracture, thus creating earthquakes. The likelihood for this depends on the initial stress field.

p0480 Utilization of low-temperature fields (<150 °C), which are developed for direct use of the geothermal heat, generally has much less environmental impact than exploitation of volcanic hydrothermal systems for power generation. This is so partly because low-temperature fields tend to occur in areas of lower relief. Hot-water pipelines require little maintenance and can, therefore, be subsurface. Also, the hot water is generally pumped from the wells and the quantity pumped equals the usage, so no water is wasted. For example, in the low-temperature fields exploited by Reykjavík Energy in Iceland, no visual impact exists except for small shelters that cover each wellhead.

s0110 8.3. Chemical Pollution

p0485 The environmental impact of geothermal energy utilization generally of the most concern is chemical pollution due to air-borne and water-borne pollutants. Geothermal waters have, as a rule, much higher salt content than nonthermal groundwater. Many elements can occur in concentrations much higher than acceptable for domestic use, irrigation, stock watering, various industries, and aquatic life. This is particularly the case for arsenic, boron, hydrogen sulfide, and overall salt concentration. Furthermore, the concentrations of some trace elements, especially in saline fluids, may be unacceptably high. These include elements such as arsenic, mercury, lead, manganese, and zinc. Aluminum concentrations may be quite high in dilute high-temperature water and may far exceed permitted concentrations in domestic water and is too high for aquatic life.

Geothermal steam always contains some gases and other volatiles, including carbon dioxide (CO_2), hydrogen (H_2), hydrogen sulfide (H_2S), methane (CH_4), atmospheric gases, as well as mercury (Hg) and sometimes boron (B). Generally, the most abundant gases are CO_2, H_2S, and H_2. The source of the geothermal gases may be the magma heat source, the rock with which the geothermal fluid has interacted, or they may form by chemical reaction such as CH_4 by reduction of CO_2. The greenhouse gases, CO_2 and CH_4, are present in highly variable concentrations. The CO_2 concentrations are sometimes equilibrium-controlled but sometimes source-controlled. Methane and boron may be present in very high concentrations in steam in high-temperature systems associated with marine sediments such as at Ngawha in New Zealand. At least some volcanic geothermal systems in the Eastern Rift Valley of Kenya contain fluids rich in CO_2 (up to 10% in the steam). p0490

The gas in geothermal steam that is usually of the greatest concern from an environmental perspective is H_2S. This gas is highly poisonous, is corrosive, and has a noxious odor. It is common to remove H_2S from the noncondensable gases extracted from the turbine condensers to reduce atmospheric pollution. Many removal methods are known, but the ones most commonly used involve oxidation of the H_2S into either native sulfur or sulfate. p0495

8.4. Mitigating Measures s0115

In addition to various mitigation measures such as plant design and effluent treatment, basically two types of measures have been implemented to reduce the environmental impact: directional drilling and injection of spent fluid. p0500

Today, directional drilling is very common in hydrothermal fields, mainly for environmental reasons but also to reach difficult targets under mountains or rugged terrain. When drilling directionally, several wells can be drilled from the same platform requiring fewer roads and rig platforms. The success of directional drilling depends on the depth of producing horizons. If aquifers are abundant in the reservoir just below the production casing, the directionally drilled wells will be closely spaced at the depth p0505 level of these aquifers and interference between them is likely. Directional drilling works best when productive aquifers occur at deep levels in the reservoir. It seems logical to first drill vertical wells in a new field to obtain information on the depth level of producing horizons and subsequently deviated wells when, at least, several appraisal wells have been drilled in a prospective wellfield.

p0510 During the early years of geothermal energy utilization, the waste fluid was generally disposed of by the least expensive method available. This most often involved surface disposal into the nearest stream or into ponds constructed for this purpose. To reduce harmful chemical pollution, injection of all waste fluid into wells is the norm today. Injection may involve the drilling of special wells, either within the hydrothermal reservoir or outside of it. Alternatively, wells drilled for the purpose of production that turn out to be nonproductive or very poor may be used for injection. In any case, if injection is intended, this has to be taken into account during phase 3 (see Figure 71.8) in the development strategy.

p0515 Injection of spent hydrothermal fluids was seriously discussed for the first time at the UN Conference on Geothermal Energy held in Pisa, Italy, in 1970. There were two basic reasons for the interest to inject spent geothermal fluid. One is that injection helps maintain reservoir pressures, thus reducing temporal decline in well flow. The second reason is to eliminate the environmental impact caused by surface disposal of water with high concentrations of undesirable chemicals.

p0520 The waste fluid may be injected into shallow or deep wells. Injection back into the reservoir is generally considered to be the best solution assuming that scaling is not troublesome. Caution is, however, advised on such injection because of the risk of thermal breakthrough, i.e., the relatively cool injected water may flow rapidly into the aquifer of producing wells and cause their performance to deteriorate. Because permeability within hydrothermal reservoirs is variable and anisotropic, it is not possible to predict with confidence how an injection well will perform with respect to its capacity or to which way the injected fluid will flow once in the reservoir. Although injection will have a positive effect on reservoir pressure, it may reduce mining of the heat stored in the reservoir rock. Extensive depressurization boiling in a high-temperature reservoir that occurs as a consequence of the reservoir pressure drop will cause cooling of the depressurized flowing fluid. This creates a positive temperature gradient from rock to fluid that could enhance boiling of immobile water in micropores (vesicles in volcanic rocks), but the steam formed would flow due to its better flowing properties and end up in production wells.

p0525 A problem sometimes associated with injection is deposition of minerals from the fluid in the well, in the receiving formation, or in both. The mineral that is most often of concern is amorphous silica. Other common scale-forming minerals are calcite and anhydrite. The solubility of amorphous silica decreases with decreasing temperature. For this reason, deposition of this phase is only expected to occur in surface equipment and possibly in wells, if cooling is sufficient to make the initially quartz-saturated fluid oversaturated with more soluble amorphous silica. Calcite and anhydride have retrograde solubility with respect to temperature, so they may deposit in the receiving aquifer, where the wastewater gains temperature. Deposition will reduce the well capacity, which can be restored by acid cleaning. Sulfide minerals have both prograde and pH-dependent solubility and deposit readily from solution. Scales of sulfides invariably form from high-temperature fluids when they cool. These are minor from dilute waters but may be severe from very saline fluids. It is possible to predict with reasonable confidence the temperature range in which deposition of different minerals does not occur or is minimal in order to reduce mineral deposition. Injection plans should take this into consideration.

FURTHER READING

Arnórsson, S., 2004. Environmental impact of geothermal energy utilization. In: Gieré, R., Stille, P. (Eds.), Energy, Waste and the Environment: A Geochemical Perspective. Geological Society of London, pp. 297–336. Special Publication 236.

Arnórsson, S., Axelsson, G., Saemundsson, K., 2008. Geothermal systems in Iceland. Jökull 58, 269–302.

Arnórsson, S., Stefánsson, A., Bjarnason, J.Ö., 2007. Fluid-fluid interaction in geothermal systems. In: Liebscher, A., Heinrich, C.A. (Eds.), Reviews in Mineralogy and Geochemistry, vol. 65, pp. 259–312.

Bertrani, R., 2012. Geothermal power generation in the world 2005–2010 update report. Geothermics 41, 1–29.

Coumou, D., Driesner, T., Heinrich, C.A., 2008. Heat transport at boiling, near-critical conditions. Geofluids 8, 208–215.

Davis, J.H., Davis, R.D., 2010. Earth's surface heat flux. Solid Earth 1, 5–24.

Duffield, W.A., Sass, J.H., 2003. Geothermal Energy – Clean Power from the Earth's Heat. U.S. Geological Survey Circular 1249.

ENGINE Coordination Action, 2008. Best Practice Handbook for the Development of Unconventional Geothermal Resources with a Focus on Enhanced Geothermal Systems. BRGM Editions, Orleans, ISBN 978-2-7159-2482-6. Collection Actes/Proceedings.

Finger, J., Blankenship, D., 2010. Handbook of Best Practices for Geothermal Drilling. SANDIA Report, SAND 2010-6048, 84 pp.

Girardet, H., Mendonça, M., 2009. "A Renewable World – Energy, Ecology, Equality." A Report for the World Future Council. Green Books Ltd, Darlington, UK.

Glover, R.B., Mroczek, E.K., 2009. Chemical changes in natural features and well discharges in response to production at Wairakei, New Zealand. Geothermics 38, 117–133.

Grant, M.A., Donaldson, I.A., Bixley, B.F., 1982. Geothermal Reservoir Engineering. Academic Press, New York.

International Geothermal Association, 2010. In: Proceedings of the World Geothermal Congress 2010, Bali, Indonesia, 24–29 April, 2010.

Lund, J.W., Freestone, D.H., Boyd, T.L., 2010. Direct use of geothermal energy 2010 worldwide review. Geothermics 40, 159–240.

Mannington, W.I., O'Sullivan, M.J.O., Bullivant, D.P., Clotworthy, A.W., 2004. Reinjection at Wairakei-Tauhara: a modelling case study. In: Proceedings Twenty-ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, 26–28 Jan., 2004. STP-TR-175.

O'Sullivan, M., Yeh, A., Mannington, W.I., 2010. Renewability of geothermal resources. Geothermics 39, 314–320.

Rybach, L., Muffler, L.P.J., 1981. Geothermal Systems: Principles and Case Histories. Wiley, Chichester.

Sanyal, S.K., 2005. Sustainability and renewability of geothermal power capacity. In: Proceedings World Geothermal Congress 2005, Antalya, Turkey abstract 0520.

Schwarzschild, B.M., 2011. Neutrinos from Earth's interior measure the planet's radiogenic heating. Phys. Today 64, 14–17.

Stefánsson, V., 2000. The renewability of geothermal energy. In: Proceedings of the World Geothermal Congress 2000, Kyushu – Tohoku, Japan, 28 May to 10 June 2000, pp. 883–888.

Williams, C.F., Reed, M.J., Mariner, R.H., DeAngelo, J., Galanis Jr, S.P., 2008. Assessment of Moderate- and High-temperature Geothermal Resources of the United States. U.S.G.S. – science for a changing world.

World Energy Council, 2010. 2010 Survey of Energy Resources.

Non-Print Items

■■■
■■■

■■■
■■■.