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**GEOTHERMAL ENERGY ENVIRONMENTAL
PROBLEMS AND CONTROL METHODS**

Review of Recent Findings

By
Van Thanh Nguyen
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Richard T. Pfundstein
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June 1980

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The Mitre Corporation
Metrek Division
McLean, Virginia

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Geothermal Energy Environmental Problems and Control Methods

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ABSTRACT

This report presents the findings of a literature review on the environmental concerns and associated control methods of geothermal energy utilization. The document introduces the environmental problems associated with geothermal energy utilization; assesses the current status of control methods; references appropriate environmental documents; and identifies areas where additional environmental research is needed. The review attempts to consolidate current understanding of the environmental impact of geothermal energy development. Approximately 180 reports written by authors in industry, government and academia have been reviewed in the areas of air emissions, surface and subsurface liquid discharges, solid wastes, noise, subsidence, and induced seismicity.

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EXECUTIVE SUMMARY

This report presents the results of a literature review to identify the environmental concerns associated with geothermal energy development, the state-of-the art technology to address these concerns, and recommended future research and development (R&D) activities.

The literature review was conducted upon request by the Division of Geothermal Energy (DGE) of the Department of Energy (DOE). It covers 182 articles which were in the possession of the relevant DGE Program Manager and MITRE. Thus, it does not claim to be exhaustive.

Results of the literature review are summarized below.

Geothermal energy development has both surface and subsurface environmental effects.

SURFACE ENVIRONMENTAL CONCERNS include air pollution, discharge of wastewater, discharge of solid wastes, and noise. Attention has focused on development of control methods for hydrogen sulfide (H₂S), which is considered the most serious air pollution source from geothermal activities. Several control processes are judged promising: the EIC process, the Stretford process and the iron catalyst process. These processes are described in the report. Further R&D efforts are recommended for the EIC process, Dow oxygenation process, Stretford process, H₂O₂ process and Deuterium process.

Wastewater discharges may cause chemical and thermal pollution. The literature reviewed suggests that additional research is needed on the chemistry of geothermal waste fluids. Current technology can

remove almost any chemical constituent from wastewater and may be applicable to geothermal wastewater with only minor modifications. More attention should be given to methods for removal of mercury, other heavy metals and radioactive contaminants from geothermal fluids.

Thermal pollution has received less attention than chemical pollution in the literature reviewed, probably because methods already exist to cool the geothermal wastewater prior to surface disposal.

Water availability may also be adversely affected. Geothermal activities also have positive effects on water resources, however. In some cases, treated geothermal wastewater may be used for drinking or irrigation purposes.

Solid wastes from geothermal operations consist mainly of residual sludges from air and water treatment, scale, cuttings and drilling muds. Adequate control methods are available, although their costs may be prohibitive if stringent limits are placed on solid waste discharge. Little is known about the toxicity of these wastes and research is needed to characterize them.

Noise is considered to be the least important environmental concern in geothermal activities. However, it may be an obstacle to widespread geothermal development and further research on noise control techniques is recommended.

SUBSURFACE ENVIRONMENTAL CONCERNS relate to fluid reinjection, subsidence, seismicity and hydrological alterations.

Fluid reinjection is used as a method to dispose of steam condensate and other geothermal fluids. It presents the advantages of possible increased geothermal reservoir life, reduced wastewater cooling requirements, reduced operating noise and reduced subsidence. However, it may cause groundwater contamination and induced seismicity. No control method is known to prevent groundwater contamination. Little is known also on prevention of induced seismicity. Thus research is needed in both areas.

Geothermal subsidence is caused by compaction of the rock and sediment underlying an area following removal of the geothermal fluid. Geopressured reservoirs are more susceptible to subsidence than hydrothermal reservoirs. Subsidence monitoring methods for geothermal areas are limited. Particularly, high temperature monitoring instrumentation needs to be developed, as well as guidelines for field data acquisition and analysis.

Areas which are geothermally active are also susceptible to seismicity. Research is recommended to characterize this susceptibility, to model geothermal reservoir, and to develop control and mitigation process.

Hydrological alterations were not addressed by the reviewed literature as a possible environmental concern, probably because it has come to attention only recently. Research should be conducted to determine the probability and the nature of these alterations.

1.0 INTRODUCTION

1.1 Background

Geothermal energy resources have been used commercially for about 80 years. However, environmental problems arising from geothermal resource utilization have become concerns only in the last five years, particularly in the U.S. and Japan. During these five years, the literature addressing geothermal environmental problems and their control technologies has grown considerably.

In an attempt to bring the current understanding of environmental aspects of geothermal energy into perspective, the U.S. Department of Energy (DOE), Division of Geothermal Energy (DGE), requested MITRE to review recent literature on this subject.

1.2 Scope

This review addresses only environmental concerns and control technologies. Related aspects, such as environmental plans and regulations, although mentioned occasionally, are outside the scope of this report.

At the request of DGE, the literature review was limited to 182 reports and papers that were in the possession of DGE and MITRE. The results reported here represent the content of the literature reviewed, and therefore, are not exhaustive.

1.3 Report Organization

The report is organized by areas of concern. Section 2.0 relates to surface concerns. Section 3.0 contains the review of the

literature on subsurface concerns. In each section, the results are reported by types of concerns, which include: air pollution, liquid and solid discharges, and noise for Section 2.0; and fluid reinjection, subsidence, and induced seismicity for Section 3.0.

2.0 SURFACE CONCERNS AND CONTROL METHODS

2.1 Surface Environmental Concerns

The surface environmental concerns associated with geothermal development center on air pollution, discharge of solid and liquid wastes, and noise. Major concerns are summarized below:

- Air pollution. Hydrogen sulfide emissions (H_2S), because of their prevalence and offensive odor, have received the most attention among air pollutants from geothermal activities. H_2S emissions occur during well drilling, venting and cleanout, powerplant operation, and steam stacking. Other emissions of concern include: ammonia, hydrocarbons, mercury, boron and radon.
- Discharge of wastewater. The main source of wastewater comes from geothermal operations at liquid-dominated fields. The discharge includes the geothermal spent brine, and to a lesser extent, condensate and cooling water. Wastewater discharge poses the risk of contaminating drinking groundwater and surface water used for drinking, irrigation, and recreation.
- Discharge of solid wastes. Concerns about solid wastes result from their largely unknown character and the possibility that they may be classified as hazardous wastes under the Resource Conservation and Recovery Act. Principal sources of solid wastes from geothermal systems include drilling muds, and sludges from wastewater and air emission treatment facilities.
- Noise. Noise from geothermal operations, particularly from well drilling and steam venting, may be excessive. Other noise sources include well cleanout and flow testing and generating unit operations.

In the following sections, results of the literature review are reported for each of the above areas of concern. Some gaps also have been identified in the ongoing efforts to develop control technologies, and recommendations have been developed for filling these gaps.

2.2 Control Methods

2.2.1 Air Pollution

Control of hydrogen sulfide emissions occupies the center of attention in the literature reviewed.

2.2.1.1 Effects and Monitoring. The effects of acute doses of H_2S are known, but long term effects on human health of subacute exposure is not well known. According to Axtmann⁽¹⁾ no study had been done relating H_2S emissions to ambient air quality and human health prior to 1976. This subject is not addressed in the reviewed literature published in 1976 either.

The effects of H_2S on vegetation, now a minor concern, would also need to be given more attention as geothermal development increases. One of the concerns about these effects relates to the photosynthetic process. Short term experiments have been conducted on the effects of H_2S on photosynthesis.^(2,3) These experiments seem to indicate that at high concentration, H_2S has an important depression effect on photosynthesis.⁽²⁾ But at low concentrations, photosynthesis is stimulated and stomatal resistance is relaxed,⁽³⁾ Long-term effects of vegetation exposure to H_2S is unknown, however.

Several ongoing programs aim at identification, measurement and analysis of air pollutants from geothermal development. An Air Quality Program is active in the Imperial Valley Environmental Project.⁽⁴⁾ Six fixed location stations have been installed to

monitor ambient air quality and, a mobile field laboratory is equipped to measure releases at specific sites.⁽⁵⁾ Atmospheric concentrations of H_2S , SO_2 , O_3 , NO , NO_x , CO_2 , Hg , R_n and particulates are measured. Also, as a part of the air pollution abatement efforts, the Geothermal Overview Project was established by the Department of Energy and Lawrence Livermore Laboratory and operates at several known geothermal resource areas (KGRA).⁽⁶⁾

The California Air Resources Board has recommended the use of the Cadmium-Stractan Colorimetric Method to determine H_2S concentrations in air.⁽⁷⁾ This method is used extensively in the geothermal fields at the Geysers, California. Another method, silver ion selective electrode titration, has also been found to be well suited for field determination of H_2S concentrations.⁽⁷⁾

Numerical atmospheric transport models also exist for assessment of air quality impact of geothermal development. Three such models are used by the Lawrence Livermore Laboratory: the ATMAS (Atmospheric Multiple Area Source) and the MSDM (Multiple Source Dispersion Model) and the ADPIC (Atmospheric Dispersion Particle-In-Cell)⁽⁸⁾

2.2.1.2 Removal of H_2S . Commercial processes for removing H_2S from steam are available. However, these processes have been found unsuitable for the steam conditions normally encountered in geothermal systems. The Claus process involves a two-stage reaction:

Stage 1 - H_2S is burned in air:

Stage 2 - SO_2 joins gas streams and reacts with H_2S :

The process is highly exothermic. Its drawback is the difficulty in sustaining the first stage of reaction if the CO_2 concentration in the feedstream is greater than 50%. Reduction of this CO_2 concentration, though feasible, would require a very expensive front-end process. The first experimental Claus plant was built in Iceland's Naramfjall field in 1952; considerable operational problems have been found since.(1)

Solid sorbents were evaluated by Pacific Northwest Laboratories for removal of H_2S , but results of the evaluation recommended against their use because it is economically infeasible.(9)

A process for H_2S removal by catalytic oxidation was investigated by the Pacific Northwest Laboratory (PNL). In this process, H_2S oxidation takes place in the presence of oxygen and a catalyst. Sulfur and water are formed as a result.(10) Activated carbon served as a catalyst which can be regenerated after use, and air was the oxidant. Both activated carbon and air are inexpensive materials. It is claimed that the process is simple to operate and that no by-product or process waste must be disposed of. A bench scale apparatus has been built to test this concept.(11).

The shortcoming of the PNL process is that it applies only to superheated steam. To address saturated steam, PNL is investigating

two modified processes: the throttling process and the steam superheating process, which require additional research in the following areas:

- Development of H₂S removal process for saturated geothermal steam
- Improvement of catalyst regeneration processes
- Research on the effects of trace amounts of boron and heavy metals (mercury and arsenic) on the activity of the catalyst.

The EIC Corporation evaluated, in laboratory scale equipment and by process engineering analysis, the scrubbing of geothermal steam with a metal salt solution before this steam enters the turbine.⁽¹²⁾ H₂S is reacted with the metal salt to form metal sulfide which precipitates out of the solution. The metal sulfide is then roasted or oxygen/acid leached to regenerate the metal salt. Sulfur is rejected as elemental sulfur or as sulfate. EIC used Cupric ion Cu²⁺ as the H₂S precipitant, and obtained up to 95% removal of H₂S from simulated geothermal steam. The estimated capital costs of the proposed process for a 50 MW plant are \$4.4 million (in 1976 dollars) and annual operation and maintenance costs were estimated at \$1 million.

A similar process to the EIC process was proposed by G.E. Coury and M. Vorum.⁽¹³⁾ In this process, H₂S would be absorbed in an aqueous solution of copper salts by precipitating copper sulfides. The process also absorbs ammonia present in geothermal steam. It uses part of the cooling tower blowdown stream for make up water.

According to the authors, the concept has been applied to remove H_2S from the carbon dioxide feedstream to a dry ice plant, and its economics appear comparable to the costs of flue gas desulfurization for fossil-fired boilers.

The Holmes Stretford process has been shown to remove as much as 99% of H_2S from geothermal gas streams.⁽¹⁴⁾ The process converts H_2S into elemental sulfur in simple sequential steps at moderate temperatures. The process uses sodium vanate as the chemical oxidant and requires no special construction materials. The Holmes Stretford process is the only process available capable of purifying the gas stream when the CO_2/H_2S ratio is high. The Holmes Stretford process is commercially available and has been applied in coal gasification plants.

The Citrex process offers another H_2S removal alternative, apparently at lower investment and operating costs than the Holmes Stretford process.⁽¹⁴⁾ Here, H_2S is converted into sulfur using a solution buffered with citrate.

Other H_2S removal processes are being developed for non-geothermal gas (e.g. coal gasification, sour gas from oil refinery), but may be applicable to geothermal steam:⁽¹⁴⁾

- Consol Dolomite process
- Bureau of Mines hot iron-oxide process
- Air Products' solid absorbent
- Battelle's molten salt process.

None of these are commercially proven or available, however. H₂S emission control at geothermal well sites was attempted as early as 1974 at The Geysers. Ironite sponge was suggested for scavenging H₂S to form Fe₂S, which is stable and safe. Laboratory results show that one pound of iron oxide will remove .74 pounds of H₂S. The reaction is instantaneous, complete and irreversible.

An estimated 12 to 15 percent of the annual average emissions of H₂S at The Geysers comes from the steam field rather than power-plants.⁽¹⁶⁾ These emissions may be reduced by 80% by applying a vent control system to each wellhead. An iron oxide absorber may further reduce emissions by more than 90%. However, this has not been demonstrated.

Also at The Geysers, the combined use of a Stretford system to remove H₂S from gas stream emerging from a surface condenser and a hydrogen peroxide (H₂O₂) treatment system for H₂S removal from condensate liquid stream was suggested for new geothermal plants equipped with surface condensers.⁽¹⁶⁾ This method is expected to reduce H₂S emissions by 99%. However, it is not applicable to old geothermal plants, which have direct contact condensers. In addition to H₂O₂, ozone and sulfur dioxide may be suitable as oxidizing agents. H₂O₂ is in short supply and cannot be conveniently produced on site. Ozone can be generated on site and has been used in wastewater treatment. However, little is known on its oxidizing utility

on H_2S . Little is known also about the performance of SO_2 , which may be even less convenient than H_2O_2 .

Oxidation of H_2S by H_2O_2 is advocated by two commercial producers of H_2O_2 , E.I. DuPont de Nemours and FMC Corporation.(17) H_2O_2 is currently used for sulfur control in both industrial and municipal wastewater systems. The products of the oxidation are sulfur and water and the process is claimed to be competitive with other systems. Study on the use of SO_2 as a reactant for H_2S control has been proposed to DOE.

For old plants equipped with direct contact condensers at The Geysers, there is no satisfactory H_2S control process. The iron catalyst system used by the Pacific Gas and Electric Company creates severe corrosion problems in condensers.(16)

The Dow Chemical Company proved feasible, in pilot plant scale, the oxidation of H_2S by oxygen.(18) Injection of oxygen is done at the wellhead. There are two designs for the injection system, which differ in the manner of achieving complete mixing of gas with water. The estimated capital costs per well for the in-line mixer system is \$209,000 and for the packed tower system is \$362,000 (in 1977 dollars). The reaction time is less than one minute, and the reaction products are free sulfur, sulfite, and sulfate.

2.2.1.3 Summary and Costs. Of the H_2S control technologies presented, the most promising control processes, on the basis of current information, are:(19)

- The EIC process, for upstream cleaning of liquid dominated sources. This process is in pilot development stage.
- The Stretford process for condenser vent emissions, also at pilot stage.
- The iron catalyst process, followed by the H_2O_2 process for cooling tower emissions.

A summary of these processes is shown together with their costs in Figure 2-1.

The Midwest Research Institute recommends that the following priority be given for further development:

1. EIC process
2. Dow oxygenation process
3. Stretford process
4. H_2O_2 process
5. Deuterium process

Next to hydrogen sulfide, mercury emissions from geothermal powerplants have received the most attention. Efforts to date have concentrated on the measurement and characterization of these emissions. Results of a study conducted at The Geysers geothermal field in California and at Cerro Prieto in Baja California, Mexico, show that on a per megawatt basis, atmospheric releases of mercury from geothermal powerplants are comparable to those from coal-fired powerplants.(20) Mercury emissions from 25 Mwe to 75 Mwe geothermal powerplants are below the limits set by EPA standards.

Other noncondensable gases emitted by geothermal plants include:

FIGURE 2-1
APPLICATION POINT IN A GEOTHERMAL POWER PLANT AND
COSTS IN 1978 DOLLARS OF THREE PROMISING H₂S
REMOVAL PROCESSES: STRETTFORD PROCESS (LEFT), IRON
CATALYST PROCESS (CENTER), AND EIC PROCESS (RIGHT)

CO₂: most abundant in terms of emissions from geothermal plants,⁽¹⁾ these are still small compared to atmospheric concentrations of CO₂.⁽²¹⁾

Radioactives: measurements of radon and daughter products at geothermal sites, and characterization of their effects must be conducted.

Sulfates and Sulfur: measurements are also needed for these substances.

Particulate matter: current technology is adequate for controlling particulate emissions from geothermal plants.

Other contaminants: these need to be identified, measured, and their effects studied.

Water vapor emissions from geothermal sites have also been of concern. Their climatic effects are being studied. However, their biological effects are not perceived as imminently harmful.⁽²¹⁾

2.2.2 Surface Discharge of Liquids and Solids

2.2.2.1 Liquid Wastes. Liquid wastes associated with geothermal energy development and utilization come from spent brines, condensate/cooling water, site runoff, and sanitary wastes. Spent brines and condensate/cooling water present the greatest environmental concern because of their chemical composition and thermal characteristics. Options available for disposal of these fluids are surface disposal, discussed in this section, and subsurface disposal (reinjection), discussed in a later section. Reinjection is the desired disposal approach except where water supplies are limited, geothermal fluid is abnormally clean, or the volume of wastewater is low. However, even if reinjection is used, some fluid constituents may still need to be removed for regulatory and/or technical reasons.

The studies reviewed that addressed problems of surface disposal of geothermal wastewaters are both site-specific(5,22,23) and generic.(34-40) The possible environmental impacts of geothermal liquid wastes are chemical and thermal pollution. The chemical pollutants include arsenic, boron, fluoride, ammonia, chlorides and mercury.

Of the reports reviewed, only one(30) addresses the damage to streams caused by sediment and silt deposits from construction-related erosion. In general, this problem can be controlled by careful site development techniques already practiced by nongeothermal industries.

Chemical Pollution

Fluid chemistry has been the subject of many reports and published articles. The emphasis has basically been on the geothermal fluids as they leave the wells, however. Little work has been done on the waste fluid chemistry. In assessing the extent of chemical pollution caused by liquid discharges, Pimentel(30) suggests that baseline monitoring is needed for boron, ammonia, mercury and arsenic, particularly in The Geysers area. Chemical and physical modeling simulation techniques need also be developed for predicting the change in well-head fluid characteristics over the life of the well and fluid behavior as the fluid flows through the energy conversion systems.

Treatment technologies exist to remove almost any constituent from wastewater. With some modification, experts believe that existing technologies can be transferred to the treatment of geothermal wastewaters. Low cost treatment/removal processes such as chemical precipitation and flocculation, sedimentation, and filtration have been identified.(40-42) Hartley's report(40) describes liquid waste treatment as well as other control-related technologies, their costs, and applicable regulations.

Experiments reported by Rothbaum and Anderton(42) have shown that essentially all the silica and arsenic contained in geothermal wastewater can be removed via chemical precipitation using slaked lime and flocculation. In addition the waste product, calcium silicate, is suitable for making wallboard and other insulants. Although this treatment reduces boron content, its removal efficiency is low.

More sophisticated and more expensive technologies for removing pollutants from geothermal wastewater including absorption, adsorption, forced evaporation, ion exchange, reverse osmosis, and electrodialysis have also been discussed.(40)

Choi and Chen(43) performed some experimental studies on the removal of boron from geothermal fluid by absorption. They tested various absorbents/adsorbents including activated carbon, activated bauxite, and activated alumina. They found that activated carbon has greater boron removal efficiency than other tested absorbents at initial concentrations of boron below 30 mg/l. The experiments have

also shown that the presence of calcium, magnesium, silica, or sulfate in the fluid reduces the boron removal efficiency.

Chen et al.⁽⁴⁴⁾ also tested the removal rates of trace metals, arsenic, boron, and fluoride by absorption. Final results are shown in the reference for arsenic, boron, and fluoride.

Electrolytic methods of arsenic removal have been tested using iron and aluminum electrodes for precipitation, and iron and platinum cathodes for reduction. The most promising arsenic removal technique combines both precipitation and reduction. However, individual improvements are needed before a combined technique can be developed.*

The removal of mercury and other heavy metals from geothermal wastewater has received relatively little attention. Sabadell and Axtmann⁽⁴⁵⁾ feel that these contaminants may pose problems for geothermal commercialization and recommend monitoring for mercury, other heavy metals, and radioactive contaminants.

Thermal Pollution

Thermal pollution is caused by liquid waste discharges from geothermal systems. Methods considered for cooling the brine before surface disposal include cooling towers, pipeline cooling, evaporation ponds or canals, and forced dispersion at the disposal point. Compared to chemical pollution, thermal pollution has received less attention.

Translated from an unreferenced Japanese paper by DOE, DOE TR 150, undated.

Most of the references consider the thermal pollution problem to be small. For example, Willis (31) concludes that the thermal impact on the Waikato River from the New Zealand Electricity Department's Geothermal Facility at Wairakei would be negligible if cooling towers were used for closed cycle condenser cooling and waste bore-water rejected at well heads is reinjected.

A report by the University of Texas⁽⁴⁶⁾ is particularly useful for its discussion of the thermodynamics of disposal systems and its guidelines for calculating heat losses in disposal systems.

Impacts on Water Resources

Geothermal energy development may impact nearby water resources in other ways than through chemical or thermal pollution. First, the removal of huge quantities of fluid from geothermal resources may lower the nearby water table or reduce supplies contained in aquifers. In addition, large amounts of nongeothermal water may be consumed for control equipment (e.g., wet scrubbers), cooling, or injection.⁽⁴⁷⁻⁵⁸⁾ The impact of geothermal activities on water availability may limit the expansion of geothermal energy use.

Geothermal development does not have only negative impacts on water resources, however. Treated geothermal wastewater may be used for drinking or irrigation in areas that have limited water supplies. This may be done if injection is not needed to control subsidence or if nongeothermal water unsuitable for drinking or irrigation can be substituted for injection liquid. Stanley and Schmitt⁽⁵¹⁾ discuss

the effects of using geothermal water for irrigation in the Raft River area. Raber et al.(55) and Wiegand(58) discuss the possibility of substituting Salton Sea water for injection and using treated geothermal water for irrigation in the Imperial Valley, California.

2.2.2.2 Solid Wastes. Solid wastes from geothermal operations consist mainly of the residual sludges from air and water treatment, scale from cleaning the fluid distribution and conversion networks, and the cuttings and drilling muds from production and injection well drilling. Residual sludges contain hydrogen sulfide, arsenic, boron, mercury, as well as treatment chemicals added to reduce equipment deterioration. Drilling wastes contain rock cuttings and a variety of chemical materials in drilling muds.

The characteristics, particularly the toxicity, of the solid wastes are still largely unknown. If the wastes are determined to be hazardous, they will be subject to restrictive regulations. Adequate control methods are available.(34) However, the costs may be prohibitive if strict environmental standards are imposed. A significant amount of research, particularly in the area of characterization, appears to be needed in order to determine the toxicity of solid wastes from geothermal activities.

2.2.2.3 Summary and Treatment Costs. Treatment and disposal methods for geothermal liquid and solid wastes are generally available or can be transferred from nongeothermal industries. Areas for

future research include chemical and physical modeling and in-line monitoring for liquid wastes, and characterization studies for solid wastes. In addition, attention could be given to the impact of geothermal development on water resources.

Discussion of costs for controls of liquid and solid wastes is limited in the reviewed literature. Hartley discusses costs for each of the control approaches and provides a very good reference source.⁽⁴⁰⁾ In addition, Wells et al.⁽³⁹⁾ present cost estimates for treatment and injection of geothermal brine and solid waste disposal for the Salton Sea, California, and Baca, New Mexico. Wells et al.⁽³⁹⁾ found sludge disposal costs to be the most significant part of the annual operating costs of treatment systems. They conclude that the commercial viability of geothermal resources may be reduced by the imposition of stringent standards because of the cost of compliance. Estimated cost for liquid treatment may range from 2.4 mills/kwh to 26.0 mills/kwh depending on applicable standards and site characteristics.

2.2.3 Noise Pollution

2.2.3.1 Effects and Perception. Controlling noise from geothermal resource development is important to ensure both worker health and safety and community acceptance. The noise produced by unsilenced steam escaping from an 8-inch diameter pipe temporarily damages hearing up to about 150 feet away, and is annoying up to several miles away.⁽⁵⁹⁾ The intensity of the noise level from an

unmuffled well start-up, heard from 50 feet distance, is shown in Figure 2-2 in comparison to other noises.(60)*

Of the many factors which can affect the measured noise volume, the primary factor is distance. Wave divergence reduces the sound pressure level by 6 dB every time the distance from the source doubles.(60) Other factors include:(60,61)

- The shape of the frequency spectrum - some sounds are easier to attenuate than others of the same volume.
- Air absorption - the effect depends on temperature, atmospheric pressure, humidity, windspeed and direction, and the sound's frequency.
- Sound barriers - buildings, terrain, and vegetation can absorb sound.
- Direction of steam flow - there is less noise in the direction opposite the flow of steam.
- Temperature inversions - nighttime temperature inversions tend to curve a soundwave back toward the surface; therefore a sound emitted beneath the inversion may be propagated a greater distance from the source. A sound emitted above an inversion will disperse upward and minimize the sound level at the surface.

The residents' perception of noise volume is an important consideration. Low ambient noise levels in some geothermal regions make the noises appear louder by comparison. Many residents chose to live in a sparsely populated region because it is quiet, and therefore, they can be expected to be extremely sensitive to noise intrusion.

*Sound pressure levels (SPL) are normally expressed in decibels, which are a logarithmic ratio of the measured sound pressure to a reference level, 20MPa. Most meters read SPL in A, B, or C scales. The A scale (dBA) corresponds most closely to the response of the human ear in most situations; therefore, it is the scale used here.

*Typical A-weighted sound levels taken with a sound level meter and expressed as decibels on the scale.

† Figure adapted from Reference 61.

FIGURE 2-2
TYPICAL A-WEIGHTED SOUND LEVELS AND HUMAN RESPONSES

Also, negative attitudes towards other impacts of geothermal, e.g., H_2S and aesthetics, may increase sensitivity to the noise.(60)

Most geothermal noise problems result from truck traffic, well drilling, and steam venting. Table 2-1 lists the noise sources associated with geothermal development.(60)

2.2.3.2 Control Methods. Discussions of geothermal noise control technology in the reviewed literature center on the noise from steam vented during well startup, either initially or after a shutdown. The effectiveness of some controls are shown in Table 2-2.

Conventional mufflers are not used because debris vented with the air and steam would damage them. The new methods discussed in the reviewed literature(59-63) are:

- An open-ended steel pipe discharging the steam at least 3 feet under the surface of a river. The impact of this method on water quality is not clear.
- A perforated steel pipe at least 3 feet under the surface of a pond to distribute the steam flow horizontally.
- A horizontal straight-through type silencer. A six-foot diameter reinforced concrete pipe expands the steam flow and thereby decreases the noise. Piling earth on the silencer helps dampen pipe vibration. This can be used where the site characteristics prevent using a pond silencer. This method is not usable where working space is limited.
- Vertical twin cyclones. The vertical silencer depends on a small carryover of water with the steam discharge to muffle the high-pitched sounds. The two major design constraints are 1) the pipe and cyclone materials must withstand thermal pressure and silicone erosion, and 2) the amount of water must be sufficient to act as a silencer.

Table 2-1

NOISE SOURCES ASSOCIATED WITH GEOTHERMAL
DEVELOPMENT IN THE GEYSERS-CALISTOGA
KNOWN GEOTHERMAL RESOURCE AREA*

Site preparation/road construction

Geothermal well drilling

Geothermal well clean-out and testing

Geothermal steam venting

Construction of facilities

Generating unit operation

Turbine/generator building

Steam-vent gas ejector

Cooling tower

Vehicular traffic

*Table adapted from Reference 60

Table 2-2

EFFECTIVENESS OF WELL START-UP NOISE CONTROL METHODS*

<u>CONTROL METHOD</u>	<u>NOISE LEVELS (dBA)</u>
Unmuffled	125 at 50 feet
Blooiie line expandertube	120 at 50 feet
Large metal test muffler	100 at 50 feet
Cyclone muffler	90 at 50 feet
Rock muffler	72 at 50 feet

*Values from References 60 and 61.

- Rock mufflers. Rocks are used as mufflers either in a large pit, or mounted on a flat-bed semi-trailer which can be driven to the well where it is needed.

Other methods for controlling geothermal noises include:

- Avoid venting to well. During emergency shutdown or short-term outage of a generating unit, there are alternatives to venting the steam, or shutting the well and then starting it up again. One alternative is to use a V-ball throttling valve, and then vent the reduced steam flow to a rock muffler. Another alternative is to interconnect steam supply lines and reduce production rate on all wells proportionately.
- Separate the noise sources from people who are likely to be annoyed, by use of zoning and land use planning mechanisms.

2.2.3.3 Summary. Only limited information is available on noise control for geothermal sites, perhaps due to the fact that noise is usually considered to be the least of the environmental problems associated with geothermal development. Steam venting is the loudest source of noise. It is also the most difficult to control because of the need for mufflers which can withstand the force from the debris and steam. Diesel engines and compressors are the second most annoying noise source, but there is little mention in the literature reviewed of noise controls for these sources. Because the existing methods of noise control are not sufficiently sophisticated, it is difficult to predict noise impact on a given location.(61)

Additional work is suggested in the following order of importance:

- Develop a muffling system which can attenuate by at least 20-30 dBA the noise from production testing of new wells and cleanout of previously shut-in wells.⁽⁶⁰⁾
- Develop inexpensive methods to control drilling noise, in particular the low-frequency components of noise from large diesel engines and compressors.⁽⁶⁰⁾
- Perform field studies of the accuracy of various predictions concerning noise pressure levels.
- Identify factors which annoy some residents even when the geothermal noise is barely audible (40-55 dBA).
- Consider relaxed noise standards for the geothermal industry in areas where no residential or other sensitive receptors would be affected.

2.3 Conclusion

The development of geothermal resources may be impeded unless further research and development is conducted to address air pollution, solid and liquid waste and noise concerns.

In reviewing the surface environmental concerns associated with geothermal development, the Environmental Controls Panel of the Interagency Geothermal Coordinating Council (IGCC) recommended the research toward their resolution⁽⁶⁴⁾ in the following order of urgency:

- Development and demonstration of control methods for hydrogen sulfide emissions to the atmosphere from wells and electricity generating plants.
- Development of control methods for atmospheric emissions of non-H₂S substances
- Characterization of solid and liquid wastes from geothermal energy production, and evaluation of available disposal methods for solid residuals, whether hazardous or nonhazardous in nature.

- Development of noise control methods.

The IGCC recommendations summarized above generally concur with the literature reviewed in this section.

3.0 SUBSURFACE CONCERNS AND CONTROL METHODS

3.1 Subsurface Concerns

Subsurface concerns related to geothermal development are fluid reinjection, subsidence, seismicity, and hydrological alterations:

- Reinjection of spent geothermal fluid has been the favored disposal method, but is not without disadvantages.
- Subsidence may result from the withdrawal of large amounts of fluids. Subsidence may be reduced or limited by injecting geothermal fluid or other fluids. However, high pressure injection of large volumes of geothermal fluid can lubricate geologic faults, and consequently might induce microseismic events.
- Geothermal development may cause hydrological alterations. It may affect surface features such as hot springs, fumaroles, mud pots, and geysers, and may deplete reservoirs used for drinking water or agricultural purposes.

Current control methods and research efforts to deal with the above concerns are discussed in the following sections, and recommended areas for further research and development are identified.

3.2 Experience and Control Methods

3.2.1 Reinjection

3.2.1.1 Problems and Solutions. Reinjection of spent geothermal fluid (brine) to a subsurface reservoir represents the simplest and most economical disposal method for steam condensate and other geothermal fluids, according to Chastun.⁽⁶⁵⁾ Additional advantages of reinjection include the possibility for increased geothermal reservoir life, reduced wastewater cooling requirements, reduced operating noise, and reduced subsidence.⁽⁶⁶⁾ However, according to

Bowen(67) and others, (68-71) wastewater disposal and subsidence control are the major reasons for selecting injection.

Geothermal reservoir life may increase as a result of reinjection because it replenishes the fluids in the reservoir. Reinjection also implies that brine cooling prior to disposal is not required, as it may be in surface disposal. Kubota and Aosaki(72) found that 8.7 MW to 10 MW of station output was recovered at the Otake Geothermal Field in Japan from 1972 to 1975 as a result of reinjection.

The disadvantages of reinjecting fluid include possible ground water contamination and induced seismicity. These concerns are particularly critical because of the magnitudes of possible damages. There are disagreements about these disadvantages, however. Cameli(73) reports that a reinjection experiment in the Viterbo Region of Central Italy has shown that seismicity is not affected by reinjection. Similarly, Kubota and Aosaki(72) have found no problems with groundwater contamination or earthquakes resulting from the reinjection of geothermal hot water at the Otake Geothermal Field in Japan.

The reported experience in some sites in Italy and Japan seems to validate the reinjection approach. However, until there is sufficient evidence that such experience applies to geothermal sites in the United States, precautions must be taken in this country to assure that there will be little if any future adverse impact at any

geothermal site. What these precautions are is not yet fully understood. Intuition suggests that induced seismicity can probably be reduced if low pressure injection is used in coordination with careful site selection. Additional research in this area is needed.

No control methods exist to prevent groundwater contamination from brine reinjection other than to monitor the migration of the injected fluid and terminate or reduce injection if contamination or the threat of contamination is detected. In most cases, monitoring wells are drilled surrounding the injection well or surrounding the nearby clean water aquifers. These wells monitor pressure transients,⁽⁷⁴⁾ temperatures or fluid composition. In some cases, the detection of the injected fluid is enhanced by the addition of a tracer.⁽⁷⁵⁾ Vetter suggests the use of radioactive tritium as a tracer.^(71,76)

The placement and number of wells required for monitoring will normally be defined by subsurface disposal regulations.^(77,78) If these regulations require several monitoring wells for each injection well, the monitoring costs may be prohibitive.

Numerous technological problems must be solved if injection is to be a viable disposal option. These problems relate to fluid characteristics (volume, pressure and temperature), cost, scale deposition, and production/injection well spacing.

The volume per unit time of fluid injected should be sufficient to control subsidence adequately. Yet, the pressure of injection

must be low enough as to not induce seismicity. In addition, the injection well should be near the production well so that injected waste heat and fluid can reduce the rate of reservoir depletion. Yet, the wells must be sufficiently separated so that cooler injected fluid does not flow directly to the production well and reduce or destroy its usefulness.(66,72,79-81)

Miller et al.(81) presents the theory of water influx that was developed by the petroleum industry. This theory may aid geothermal engineers in developing production/injection well spacing criteria to avoid reservoir cooling. Einarsson et al.(66) studied reinjection at the Ahuachapan geothermal field in El Salvador and found that the minimum spacing between injection well and production well should be 1.5 km in that field.

Additional technological concerns of reinjection are scale deposition and plugging in the well and rock formations. These topics have received considerable attention.(1,56,70,82-91) Cuellar(84) suggests that silica deposition is a problem for both surface and subsurface brine disposals, but has determined that no deposition occurs above 150°C. Axtmann(83) feels that significant gaps exist in the knowledge of chemistry related to silica deposition.

Many of the reviewed reports focus on cost-effective, pre-injection treatments for geothermal brine. Tewhey et al.(82) and Nichols and Malgier(89) suggest the use of clarifier units ahead of the reinjection pump for precipitate removal. Featherstone

et al.(86) and Van Note(92) recommend the use of a reactor-clarifier to produce a nonscaling liquid suitable for well injection. Jorda(87) discusses the use of a large diameter reinjection well to compensate for reduced fluid flow capacity resulting from corrosion and scaling over the life of the well.

Messer et al.(88) found that reinjection of the silica-rich fluid at Imperial Valley, California, resulted in injectivity loss from silica particle plugging. However, the injectivity was then restored by a hydrofluoric-hydrochloric acid treatment of the brine prior to injection. Netherton(70) tested various filters at the Salton Sea Geothermal Field and achieved the minimum clarification required prior to brine injection. An additional study by Owen et al.(90) found that direct reinjection into reservoir zones with original porosity is not feasible unless particulates of a certain diameter size are removed.

3.2.1.2 Summary and Cost Estimate. Reinjection of geothermal wastewater poses many environmental, as well as technical, problems that need to be addressed. However, reinjection represents the most acceptable disposal method for liquid wastes. In addition, reinjection can be used to control subsidence and, if done properly, can increase the thermal efficiency of the geothermal reservoir.

The main environmental problems of reinjection are the possible contamination of groundwater and induced seismicity. Groundwater may be protected by monitoring pressure transients, temperatures, tracers

or fluid composition. Seismicity has not been shown to be a significant risk, but this risk may still be reduced with careful site selection and probably with lower pressure injection.

Several of the reviewed reports present costs for treating and reinjecting wastewater.(35,40,66,78,86,93-96) Einarsson et al.(66) estimated the costs of geothermal wastewater injection to be approximately 1 mill/kwh (in 1974 dollars). Defferding(78) presents costs of salt water injection at the East Texas oil field and Quong(96) provides cost data for a pilot sized clarifier of geothermal brine. Hartley(40) reports costs for brine injection as well as detailed costs for wastewater treatment prior to surface disposal.

3.2.2 Subsidence

3.2.2.1 Causes and Concerns. Subsidence is the sinking of part of the earth's crust. Subsidence is caused by compaction of the sediment and rock underlying an area following removal of a geofluid (oil, gas, groundwater, or geothermal fluids). In geothermal energy development, two major factors that influence subsidence potential are: 1) energy conversion plant design and operation as they affect the distribution and quantity of withdrawn and injected fluids and 2) the site's geologic structure and geohydraulic characteristics. The geothermal resources in the U.S. can be broken down into five geologic regimes.(97) These are:

- Basin and range (e.g., Nevada)

- Volcanic calderas (e.g., Valles Caldera)
- Rift valley structures (e.g., Imperial Valley and Rio Grande graben)
- Highly metamorphosed regions (e.g., Geysers)
- Sedimentary basins with associated geopressured systems (e.g., Northern Gulf of Mexico Basin)

Subsidence is of particular concern at those sites where large quantities of water must be extracted to maintain production of needed thermal energy or, in the case of geopressured reservoirs, methane must be extracted. These sites are some of the low to moderate temperature liquid dominated resources and the geopressured resources. High temperature vapor-dominated sites are not as subject to subsidence, since the rock units in the reservoir must be competent in the first place.⁽⁹⁸⁾ Even though this is generally true, Crow⁽⁹⁹⁾ reports a subsidence rate of 4 cm/yr between 1973 and 1975 at The Geysers, which decreased to 2 cm/yr between 1975 and 1977. He also reports that the rates and amount of subsidence at The Geysers correlate directly with the amount and rate of pressure drop in the reservoir.*

While there is a subsidence potential, hydrothermal reservoirs are not as subject to subsidence as geopressured reservoirs, where

*Measurements of subsidence have also been made by Thomas C. Gustavson and Charles W. Kreidler on the Texas Gulf Coast. See "Environmental Concerns Arising from the Production and Disposal of Geothermal Waters," Bureau of Economic Geology, the University of Texas at Austin, GC76-7.

subsidence is almost a certainty. Geopressured zones have such a high subsidence potential because the thick sedimentary sequences in which they are found are undercompacted and the water trapped in these sequences actually bear part of the lithostatic load. Withdrawing the water from a geopressured reservoir allows compaction of these rock units and results in subsidence.⁽¹⁰⁰⁾ The Geysers and the geopressured zones represent the two ends of the spectrum. The resources with characteristics between these extremes will have variable potential for subsidence, depending on geologic structure and the reservoir rock's potential for compaction. The plant design, and withdrawal and reinjection strategies will determine the rate and amount of subsidence.

The major concerns with subsidence are the effects on the surface. The amount of economic damage done on the surface, however, depends on surface land usage. The indirect effects of subsidence are frequently more severe than the direct effects of land movement.⁽¹⁰¹⁾ Flooding is the most common indirect effect. Other indirect effects include aggravation of surface faulting, tilting of irrigated lands, and dam failures.

3.2.2.2 Control Methods. It has been suggested⁽⁹⁷⁾ that a method is needed to differentiate between subsidence caused by:

- Geothermal development,
- Other activities of man, and
- Natural subsidence

This might be accomplished by site-specific monitoring programs starting before geothermal development and continuing through development of the resource. However, methods of monitoring subsidence in geothermal areas are limited. For example, temperature is the principal limiting factor in instruments to measure changes at depth. Therefore, high temperature monitoring instrumentation needs be developed to measure compaction of rock at various depths due to removal and/or injection of fluids.(97) Also, few or no guidelines are available for relevant field data acquisition and analysis for geothermal areas.

Several control techniques may be employed to limit the amount of subsidence. All of the documents reviewed on subsidence control agree that reinjection of the withdrawn fluids is a viable control method and that it will limit the amount of subsidence experienced at and around the resource. However, injection of water into areas that are seismically active can increase the level of seismicity.(101)* Limiting fluid withdrawal or avoiding fluid withdrawal are other ways of controlling subsidence.(102) Swanberg(98) suggests that the use of down-hole heat exchangers may be one method of extracting the thermal energy from a reservoir without extracting the fluid and risking subsidence. This assumes that the groundwater flow in the reservoir will be sufficient to provide adequate amounts of heat to the heat exchanger, which is seldom the case.

*Seismicity is covered in Section 3.2.1 and in Section 3.2.3.

The developer of geothermal energy must account for subsidence in the design of the geothermal plant and field for both environmental and economic reasons. Crow⁽⁹⁹⁾ suggests a three-step process for this. These steps are:

- 1) Determine how much subsidence must occur in order to cause damage in the area of the resource
- 2) Estimate the likelihood of that much subsidence occurring
- 3) If that amount can reasonably be expected, estimate the cost to repair the damage.

3.2.2.3 Summary. Subsidence due to geothermal energy use is caused by the withdrawal of fluids. The methods suggested to determine and control such subsidence are:

- Monitoring before and during development of the resource
- Reinjecting the withdrawn fluids
- Limiting fluid withdrawal
- Not withdrawing the fluid but using other technology to extract the thermal energy.

Monitoring techniques should be developed, and alternative subsidence control methods are needed with more effective results and without undesirable side effects (as in the case of fluids reinjection which may induce seismicity and contaminate nearby water aquifers).

3.2.3 Induced Seismicity

3.2.3.1 Causes and Concerns. Geothermal resources are located in areas of high heat flow along thinning crustal zones.⁽¹⁰¹⁾ Thus,

areas which are geothermally active also have a high likelihood of being seismically active.

The major concern with induced seismicity is the potential for injury and loss of life, as well as property and environmental damage resulting from an earthquake. The mechanism by which seismic activity is induced is not well understood. One study indicated that much of the seismicity at The Geysers steam field may be induced by steam withdrawal, condensate reinjection, or both.(99) However, Italian researchers conducting a water reinjection experiment found no increase of seismic background activity or micro-shocks resulting from water reinjection.(73) The Italian experiment was conducted with reinjection under gravity flow. Oil field secondary recovery experience shows that reinjection under pressure can produce increased seismic activity. Since it is not possible to establish the danger limits of flow rates and reinjection times, the Italian researchers state they "intentionally limited" their experiments to modest flow rates and reinjection times.(73)

3.2.3.2 Control Methods. It is generally accepted that "...the physical mechanism of geothermal seismic noise generation is not well understood quantitatively."(104) More research is needed to understand these mechanisms before they can be controlled. Within the current knowledge, steps to control induced seismicity can be taken before development of the resource starts. The recommended sequence of actions(101) are:

- 1) Geologic Mapping - develop detailed geologic maps of site area to assess specific hazards such as landslides, surface fault rupture, etc.
- 2) Subsurface Exploration - conduct detailed subsurface exploration (sample collection) to determine potential hazards.
- 3) Geophysical Surveys - to determine performance, during an earthquake, of site materials.
- 4) ReInjection Evaluation - to determine potential of inducing earthquakes by reinjection at the site.

The U.S. Department of Energy (DOE) Geothermal Induced Seismicity Program covers three major areas:(103)

- Characterization
- Modeling
- Control and Mitigation.

The needed research in each of these three major areas is identified in Table 3-1.

The objective of the program is to improve understanding of the relationships between geothermal production and induced seismicity. Such understanding would lead to improved techniques to estimate the seismic risk at specific sites and for various production processes, and to better procedures for control and mitigation of induced seismicity.

3.2.3.3. Summary. Ridley and Taylor⁽¹⁰¹⁾ wrote, "Due to the potential injury and loss of life, as well as property and environmental damage, a thorough evaluation of earthquake-related and seismic hazards would provide a basis for reducing risks and ensuring a

Table 3-1

RECOMMENDED RESEARCH FOR INDUCED SEISMICITY

<u>Element</u>	<u>Recommended Research</u>
Characterization	<ol style="list-style-type: none"> 1. Seismic Parameters 2. In Situ Stress 3. Structural Geology and Geophysics 4. Reservoir Pressure, Temperature and Production Parameters 5. Rock Properties
Modeling	<ol style="list-style-type: none"> 1. Reservoir Models 2. Failure Process Models
Control and Mitigation	<ol style="list-style-type: none"> 1. Seismic Hazard Assessment 2. Production Procedures and Guidelines

functionally designed, environmentally compatible geothermal development." The U.S. DOE program described above has been designed to address these needs.

3.2.4 Hydrological Alterations

None of the literature reviewed addresses the subject of possible hydrological alterations as a result of geothermal development. This may be because this concern has received attention only recently, particularly in the resource areas near national parks. Hydrological alterations include any effects on surface features such as hot springs, fumaroles, mud pots, or geysers as a result of geothermal energy development. Although no existing regulations specifically mention hydrological alterations, these effects are the subject of proposed regulations* which could severely impact geothermal development if they were passed.

3.3 Conclusion

Subsidence and induced seismicity are real risks in geothermal development and their destructive impacts can be significant. While the causes of subsidence are known, few subsidence control methods are available. Reinjection, a favored subsidence control method, could induce seismicity. The potential of induced seismicity at geothermal sites cannot be assessed because causes and mechanisms of induced seismicity are not well understood. Thus, research and

*As discussed in the 6 February 1980 IGCC meeting, Federal Building, Washington, D.C.

production experience is needed to allow prediction of seismicity risks. Techniques for controlling subsidence and induced seismicity need be developed. More attention should also be devoted to hydrological alterations resulting from geothermal development, because the effects of these alterations may be significant and may be subject to environmental regulations.

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