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Ch. 2, Environmental Compatibility of Geothermal Energy

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CONTENTS

INTRODUCTION

Geothermal energy is one of the cleaner forms of energy now available in commercial quantities. The use of this alternative energy source, with low atmospheric emissions, has a beneficial effect on our environment by displacing more polluting fossil and nuclear fuels. Rapidly growing energy needs around the world will make geothermal energy exceedingly important in several developing countries. In the production of geothermal energy, wells are used to bring hot water or steam to the surface from underground reservoirs. The thermal energy carried in the produced fluid can be used for direct heating in residential, agricultural, and industrial applications; or the thermal energy of higher temperature systems can be used to produce electricity.

Geothermal energy provides an enormous resource for low-temperature applications such as heating and cooling buildings, drying agricultural products, and process heating for industry. For example, geothermal heat pumps can be installed in almost all areas of the U.S. to provide greater efficiency in heating and cooling of buildings and supplying hot water than either all electric systems or systems with air-source heat pumps. Only a modest part of the potential of geothermal energy has been developed because the service industry is small and the price of competing energy sources is low. Electrical power production is the most profitable use of geothermal energy and has grown the most. Our discussion of the environmental aspects of geothermal energy utilization will concentrate on the production of electricity.

The U.S., Japan, and the European Community are continuing experiments in the extraction of thermal energy from high-temperature, subsurface zones with low initial permeability (often called "hot dry rock"). In these investigations, one deep well is used for the injection of water, at high pressure, into artificially fractured rock, the water extracts heat from the fracture surface, and a second deep well produces steam and hot water. This method of energy production is not yet economic, and the presently commercial geothermal operations depend on naturally occurring hydrothermal systems.

The U.S. Department of Energy (DOE) conducted research into the extraction of energy from the geopressured (very high pressured) brines in the Gulf Coast area of Texas and Louisiana, and concluded that even the extraction of methane as a byproduct did not make this energy source economic. Experiments were also conducted by the DOE to investigate the recovery of thermal energy from magma systems. The technique considered for energy extraction involved the injection of water to cool the magma to a fractured glass and then the continued injection and production of water to carry heat to the surface.

Geothermal energy performs a small but important role in the supply of energy for electric power generation in the U.S., and geothermal electricity plays an even greater role in some developing countries (the Philippines, Mexico, Indonesia, El Salvador, Kenya). In 1991, geothermal electrical production in the U.S. was 15,738 GWh (gigawatt hours), and the generation of this electricity provided approximately $1 billion dollars in revenue.[1] This use of geothermal energy displaces the equivalent of over 30 million barrels of imported oil per year.

The U.S. geothermal electric-power industry has grown to be the largest in the world, with over 2100 MW (megawatts electricity) generating capacity operating at over 90% availability. Slightly over half, 1100 MW generating capacity, is from The Geysers geothermal field in California. The magnitude of development in the U.S. is followed by the Philippines with 890 MW, Mexico with 700 MW, Italy with 545 MW, and New Zealand with 460 MW.[1] Iceland has the unique situation of an overabundance of hydro-electric potential, and most geothermal energy is used to provide heating and hot water for commercial and residential customers.

Geothermal energy use avoids the problems of acid rain, and it greatly reduces greenhouse gas emissions and other forms of air pollution. Geothermal reservoirs, either dry steam or hot water, are naturally occurring hydrothermal convection systems. Natural fluids are usually complex chemical mixtures, and geothermal waters exhibit a wide range of compositions and concentrations of solutes. The concentrations of solutes generally increases with the temperature of the geothermal system, and higher concentrations of some elements often require remedial action for protection of the environment. Potentially hazardous elements (Hg, B, As, and Cl) produced in geothermal brines are largely injected back into the producing reservoir. A continuing strong market for geothermal electrical generation is anticipated as a result of the increasing interest in controlling atmospheric pollution and because of the spreading concern about global warming. Geothermal development will serve the growing need for energy sources with low atmospheric emissions and proven environmental safety.

Land use for geothermal wells, pipelines, and power plants is small compared to land use for other extractive energy sources such as oil, gas, coal, and nuclear. Low-temperature geothermal applications are usually no more disturbing of the environment than a normal water well. Geothermal development projects often coexist with agricultural land uses, including crop production or grazing.

GEOTHERMAL ENERGY APPLICATIONS

High-Temperature Electrical Use

The production of electricity requires a greater concentration of energy than other applications. Many geothermal systems contain water or steam at temperatures above 175°C, and temperatures up to 400°C have been recorded. If hot fluid is available in great enough quantities, a geothermal power plant can be installed that uses the produced steam directly to drive a turbine generator system.

In 1960, The Geysers in northern California became the first U.S. geothermal field to produce electricity, and this remains the only commercial development in the U.S. that is classified as a dry-steam geothermal system. In this low-pressure, single-phase system, dry steam is the pressure-controlling medium filling the fractured rocks. The pressure increases only slightly with depth due to the density of the steam. Initial conditions in The Geysers reservoir at a depth of 1.5 km (kilometers) included temperatures near 250°C and pressures near 3.3 MPa (megapascals). Over 30 years of production, the pressure has dropped to less than 1 MPa in the areas of production wells, but the temperature has remained constant. Early developers found that this dry- steam type of geothermal system is very rare.

Most geothermal fields are water-dominated, where liquid water at high temperature, but also under high (hydrostatic) pressure, is the pressure-controlling medium filling the fractured and porous rocks. The pressure increases along a hydrostatic gradient in water-dominated reservoirs, and the temperature will often increase along the boiling point (liquid-vapor equilibrium) curve with depth. In water-dominated geothermal systems, water comes into the wells from the reservoir; and, in the flashed-steam power-plant technology, the pressure decreases as the water moves toward the surface, allowing part of the water to boil. Since the wells produce a mixture of flashed steam and water, a separator is installed between the wells and the power plant to separate the two phases. The flashed steam goes into the turbine to drive the generator, and the water is injected back into the reservoir.

The water-dominated geothermal system in Dixie Valley, Nevada has several features that are common to many of the geothermal fields in eastern California, Nevada, and western Utah. The water contains 0.45 weight percent dissolved solutes, and these constituents are in chemical equilibrium with the reservoir rocks. At a depth of 2 km, the temperature is 240°C and the fluid pressure is 24 MPa; this is the hydrostatic pressure from the overlying column of water.[2] At these conditions, the geothermal fluid is liquid water. The production wells penetrate permeable zones along the active Stillwater fault, which is the physical boundary between Dixie Valley and the Stillwater Range. Steam is allowed to flash in the wells and is separated at the surface to drive the turbines. The separated water is injected to maintain reservoir pressure.

Binary-Plant Electrical Generation

Most water-dominated reservoirs below 175°C are pumped to prevent the water from boiling as it is circulated through heat exchangers to heat a secondary liquid. In these binary power systems, heat is transferred to an organic compound with a low boiling temperature (commonly propane or isobutane), and the resulting organic vapor then drives a turbine to produce electricity. Binary geothermal plants have no emissions because the organic fluid is continuously recirculated in a closed loop, and the entire amount of produced geothermal water is injected back into the underground reservoir. A higher conversion efficiency is required to economically use lower-temperature water for electrical production, and the binary equipment has a higher capital cost to achieve this greater efficiency. The identified reserves of lower-temperature geothermal fluids are many times greater than the reserves of high-temperature fluids, providing an economic incentive to develop more efficient binary power plants.

Low-Temperature Direct Heat Use

Warm water, at temperatures above 20°C, can be used directly for a host of processes requiring thermal energy. Thermal energy for swimming pools, space heating, and domestic hot water are the most widespread uses, but industrial processes and agricultural drying are growing applications of geothermal use. In a 1990 inventory, the U.S. was using over 5 x 10^{12} kJ (kilojoules) of energy annually from geothermal sources for direct heating of commercial and residential installations.[3] In Iceland, more than 95% of the buildings are supplied with heat and domestic hot water from geothermal systems, and this heat has directly replaced the burning of fossil fuels. The cities of Boise, Idaho; Elko, Nevada; Klamath Falls, Oregon; and San Bernardino and Susanville, California; have geothermal district-heating systems where a number of commercial and residential buildings are connected to distribution pipelines circulating water at 54 to 93°C from the production wells.[4] There is believed to be a high potential for growth in district heating because numerous geothermal resources are co-located with population centers, especially in the western half of the U.S. The U.S. Department of Energy currently is funding a comprehensive inventory of low-temperature geothermal systems with special emphasis on co-location with population centers. Preliminary results indicate that there may be twice the number of systems that have been identified previously.

Typical direct-use applications are either closed systems with the produced fluids being injected back into the geothermal reservoir, or systems where the produced water is pure enough for beneficial use or disposal to surface waterways. Experience has shown that it is worthwhile to inject as much of the cooled geothermal water back into the reservoir as possible to maintain pressure and production rates. The direct use of geothermal energy for heating offsets the carbon dioxide production from combustion of fossil fuels - usually oil or gas - in a large number of residential or commercial furnaces.

Geothermal Heat Pumps

The use of geothermal energy through ground-coupled heat pump technology has almost no impact on the environment and has a beneficial effect in reducing the demand for electricity. Geothermal heat pumps use the reservoir of constant temperature, shallow groundwater as the heat source during winter heating and as the heat sink during summer cooling. Shallow groundwater is normally about 5°C above the mean annual air temperature for any locality in the U.S. Because of this constant temperature, the energy efficiency of geothermal heat pumps is about 30% better than that of air-coupled heat pumps and 50% better than electric-resistance heating. Depending on climate, advanced geothermal heat pump use in the U.S. reduces energy consumption and, correspondingly, power plant emissions by 23 to 44% compared to advanced air-coupled heat pumps, and by 63 to 72% compared to electric-resistance heating and standard air conditioners.[5] The need for electrical generation capacity at the central power station is reduced by 2 to 5 kW for each residential installation and by about 20 kW for average commercial installations. Thus, for each 1000 homes with geothermal heat pumps, the utility can avoid the installation of 2 to 5 MW of generating capacity.

Geothermal heat pumps can be used in a variety of installations. A system is comprised of 1) the heat pump mechanical unit, 2) the closed-loop or open-system ground heat exchanger, and 3) the building water loops. In closed-loop systems, water or a mixture of water and an environmentally safe antifreeze solution is circulated through a pipe to remove heat from, or reject heat to the ground. There is thus no contact between the solution in the closed-loop pipe and the groundwater or soil. In a vertical installation, the heat exchanger loop is a U-shaped pipe inserted in a hole 50 to 150 m (meters) deep. In horizontal installations, the heat exchanger loop is either rigid or flexible pipe laid in trenches about 2 m deep. Flexible tubing shaped in a spiral (often called a "slinky") and placed in a trench can be used to increase the effective heat exchange surface area of a horizontal loop and to reduce the length of trenching by 40%. The open vertical system uses a water well to provide groundwater to the heat pump, and, depending on need, the water can be used within the building, can be discharged at the surface, or can be injected in a second well. In single-well, open installations, water can be withdrawn from the bottom of the well, circulated through the heat pump, and returned to the top of the well. This method depends on the open communication with the groundwater system, is often a lower cost option, and is used in large commercial applications where space is limited.

The use of heat pump technology is associated with disturbance of soil during installation; however, since this application is normally associated with the simultaneous construction of homes and industrial buildings, there is only a small and transient surface disturbance. Geothermal heat pumps require less frequent maintenance and repair; refrigerants are installed in sealed systems at the factory (like a refrigerator) and no field connections are required. Equipment has a much longer lifetime since no part of the heat pump is outside the building and exposed to the elements. During operation, there are no emissions from closed-loop systems because the ground-loop heat exchange fluid (usually water) is contained. If an antifreeze is needed, environmentally compatible antifreeze such as potassium acetate can be used so that there is no risk of accidental release of polluting compounds to ground or surface waters.

ENVIRONMENTAL CONSIDERATIONS

Air Quality

All known geothermal systems contain the equilibrium distribution of carbonate, bicarbonate, and aqueous carbon dioxide species in solution; and, when a steam phase separates from boiling water, carbon dioxide is the dominant (over 90% by weight) noncondensible gas. Most hydrothermal systems have very low oxygen activity, and these systems commonly contain the reduced species H_2S, NH_3, and CH_4, in the steam phase. In most geothermal systems, noncondensible gases make up less than 5% by weight of the steam phase. Thus, for the same output of electricity, carbon dioxide emissions from geothermal flashed-steam power plants are only a small fraction of emissions from power plants that burn hydrocarbons. Binary geothermal power plants do not allow a steam phase to separate, so carbon dioxide and the other gases remain in solution and are reinjected into the reservoir, resulting in no atmospheric emissions. For each megawatt-hour of electricity produced in 1991, the average emission of carbon dioxide by plant type in the U.S. was: 990 kg from coal, 839 kg from petroleum, 540 kg from natural gas, and 0.48 kg from geothermal flashed-steam.[6]

Hydrogen sulfide can reach moderate concentrations in the steam produced from some geothermal fields, and some systems contain up to 2% by weight of H_2S in the separated steam phase. This gas presents a pollution problem because it is easily detected by humans at concentrations of less than 1 ppm in air. Development of technology to remove H_2S was the first major research effort for joint industry-government funding in the National Geothermal Program. H_2S control became a pressing problem at The Geysers because of increasingly more stringent environmental standards promulgated by the California Air Resources Board. Now, either the Stretford process or the incineration and injection process is used in dry-steam and flashed-steam geothermal power plants to keep H_2S emissions below 1 ppb.

The efficiency of these processes in removing over 99.9% H_2S from the air emissions has resulted in Lake County, California (containing part of The Geysers geothermal field) receiving the Outstanding Performance award in 1992 from the California Air Resources Board for compliance with the California Clean Air Standards.[7] Use of the Stretford process in many of the power plants at The Geysers results in the production and disposal of about 13,600 kg sulfur per megawatt of electrical generation per year. Figure 1, based on the diagram of Henderson and Dorighi,[8] shows the typical equipment used in the Stretford process at The Geysers. Some of this sulfur is contaminated with vanadium (the Stretford catalyst) and must be washed before disposal.

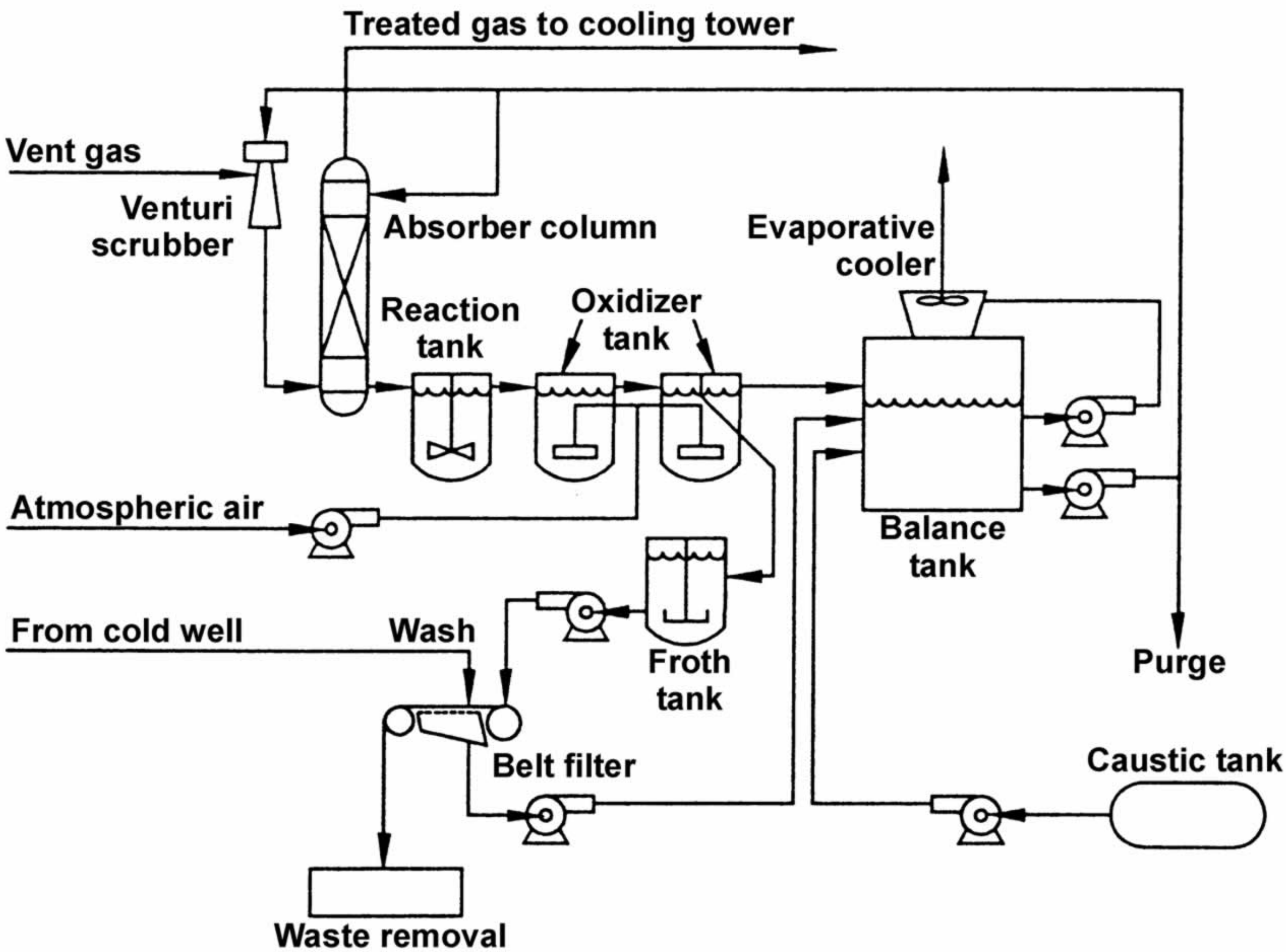

Figure 1. Typical equipment used in the Stretford process for hydrogen sulfide abatement at The Geysers geothermal field. (*from Henderson, J. M. and Dorighi, G. P., Geothermal Resources Council Trans., 13 593, 1989, with permission.)*

The incineration process burns the gas removed from the steam to convert H_2S to SO_2, the gases are absorbed in water to form SO_3^{2-} and SO_4^{2-} in solution, and iron chelate is used to form $S_2O_3^{2-}$.[9] Figure 2, derived from the diagram of Bedell and Hammond,[9] shows the incineration abatement system. The major product from the incineration process is a soluble thiosulfate that is injected into the reservoir with the condensed water used for the reservoir pressure maintenance program. Recent advances in the use of an oxidizing biocide to remove H_2S from cooling tower circulating water have the potential to decrease cost and increase efficiency of removal.[10]

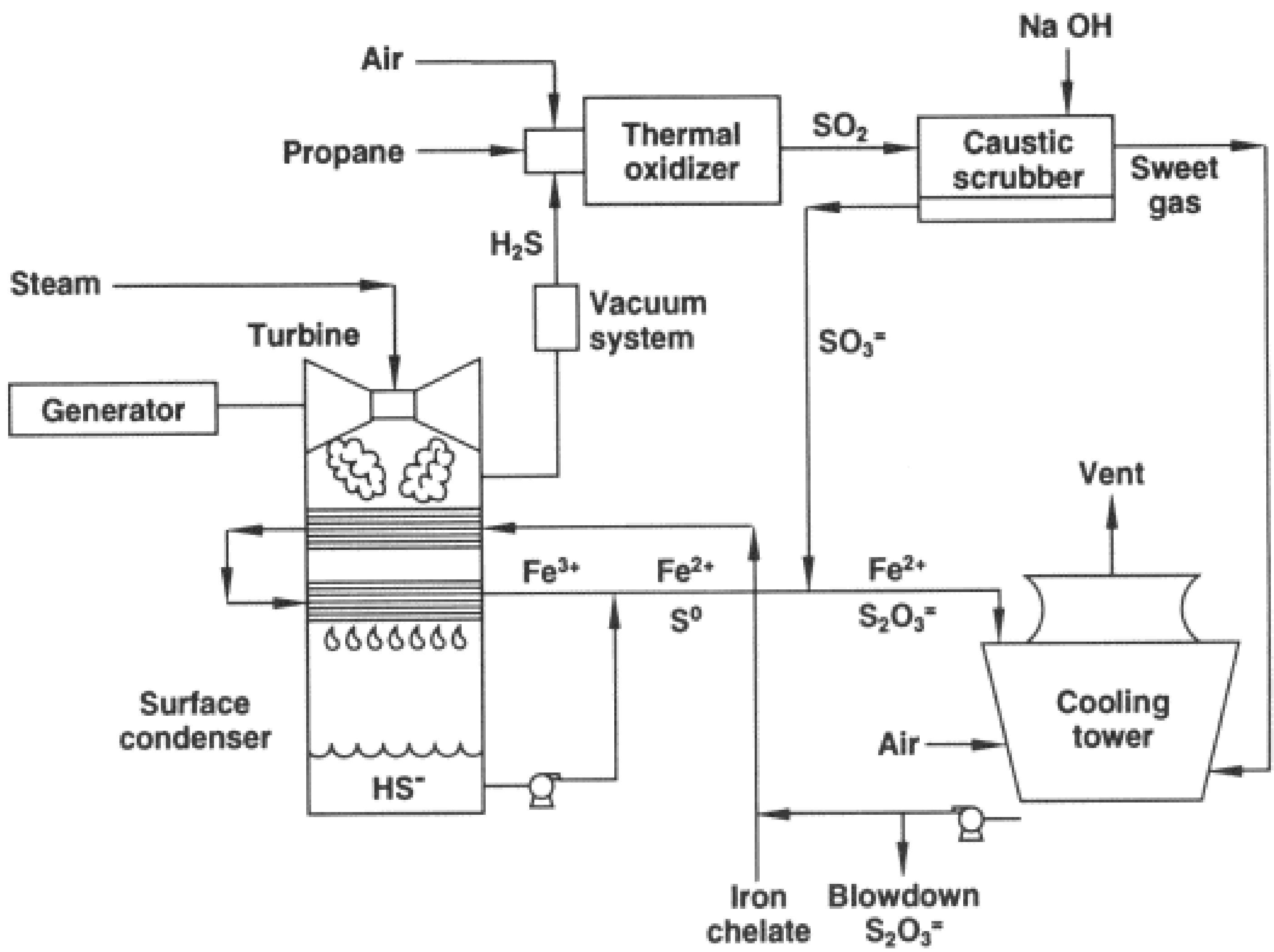

Figure 2. Equipment used in the incineration process for hydrogen sulfide abatement at The Geysers geothermal field. *(From Bedell, S. A. and Hammond, C. A., Geothermal Resources Council Bull., 16, 3, 1987, with permission.)*

The environmental effects of H_2S and SO_2 are quite different but, at a distance of 5 km downwind from the source, studies have shown that all of the H_2S has been oxidized by the air to SO_2. For discussions of air emissions, we have converted the H_2S to SO_2. Sulfur emissions from geothermal flashed-steam power plants are only a small fraction of emissions from power plants that burn solid or liquid hydrocarbons. For each megawatt-hour of electricity produced in 1991, the average emission of SO, by plant type in the U.S. was: 9.23 kg from coal, 4.95 kg from petroleum, and 0.03 kg from geothermal flashed-steam (from data of Colligan[6]).

Ammonia occurs in small quantities in many geothermal systems; but, in flashed-steam geothermal power plants, the ammonia is oxidized to nitrogen and water as it passes into the atmosphere. Because the high pressures of combustion are avoided, geothermal power plants have none of the nitrogen oxides emissions that are common from fossil fuel plants. For each megawatt-hour of electricity produced in 1991, the average emission of nitrogen oxides by plant type in the U.S. was: 3.66 kg from coal, 1.75 kg from petroleum, 1.93 kg from natural gas, and zero from geothermal (from data of Colligan[6]).

Water Quality

The waters in geothermal reservoirs range in composition from 0.1 to over 25 weight percent dissolved solutes. The compositions and concentrations of geothermal waters depend on the rock type of the reservoir, the temperature, and the pressure. Systems in sedimentary rocks seem to have higher concentrations than those in volcanic or granitic rocks, but there is wide variability within a single reservoir rock type. Temperatures up to 380°C have been recorded in geothermal reservoirs in the U.S., and many chemical species have a significant solubility at high temperature. For example, all of the geothermal waters are saturated in silica with respect to quartz. As the water is produced, silica becomes supersaturated; and, if steam is flashed, the silica becomes highly supersaturated. Upon cooling, amorphous silica precipitates from the supersaturated solution.

The high flow rates of steam and water from geothermal wells usually prevent silica from precipitating in the wells, but careful control of fluid conditions and residence time is needed to prevent precipitation in surface equipment. Silica precipitation is delayed in the flow stream until the water reaches a crystallizer or settling pond. There the silica is allowed to settle from the water, and the water is then pumped to an injection well. It is necessary to inject the geothermal water back into the reservoir to maintain the pressure and flow rate at the producing wells. Precipitated silica is removed from the water so that the solid material does not clog the injection well or reservoir. The most soluble of the other species in solution remain in solution and are injected. Other species, which have precipitated, are washed from the silica and injected with the wash water. The removed silica requires disposal, but research is underway to find a commercial use for the silica produced. Many of the solids removed from geothermal processes require drying before disposal to reduce both volume and mass.

The Salton Sea geothermal system in the Imperial Valley of southern California has presented some of the most difficult problems in brine handling. Water is produced from the reservoir at temperatures between 300 and 350°C and concentrations between 20 and 25% solutes by weight. This brine is in equilibrium with the mineral phases in the reservoir, but the concentration that occurs when 20% of the mass is allowed to vaporize leaves the brine supersaturated with respect to several solid phases. To remove solids from the steam, crystallizers are used upstream of the turbines, and to remove solids from the injection water, both clarifier and thickener tanks are needed. Figure 3, modified from the diagram of Signorotti and Hunter,[11] shows the flow stream for removal of solids from the vapor and brine. As an alternative, one power plant in the Salton Sea geothermal field uses the addition of acid to lower the pH and keep the solutes in solution.[11] The output from the crystallizers and clarifiers is a slurry of brine and amorphous silica. The methods used to de-water the salt and silica slurry from Magma Energy operations in the Salton Sea geothermal system are described by Benesi.[12]

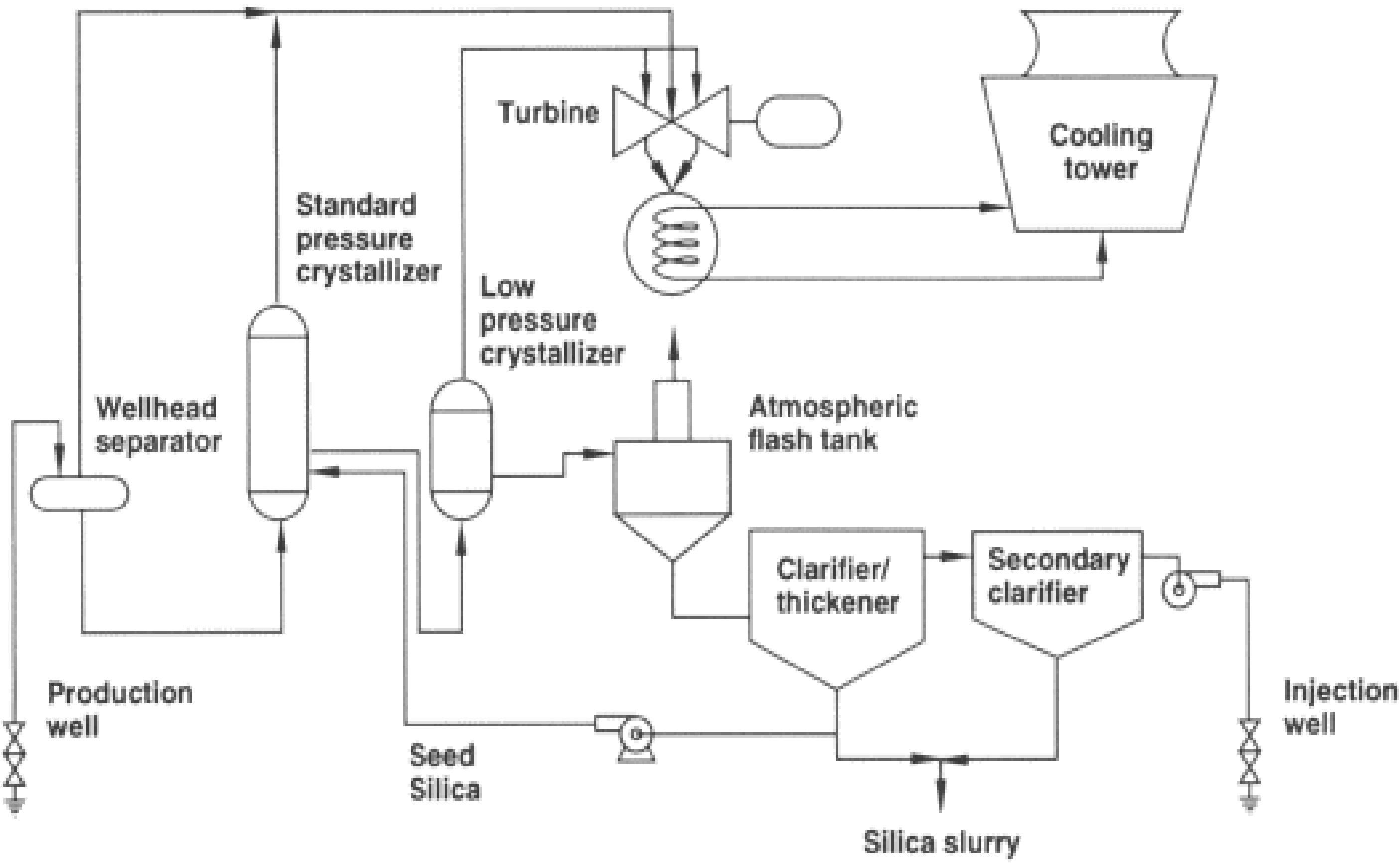

Figure 3. The flow stream for removal of solids from the vapor and brine in typical power plants in the Salton Sea geothermal field. *(From Signorotti, V. and Hunter, C. C., Geothermal Resources Council Bull., 21, 277, 1992, with permission.)*

Some geothermal systems, such as Dixie Valley in Nevada, form a high pH water through the evolution of carbon dioxide from solution.[1] This high pH permits the silica concentration in solution to remain at much higher levels without causing the precipitation of amorphous silica. At high pH, some of the silica in solution forms an ionic complex ($H_3Si0_4^-$) reducing the concentration of the neutral complex ($H_4Si0_4^0$) that controls polymerization and precipitation as amorphous silica.

In the U.S., only the lower-temperature geothermal waters that are of drinking-water quality are allowed to flow into streams or lakes. All other geothermal applications require that the cooled water be injected back into the reservoir. To protect potable ground waters in shallow aquifers, both the production and injection wells are lined with steel casing pipe and cemented to the surrounding rock. This type of well completion prevents the loss of geothermal water to any freshwater aquifers and confines the injection to the geothermal reservoir. Repeated examination of casing and cement, using sonic logging instruments, assures that no leakage occurs.

The production and injection system for geothermal water also prevents any contamination of surface waters. Water injection in the hotter geothermal systems does not require any pump pressure at the surface, since the cold injection water drops under the influence of gravity into the less dense, hot water of the reservoir. Cooler geothermal systems or those with rocks of lower permeability will require some pump pressure to inject the water into the reservoir. Geothermal power plants in the U.S. use cooling towers to condense the turbine exhaust fluid (either steam or organic fluid), and no waste heat is dumped into rivers or the sea. Waste heat disposal from fossil and nuclear power plants can cause disruption of the biota in local water bodies.

Land Use

The actual land used in geothermal operations is fairly small, and other applications such as crop growing or grazing can exist in proximity to the roads, wells, pipelines, and power plants of a geothermal field. The average geothermal plant occupies only 400 m^2 (square meters) for the production of a gigawatt hour over 30 years.[13] If the entire life cycle of each energy source is examined, the energy sources based on mining such as coal and nuclear require enormous areas for the extraction and processing in addition to the area of the power plant. The disturbed surface from open pit mining is an area with no plant life to participate in the carbon cycle or in evapotranspiration to replenish the water in the atmosphere.

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Back to Top