Environmental Considerations for Geothermal Energy as a Source for District Heating

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ABSTRACT

Geothermal energy currently provides a stable and environmentally attractive heat source for approximately 20 district heating (DH) systems in the United States. The use of this resource eliminates nearly 100% of the conventional fuel consumption (and, hence, the emissions) of the loads served by these systems. As a result, geothermal DH systems can rightfully claim the title of the most fuel-efficient DH systems in operation today.

The cost of producing heat from a geothermal resource (including capitalization of the production facility and cost for pumping) amounts to an average of $1.00 per million Btu (0.0034 $/kWh).

The major environmental challenge for geothermal systems is proper management of the producing aquifer. Many systems are moving toward injection of the geothermal fluids to ensure long-term production.

INTRODUCTION

Prior to discussing the specifics of geothermal district heating, it is useful to examine the nature of the source of the energy on which these systems depend. Geothermal energy is the heat derived from the earth's interior. Two mechanisms are believed to be responsible for production of the heat: decay of radioactive isotopes deep within the core and heat released during the formation of the earth by gravitational acceleration and subsequent mass redistribution (when heavier material sank into the earth's core). The relative contribution of these two sources is not firmly established (Wright and Culver 1991).

As a result of the elevated temperature in the interior, heat flows toward the surface of the earth. One estimate (White 1965) of the total thermal energy contained in the earth's crust (to a depth of six miles) is the equivalent of 2.3×10^{17} barrels of oil. At present, only a small fraction of this energy is economically recoverable, but clearly the potential is great.

Geothermal resources occur in a variety of forms. Among the most common are convective hydrothermal, sedimentary basin, geopressured, and radiogenic. Of these, the most commonly exploited (for district heating) are the water-dominated convective hydrothermal resources of the western U.S. These, along with vapor (steam) dominated resources, are also used in geothermal electric power generation projects. To date, geopressure resources along the Gulf Coast and radiogenic resources along the East Coast have not reached economic competitiveness.

Elevated temperatures, combined with exposure to various rock and mineral materials, result in relatively high concentrations of dissolved solids and gases in geothermal fluids. Most fluids used in direct-use projects are characterized by total dissolved solids (TDS) contents of 3,000 parts per million (ppm) or less. Commonly encountered gases include hydrogen sulfide (H_2S), carbon dioxide (CO_2), and ammonia (NH).

HISTORIC DEVELOPMENT AND CURRENT STATUS OF GEOTHERMAL DISTRICT HEATING

The first large commercial geothermal district heating system (GDH) in the U.S. was established in Boise, Idaho, in 1893. It has remained in continuous operation for more than a century and currently serves a primarily residential customer base of approximately 240 homes and a few commercial buildings (Rafferty 1994).

The success of this system resulted in feasibility studies for similar systems in a number of western cities around the turn of the century. However, no further development of large commercial systems occurred for 60 years. Several small multibuilding heating systems were developed at resorts in California, Oregon, Montana, and Idaho, but these were quite small relative to what is generally termed "district heating" today. In the early 1960s, the new campus of an Oregon university was specifically located at a site with geothermal resources. The system, installed in

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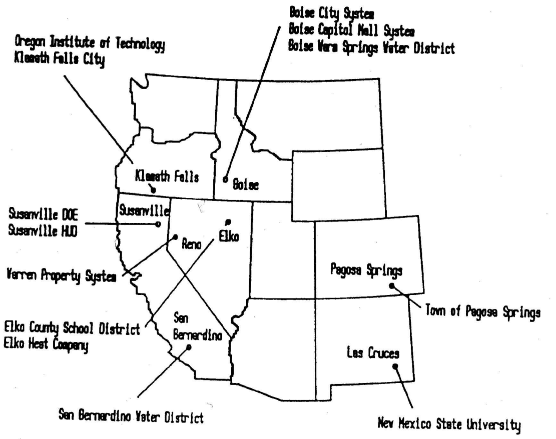

Figure 1 Location of selected operating geothermal district heating systems (Rafferty, 1990).

1963, still serves all of the heating and part of the cooling needs of the campus.

Following the oil price shocks of the mid-1970s, several systems were developed in the late 1970s and early 1980s. The locations of these systems appear in Figure 1. For the most part, these are municipally operated systems serving a commercial building customer base.

At present, there are at least 15 large commercial geothermal district systems in operation. Many more smaller systems serving multiple buildings could boost this number substantially, though documented figures are not available. The total heating capacity of the 15 largest systems amounts to approximately 550,000,000 Btu/h (161 MW) (Rafferty 1990).

DESIGN OF GEOTHERMAL DISTRICT HEATING SYSTEMS

Geothermal district heating systems in the U.S. are of two basic designs: open distribution and closed distribution. In the open configuration, the geothermal fluid is delivered directly to the individual customers, where a heat exchanger is used to isolate it from the building mechanical system. Cooled geothermal fluid is collected in a return system and delivered to the disposal point. In the closed design, a central heat exchanger is used to isolate the entire distribution system from the geothermal fluid. Treated water is delivered to the customer, who may be connected directly to the distribution system.

In either case, the geothermal fluid is delivered to the system from a production well(s). Although some early systems relied on the natural artesian head of the aquifer, all current systems employ pumps, usually the vertical turbine type, to produce the fluid. Effluent is either disposed of on the surface (river, lake, etc.) or injected into wells specially designed for this purpose. Dedicated injection pumps are typically not required.

ENVIRONMENTAL BENEFITS OF GDH

All U.S. GDH systems supply 100% of customers' energy needs with geothermal energy. This is in contrast to European district systems in which geothermal energy (when used) generally serves base-load duty with conventionally fueled boilers for peaking. The shallower, less expensive access to U.S. geothermal resources, along with the much smaller size of U.S. systems, accounts for the design difference.

As a result of this operating strategy, GDH systems in the U.S. can justifiably claim the title of highest energy efficiency of any district system currently in operation. The only energy input required for delivery of the hot water is that necessary to operate the system production well pumps. This pumping energy requirement is sometimes erroneously thought to be excessive due to the depth of the wells. It is true that typical production well depths for U.S. GDH systems are in the range of 300 to 3,000 ft (90 to 900 m) with the majority in the 800- to 1,800-ft (240- to 550-m) range. Due to the hydraulics of geothermal systems, however, the pumping requirement is less than that suggested by the well depth. Typical pumping water levels in GDH system wells are 100 to 400 feet (30 to 120 m). Because most geothermal systems are recharged by water of atmospheric origin, the fluid is at ambient temperature as it enters the system. The difference in density between the cold recharge water and hot water exiting the system causes the hot water to rise toward the ground surface. This density effect is compounded if recharge occurs at higher elevations.

As a result, assuming pump and motor efficiencies of 75% and 90%, a geothermal fluid Δ of 40°F (22°C), and a pump head of 250 ft (76 m), the pumping power required per 1,000,000 Btu (293 kW) would amount to 3.5 kW. At an average electrical cost of .08\$/kWh, this amounts to only 0.28\$/10^6 Btu (0.000950\$/kWh) "fuel" cost. Of course, these figures vary from system to system. For the 15 largest geothermal district heating systems, power requirements for well pumping vary from 0 to 5.6 kW/10^6 Btu (0 to 0.019 kW/kWh) (Rafferty 1990).

Assuming an average electrical generation/distribution efficiency of 30%, this results in a source energy requirement of 63,700 Btu (5.6 kW $\cdot$ 3,413 Btu/kWh $\div$ .30) for each 1,000,000 Btu supplied to the user. Stating this another way, each Btu (kWh) consumed at the power plant (to supply electricity to the well pump) results in approximately 15.7 Btu (15.7 kWh) available at the geothermal wellhead.

For a typical customer operating a fossil-fuel-fired heating system at an overall efficiency of 65%, connecting to a geothermal district heating system would reduce source fossil fuel energy consumption by more than 94%. The implication of this reduction on greenhouse gas emissions is obvious.

ENVIRONMENTAL CONSIDERATIONS IN GDH DESIGN

The major environmental issues related to geothermal district heating development revolve around disposal of the fluid once it has passed through the system. The nature of the potential problems is related to the type of disposal method used. There are two general disposal options in GDH systems: surface and injection.

Surface disposal is the least expensive option and, as a result, constitutes the approach taken historically for most geothermal developments. In this design, the geothermal fluid is discharged to a river, lake, irrigation ditch, sewer system, or other surface feature. Potential environmental issues relate to the temperature and fluid chemistry of the effluent stream as these characteristics compare to those of the receiving body. Beyond this, the potential for depletion of the geothermal fluid aquifer is a major issue as well.

Discharge to rivers, lakes, and irrigation bodies is especially sensitive to effluent chemistry. In addition to temperature, typical chemical constituents that have influenced past projects include boron, hydrogen sulfide, fluoride, total dissolved solids (TDS), and radioactive species.

Boron (B) is sometimes present in geothermal fluids in the range of less than 1 to 6 ppm. Elevated boron content can be damaging or lethal to certain plant and crop species. As a result, downstream (after discharge to the receiving body) concentrations of boron must be maintained below the threshold level of the most sensitive plant species in the area.

Hydrogen sulfide (H_2S) is the dissolved gas that imparts the "rotten egg" smell to many geothermal resources. Most direct-use fluids contain less than 5 ppm of H_2S. Its presence at this level is more an aesthetic issue than a serious environmental one. However, if permitted to accumulate to sufficient concentrations, H_2S can become a health hazard, although this has not been a problem in any direct-use projects in the U.S. As a gas, H_2S can be eliminated or greatly reduced by exposing the fluid to the air.

Fluoride, the chemical used in toothpaste and water supplies to reduce tooth decay, is also found in many geothermal resources. Typical concentrations in geothermal fluid are less than 1 to 14 ppm. At higher concentrations, fluoride in drinking water can cause "mottling" of tooth enamel. Current U.S. Environmental Protection Agency (EPA) drinking water standards require that fluoride be limited to 2.0 ppm. Discharge to surface bodies of water, as a consequence, requires that the downstream flow be limited to a concentration approaching this value.

Total dissolved solids is a measure of total mineral content dissolved in the fluid. Due to their high temperatures, geothermal fluids are capable of maintaining in solution a higher concentration of minerals than most cold-water sources. Typical TDS contents of direct-use geothermal fluids are 400 to 3,000 ppm. Drinking water standards call for a limit of 1,000 ppm, although this is a secondary limit and more for aesthetic (taste) value than health considerations. Except for disposal in low-flow streams and rivers of high water quality, TDS dilution generally presents no problem.

Radioactive species are present in the environment to some extent virtually everywhere. Geothermal fluids are no exception and generally no problems are encountered as a result of their presence. In areas where the geothermal fluid flows through subsurface rocks of elevated temperature, the fluid can absorb some of this energy. In only one of the currently operating geothermal projects was this an issue that warranted special attention. One project in South Dakota was required to install a chemical treatment system to remove sulfates containing radium 226. The process consisted of mixing a chemical (barium chloride) with the effluent to precipitate the sulfates that were then retained in settling ponds (Lunis 1986).

The final fluid characteristic that can affect disposal is temperature. Discharge of 100°F to 140°F (38°C to 60°C) fluid can involve both safety and environmental issues. Open channels containing fluid of this temperature present an obvious safety liability. Despite this, such discharges were common in large geothermal systems until recently. From an environmental standpoint, the thermal impact on surface bodies, particularly rivers, can be a critical factor. However, there is some mitigating influence due to weather and seasonal water flows.

Since district heating systems serve a primarily space-heating load, the flow requirements are greater in winter. This also coincides with somewhat higher flows in rivers and streams. The combined effect of higher stream flow and lower ambient temperature reduces the thermal impact upon the river. In most applications, discharge limits on the geothermal flow occur in the summer when reduced river flow and higher ambient temperature reduce the ability of the stream flow to accommodate high-temperature effluent.

The major potential problem associated with surface disposal is depletion of the geothermal aquifer. Although the geothermal heat source can be considered essentially inexhaustible, the same is not true of the medium that transports that heat to the surface. Overproduction of any aquifer—geothermal or normal temperature groundwater—can lead to declining water levels and the attendant problems of increased pumping costs, fluid chemistry changes, etc.

Geothermal aquifers are generally characterized by a meteoric (rainwater) source of recharge. The cold water enters the system at the surface, flows down to an area of elevated temperature, becomes heated, and rises toward the surface (Figure 2). If the total flow exiting the system (hot springs and well discharge) exceeds the inflow, decline of the aquifer can result. Many geothermal aquifers can and do support substantial development

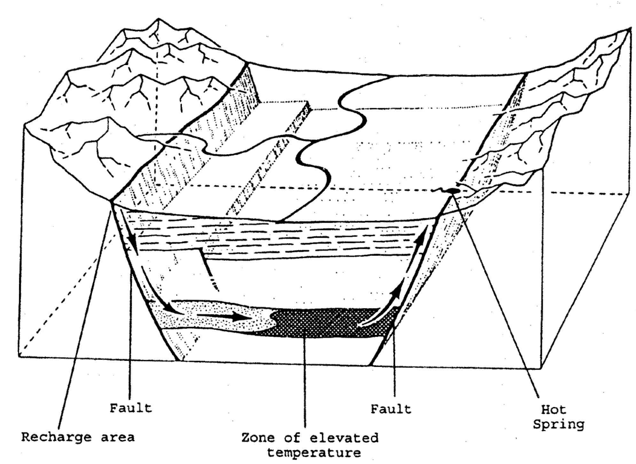

Figure 2 *Typical fault-controlled hydrothermal system (Culver and Wright 1991).*

without the use of injection. The ability to accomplish this is dependent upon the magnitude of development in comparison to the recharge of the geothermal aquifer. For every aquifer, there exists a threshold beyond which further development (pumping) will result in water level decline in the aquifer.

In the two most highly developed areas of the U.S. (Klamath Falls, Oregon, and Boise, Idaho), early development proceeded with surface disposal. After many years of operation and growth, adverse impacts were observed in the geothermal aquifer. Figure 3 presents historic geothermal aquifer levels. In this case in Klamath Falls, Oregon, a local ordinance was passed that required all major users to move toward injection over a period of years. As indicated, this strategy has been successful. Aquifer water levels have recovered in response to the increased injection. Increased use of injection in Boise, Idaho, is just beginning and is predicted to have a similar impact.

Although injection offers the potential to reduce or eliminate aquifer water level problems and surface disposal issues, it is of no use (or possibly even damaging) if implemented improperly. To be effective, injection must be into the same aquifer from which the fluid is withdrawn. Beyond this, the injection well must be sited in such a way that the injected fluid does not "short circuit" back to the production well. In homogenous aquifers, this is a relatively straightforward process. Flow through the subsurface is more predictable and well siting less complicated. In many western U.S. geothermal settings, however, the water flow occurs in fractures in the rocks. Fracture-controlled flow is much less predictable and the siting of the injection well requires careful testing and analysis. The added testing and construction costs associated with injection do increase project costs over those incurred for simple surface disposal. The compensating benefit, however, is assurance that the aquifer will support the operation of the system over the long term. Many state agencies and local jurisdictions are developing regulations that promote injection as the preferred type of disposal for large geothermal systems.

Experience with injection on large geothermal systems has been good. Although the earliest injection wells have been in service only about 10 years, no failures have occurred and no systems have been compromised by thermal breakthrough to the production wells.

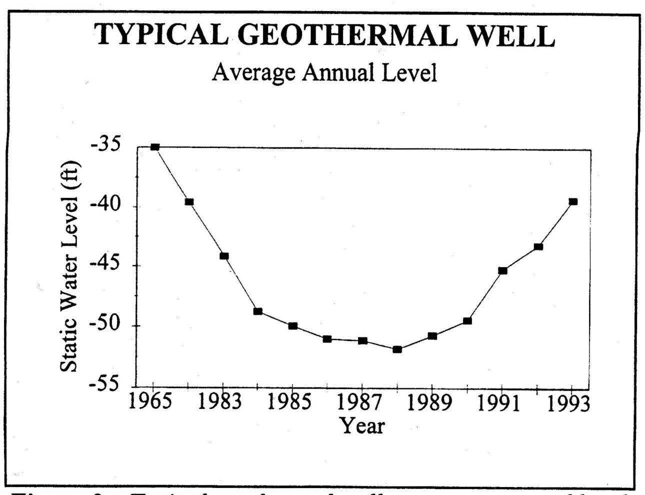

Figure 3 *Typical geothermal well—average annual level (Hart 1995).*

Some systems that have attempted injection have been unsuccessful. For the most part, this was related to the inability of the well to accept fluids. In several cases, failure of the well to accept flow was related to the drilling method used for construction of the well (Culver 1993). Conventional "mud rotary" drilling can result in problems when used for geothermal injection wells. Since the object is to penetrate the geothermal aquifer with the injection well, drilling takes place in an environment of elevated temperature. These conditions cause the drilling fluid to "set" in the region around the well, possibly compromising the ability of the formation to accept fluid. Alternative drilling methods not involving the use of heavy drilling mud (air drilling, cable tool, etc.) can reduce damage to the injection zone.

FUTURE PROSPECTS FOR GDH

Development of new GDH systems has slowed during the late 1980s and early 1990s due to competition from low-cost natural gas. The future is bright, however. A recent evaluation (Lienau et al. 1995) of western geothermal resources has identified 257 cities, towns, and population centers in eight states collocated with geothermal resources. District heating would be a natural use of the resource in many of these locations.

At present, the most likely areas for development are in states with known geothermal resource areas and a deregulated institutional setting for district heating development. This would include the states of Oregon, Washington, and California.

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