Lawrence Livermore Laboratory

HUMAN HEALTH IMPLICATIONS OF GEOTHERMAL ENERGY

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HUMAN HEALTH IMPLICATIONS OF GEOTHERMAL ENERGY

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ABSTRACT

Geothermal energy is a currently available technology that is now being used to generate electricity and for space and process heat. It has several advantages including a short "fuel cycle" and it needs no large-scale supporting technologies as do many other energy resources. Environmental problems consist of the release of noncondensable gases and vapors, disposal of saline fluids, possible land subsidence and enhanced seismicity, noise, accidents such as well blowouts, and socioeconomic impacts.

The most important issue related to human health is believed to be the emission of noncondensable gases, including hydrogen sulfide, mercury, and radon. Based upon data at The Geysers, California, Power Plant, emissions of mercury and radon are not large enough to result in concerns for human health. Hydrogen sulfide emissions, however, have resulted in complaints of odor annoyance and health impairment. These complaints have been caused by exposure to levels of up to approximately 0.1 ppmv in ambient air. This is above the California standard of 0.03 ppmv. Achievement of this standard may not eliminate annoyance complaints, as the odor detection threshold is lognormally distributed and about 20% of the population can detect hydrogen sulfide at levels of 0.002 ppmv.

Abatement systems for hydrogen sulfide have been utilized at The Geysers since 1975. This has resulted in an increase of occupational illness caused by exposure to the abatement chemicals and wastes. More effective, and hopefully safer, abatement systems are now being tested.

Occupational hazards are evaluated; the more significant ones are exposure to toxic chemicals and hazardous materials and noise. Available occupational illness data are summarized; these clearly indicate that the most significant cause of illness has been exposure to the chemicals and wastes associated with hydrogen sulfide abatement.

The conclusion is reached that, on a comparative basis, geothermal energy is a relatively benign source of energy. The most significant health problem results from the emission of hydrogen sulfide or from the abatement systems to control it. These problems are shared by many other energy technologies including oil and gas, oil shale, and nuclear. A viable, large-scale geothermal energy technology, however, will depend upon better hydrogen sulfide abatement systems that do not endanger occupational health.

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INTRODUCTION

Geothermal energy is a general term that refers to the stored heat of the earth that can be recovered using current or yet-to-be-developed technologies. At the present time, the only available current technologies are those that extract heat from hydrothermal convection systems; these are systems where water or steam transfers heat from deep parts of the system to near-surface locations where the fluid may be tapped. Hydrothermal convection systems are subcategorized as vapor-dominated (steam) or hot-water systems. Hot-water systems exist with a broad range of temperatures. High-temperature (>150°C) systems are usable for the generation of electricity with existing technology; intermediate-temperature (~90 to 150°C) systems are usable for other purposes such as space heating and perhaps for electrical energy production with near-term technology.

The use of hydrothermal energy to produce electricity has several features that are unique compared to other energy alternatives. On the favorable side the "fuel cycle" is short as the vapor or steam flashed from hot water can be used directly to supply a steam turbine and the condensate then used as cooling water or injected into the reservoir. Thus, no combustion is involved and there is no requirement for large-scale supporting technologies such as uranium or coal mines or oil refineries. On the negative side, because it is inefficient to transport heat over long distances, hydrothermal resources must be utilized where they occur although some sites might not be optimum locations. For similar transport reasons, there is little economy of scale and the optimum size (minimum cost per MW(e) of capacity) for a hydrothermal power plant is
in the range of 30 to 180 MW(e). Another drawback is that hydrothermal power plants have relatively low thermodynamic efficiencies of 8 to 20% due to the relatively low temperature of the steam; this results in a higher requirement for cooling water on a per unit power generated basis.

Although geothermal energy is sometimes regarded as a future or advanced energy technology, it has been used for non-electric applications for centuries and was first used to generate electricity at the turn of the century in Larderello, Italy. Today, the largest geothermal power plant in the world is located at The Geysers, California. Here, the first 11 MW(e) unit was placed in operation in 1960, and today thirteen units with a net capacity of 663 MW(e) are in operation with another 245 MW(e) under construction. As yet, however, this is still the only geothermal power plant in the U.S. Perhaps the primary reason for this is because The Geysers is also the only proven commercially exploitable vapor-dominated resource in the U.S. Many hot water resources exist, but this technology has not yet been demonstrated in the U.S. Other countries, however, are utilizing such resources effectively; two of the larger power plants are at Wairakei, New Zealand, 160 MW(e), and Cerro Prieto, Mexico 75 MW(e). Both of these power plants discharge their spent fluids to surface waters; this practice would not be environmentally acceptable in the U.S. under existing legislation.

Table 2 summarizes the present worldwide use of geothermal energy for both electric and nonelectric applications. Most residential-commercial use is for space heating and cooling with notable examples at Reykjavik, Iceland; Zgoudidi town, Georgia, U.S.S.R.; Boise, Idaho, and Klamath Falls, Oregon. By far the largest use is agricultural and this is dominated by about 5000 MW of energy used to heat greenhouses in the U.S.S.R.; the
relatively small use in the U.S. is also for the heating of greenhouses. Industrial uses are generally small; the two largest applications are for process heat for a pulp and paper mill at Kawerau, New Zealand, and a diatomaceous earth plant at Namafjall, Iceland. The largest industrial use in the U.S. is at the Sussex, Wyoming, oil field where geothermal energy is used for process heat to remove impurities from crude oil before it is placed in a pipeline.
GENERAL ENVIRONMENTAL PROBLEMS

Geothermal energy, like any other energy source, can have negative impacts upon the environment. Nearly all of the proposed utilization schemes for hydrothermal energy will result in releases to the atmosphere of gases that do not condense during the extraction process. Typically these noncondensed gases contain large amounts of carbon dioxide, significant amounts of hydrogen sulfide and ammonia, trace amounts of substances such as $^{222}$Rn and volatile heavy metals such as Hg.

Expansion of geothermal power plants into hot-water resource areas raises additional concerns related to water quality. As opposed to the very small total dissolved solids (TDS) content of the steam produced at The Geysers, some hot-water resources might be appropriately referred to as "rock soup". Table 2 lists the TDS of samples from The Geysers, five areas from the Imperial Valley, California, and from Cerro Prieto, Mexico. One area (Salton Sea) has a TDS content of 24% and also contains significant amounts of undesirable chemicals such as B and Pb. A typical 110 MW(e) geothermal power plant using Salton Sea fluid is projected to require $8 \times 10^7$ kg of fluid per day. Obviously, this amount of fluid cannot be disposed to surface waters and must be carefully controlled and injected back into the reservoir or some other suitable stratum.

Related to the problem of waste water management are the problems of land subsidence and enhanced seismicity. The large-scale withdrawal of hot geothermal fluids without injecting spent fluids back into the reservoir can result in significant land subsidence. At the Wairakei, New Zealand Power Plant, where waste fluids are disposed to surface waters, a roughly elliptical dish-shaped
depression has formed with a maximum rate of subsidence of about 1.3 feet per year and a total maximum subsidence of over 10 feet. Unfortunately, the relationships between fluid withdrawal, geological structure, and land subsidence are not understood; but it is hoped that the injection of spent fluids back into the reservoir will mitigate against subsidence.

However, the injection of fluids under high pressure into geologic formations can result in enhanced levels of seismic activity. Hopefully the pressures required for the injection of spent geothermal fluids will not cause such events; but this is not known with certainty, and the cooling of rock surrounding the reservoir may also produce microseismic events.

Another environmental problem associated with the development of hydrothermal resources is the production of noise. The normal procedures of well-drilling and plant operations are inherently noisy, but generally tolerable. The necessary venting of the vapor-dominated wells at The Geysers Power Plant, however, produces noise levels as high as 120 dBA and is a source of complaints from the nearby residents.

Accidental occurrences are also a problem. Well blowouts have occurred, for example, at The Geysers and at Cerro Prieto, Mexico. They have seriously disrupted the local environment and have been expensive to control. In the future, some power plants will operate with a binary cycle with secondary working fluids such as isobutane and pentane. These fluids are explosive and are a potential for serious accidents.

Finally, as in the development of any resource, there will be social, economic, cultural, and political issues. Some of the more serious are expected to be conflicts over land-use and the allocation of limited water
resources. Fortunately, geothermal resource development will probably proceed in a phased manner so that classic boom-bust economic impacts will be avoided, but changes in lifestyle and community structure may be extensive nevertheless.
PUBLIC HEALTH CONSIDERATIONS

Of the general environmental problems discussed above, only the airborne emissions and noise appear to warrant serious consideration as having a significant potential for impacting human health. (For this discussion annoyance is included as an effect upon human health.) Other problems could conceivably be of concern, but it seems unlikely, for example, that waterborne effluents will be permitted or that perceptible seismic events will occur due to power plant operations.

Table 3 is a tabulation of the measured or calculated unabated airborne release rates of several chemicals at The Geysers Power Plant. Most hydrothermal power plants would probably have similar emissions in a qualitative sense although substantial variations in emission rates have been measured. Of the chemicals listed, most are not of major concern. The carbon dioxide emission rate is about equivalent to that of a coal-fired power plant, and will add to the global CO₂ problem. However, the total contribution from geothermal energy utilization will almost certainly be a minor part of this overall problem.

Three chemicals shown in Table 3 are of concern; these are hydrogen sulfide, mercury, and radon.

**Hydrogen Sulfide**

The emission of hydrogen sulfide gas is currently the most significant public health problem related to the utilization of geothermal energy. Hydrogen sulfide is a very toxic gas; it produces immediate collapse with respiratory
paralysis at concentrations above 1000 parts per million by volume (ppmv), and the threshold of serious eye injury is 50 to 100 ppmv. The current NIOSH recommended standard$^{14}$ for occupational exposure is 10 ppmv for a 40-hour workweek with the requirement of evacuation if the concentration exceeds 50 ppmv. In addition, hydrogen sulfide has a very offensive odor, and the human nose can detect very low concentrations. There is not, however, any evidence that would indicate an association of hydrogen sulfide with carcinogenesis, mutagenesis, or teratogenesis.$^{14}$

Residents of communities nearby The Geysers Geothermal Power Plant have registered public health complaints. Most of these complaints relate to annoyance effects, particularly to odor annoyance from hydrogen sulfide.$^{15}$ Some residents have appeared at hearings held by the California Public Utilities Commission$^{16}$ and voiced complaints of headaches, nausea, sinus congestion, etc. The concentrations of hydrogen sulfide that appear to be responsible for these complaints are about 0.1 ppmv,$^{15}$ or 100 times lower than the recommended standard for occupational exposure. Whether such low concentrations of hydrogen sulfide can produce actual health effects remains to be proven, but the possibility does exist that some individuals are particularly sensitive.

At the present time, there is no national ambient air quality standard for hydrogen sulfide, but other countries and several states have established such standards. A representative sample of these standards$^{17}$ is shown in Table 4. The nearly two orders of magnitude variation is rather surprising. Most of the standards have been established upon the basis of odor annoyance, and there can be significant variation in how odor annoyance is defined. In addition, values reported for the odor detection threshold vary from 0.0005 to 0.03 ppmv and even higher in the older literature.$^{18}$
We have reviewed the more recent literature\textsuperscript{19-23} concerning the measurement of odor perception thresholds for hydrogen sulfide, and the results are shown in Fig. 1. The results that appear as straight lines are from Adams, \textit{et al.},\textsuperscript{21} who gave their results in terms of lognormal distributions. Where possible, we have plotted distributions of individual data from other workers and find that most data sets can be approximated rather well by a lognormal distribution. All but one of the studies agree fairly well and indicate that the median odor perception threshold is about 0.005 ppmv, but that there are also wide variations among individuals and that about 20\% of the population can detect hydrogen sulfide at concentrations of 0.002 ppmv.

The one study that does not fit this general pattern is the one performed by the California Department of Health Services\textsuperscript{19} that provided the basis of the California ambient air quality standard of 0.03 ppmv.\textsuperscript{24}

As indicated above, complaints of health effects from residents nearby The Geysers have arisen in areas where the maximum measured concentration of hydrogen sulfide is about 0.1 ppmv. This is substantially above the California ambient air quality standard of 0.03 ppmv; but the data shown in Fig. 1 indicate that levels much lower than 0.03 ppmv should be achieved if all annoyance complaints are to be avoided.

\textbf{Mercury}

As indicated in Table 3, there are measurable emissions of mercury at The Geysers Power Plant, and roughly comparable emissions would be expected at many locations based upon the mercury content of geothermal fluids.\textsuperscript{25} Mercury levels in surface soil samples are, in fact, considered to be a useful prospecting tool in locating geothermal resources.\textsuperscript{26}
On a per megawatt basis, the emissions of mercury from geothermal power plants are comparable to releases from coal-fired power plants, and measurements of mercury in ambient air at The Geysers were found to be at background levels of about 0.001 µg/m³. Elevated ambient levels of 0.068 µg/m³ were reported at the Cerro Prieto, Mexico, Power Plant.

There are no national or state standards for the concentration of mercury in ambient air; several eastern European countries have adopted the standard of 0.3 µg/m³, and the U.S. limit for occupational exposure is 100 µg/m³. It therefore appears that the emission of mercury by geothermal power plants is not a significant public health concern.

Radon

The radioactive noble gas \(^{222}\text{Rn}\) is present in geothermal fluids, and the measured emission rate at The Geysers is 1.4 Ci/day for the production of 502 MW(e). The significance of this release was the subject of a major study conducted for the Pacific Gas & Electric Co. One of the conclusions was that there is no discernible effect of this emission on downwind communities, or upon the general environment of the Power Plant itself. The concentration of the short-lived daughter radionuclides of \(^{222}\text{Rn}\) was measured at a total of 36 locations upwind, downwind, and in the area of the Power Plant with a one-week integration period for the measurements. The results of 575 measurements were an average concentration of 0.00036 Working Level (WL) with a range of 0.00004 to 0.0030 WL. (One WL is equal to the concentration in air of 100 pCi/l of \(^{222}\text{Rn}\) in equilibrium with its short-lived daughter radionuclides.) This is well below the federal standard for uncontrolled areas which is equivalent to 0.01 WL above background averaged over a year.
The results for The Geysers area are in fact within the ranges of background levels of $^{222}\text{Rn}$ daughters; these vary widely due to changes in the exhalation rate from soil and in atmospheric mixing. The release rate of 1.4 Ci/day by the Power Plant is equivalent to the release from only a 15 square mile area of soil with an exhalation rate of 0.75 atoms per second per cm$^2$, which is an estimate$^{29}$ of the worldwide average rate.
HYDROGEN SULFIDE ABATEMENT

The emission of hydrogen sulfide from The Geysers Power Plant and adverse reactions from local residents have been long-standing problems. The Pacific Gas & Electric Co. and the developers of the steam field have been attempting to abate this emission for several years with the urging of the local air pollution control agencies. The first operational abatement system was installed on Unit 11 when it began operation in 1975. The method consists of ducting the noncondensable gases to the cooling tower and using the cooling tower as a reaction chamber to oxidize H₂S to elemental sulfur assisted by a metal catalyst. (With a direct-contact condenser most of the H₂S is already dissolved in the condensate.) This system worked moderately well, but not as well as expected based upon smaller scale tests. In order to achieve a target abatement of 90%, it has been necessary to inject hydrogen peroxide for additional oxidation and caustic for pH control.

This system has some major disadvantages. It has significantly increased maintenance problems, and the resulting abatement product is a sludge that collects in the bottom of the cooling tower and which must be removed periodically. The sludge consists mainly of noncommercial quality sulfur with lesser amounts of other chemicals. The handling of this sludge and the chemicals used for abatement has resulted in an occupational health problem; this will be discussed later.

Because it was realized that a better abatement solution would require a major design change, the latest units now coming on line at The Geysers employ a tube and shell condenser to force more of the hydrogen sulfide into the noncondensable gas stream and treatment of this stream by a Stretford unit to convert hydrogen sulfide to commercial quality sulfur. Additional
treatment of the condensate may be necessary if a significant fraction of the hydrogen sulfide remains dissolved in the condensate stream.

Other abatement systems are also under study and test because the new condenser-Stretford unit design cannot be retrofit readily to the older power units. One of the systems under very active development utilizes copper sulfate to scrub hydrogen sulfide from steam before it reaches the turbine.30 This system is currently undergoing 1/20-scale tests at The Geysers. If demonstrated successfully, this system could be retrofit to the older units, and could also be used to control emissions when it is necessary to vent steam to the atmosphere without processing through a power unit.

Considerable progress has therefore been made in controlling hydrogen sulfide emissions and thereby eliminating the primary concern for public annoyance. Any abatement system for any energy technology, however, increases the complexity of the operation and may result in new, and perhaps unanticipated, concerns for public and/or occupational health.
OCCUPATIONAL HEALTH CONSIDERATIONS

Evaluation of Occupational Hazards

Hahn\textsuperscript{31} has recently completed an evaluation of the occupational hazards associated with the utilization of geothermal energy. The results of this evaluation are summarized in Table 5 by subcategories of the technology and by hazardous agents. This evaluation is based upon an assessment of the operations, the materials of possible exposure, measurements of concentrations of toxic compounds and of noise levels, and of reports of occupational illness.\textsuperscript{32}

As might be expected, some of the more serious hazards are due to toxic compounds like hydrogen sulfide and ammonia, and workers on or near drilling rigs have suffered acute effects.\textsuperscript{32} Hydrogen sulfide levels are also potentially hazardous in the power-generating units and on top of the cooling towers. The highest concentration measured by the Pacific Gas & Electric Co. in a power unit was 40 ppmv during startup of Unit 7.\textsuperscript{33} Conditions causing this high concentration were corrected, and typical levels are now reported to be less than 1 ppmv.

Some of the chemicals used in drilling fluids and drilling wastes are toxic, and have been the cause of several cases of chemical burns to skin and eyes.\textsuperscript{32}

Because geothermal fluids frequently contain significant amounts of carbon dioxide and other gases that can be asphyxiants, these can be hazards if they accumulate in confined spaces.
Noise can be a significant problem, especially during well drilling and during venting operations that are necessary to cleanout or test wells or when power units are temporarily shut down. Noise levels\textsuperscript{34} during drilling are about 90 dBA at 50 ft when mud is used for cooling and 102 dBA when air is used for cooling without a muffler. Other activities which involve freely venting steam can produce noise levels as high as 120 dBA at 100 feet.\textsuperscript{15}

Hydrogen sulfide abatement systems appear to use the most hazardous chemicals, and in the largest volume. These chemicals include hydrogen peroxide, caustic soda, and catalytic compounds containing iron and nickel. The waste material is also hazardous and can cause skin and eye irritation.

When binary power plants come on line, they will pose some unique problems resulting from the use of secondary and even tertiary working fluids. Current designs typically utilize fluids such as isobutane and propane, and explosions and fires might result if leaks should occur.

In addition to these hazards that are rather peculiar to geothermal energy, there are other hazards of a more general industrial nature. For example, hydrogen is typically used to cool generators, and there are general problems relating to performing maintenance operations, such as welding, in confined spaces.

Reports of Occupational Illness

California maintains a rather unique set of data referred to as "Doctor's First Reports."\textsuperscript{32} Each physician who attends an injured employee and each employer is required to file a report for each injury that results in a disability lasting beyond the day of injury or that requires medical attention.
Occupational illness is included by definition, and illness reports are separated and made available to the Department of Health Services for analysis.35

One (J.L.H.) of us inspected the illness reports that were available. These included all of the reports for 1974 through mid-1977, which were separated by county of occurrence; all illnesses related to geothermal energy were selected for Imperial, Lake, and Sonoma Counties. A few more recent reports were also found, but the later reports have not been sorted and no attempt was made to secure complete data for times beyond mid-1977. A total of 26 illness reports were found for workers in the geothermal industry. Of these, eight cases were the result of general industrial exposure to hazardous chemicals such as drilling fluids and zinc oxide fumes from welding. The remaining 18 cases were due to causes directly related to geothermal energy such as exposure to hydrogen sulfide. A significant finding was that 10 of the 18 cases were dermatoses resulting from exposure to the chemicals used for hydrogen sulfide abatement or the materials containing the abatement wastes.

The number of illnesses as a function of time is shown in Fig. 2 where the illnesses related directly to geothermal hazards and those related to general industrial hazards are shown separately. The marked increase in illnesses in 1976 corresponds to the introduction of the hydrogen sulfide abatement systems at The Geysers Power Plant. The decrease in early 1977 is presumed due to an industrial hygiene program to control a recognized problem. About 60 workers are needed to operate The Geysers Power Plant,15 so the rate of disease occurrence has been high compared to the rate of disease occurrence in privately-owned utilities, which was 5.7 cases per 1000 workers in 1975.35
A significant aspect of the data is the preponderance of illnesses that are a direct result of the installation of the abatement systems to control hydrogen sulfide emissions. At least for this period of time, the result has been a reduction in public annoyance at the expense of the health of the workers.
CONCLUSIONS

On a comparative basis, geothermal energy is a relatively benign source of energy. The most significant health problems are related to hydrogen sulfide and the systems for controlling its emission. Hydrogen sulfide, however, is not a pollutant that is unique to geothermal energy. It has been a serious problem in the U.S. petroleum industry and the Swedish oil shale industry, for example, and has even been a significant problem in the nuclear industry where it is used to make heavy water.14

It is obvious, however, that the viability of a substantial geothermal industry will require the effective abatement of hydrogen sulfide emissions. Experience at The Geysers indicates that more effort must be devoted to assuring that these abatement systems do not merely transform a public annoyance problem into an occupational health problem.
ACKNOWLEDGMENT

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REFERENCES


Table 1. Present use of geothermal energy\textsuperscript{a,b}

<table>
<thead>
<tr>
<th></th>
<th>U.S.</th>
<th>World</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Power</td>
<td>663 MWe</td>
<td>~1400 MWe</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential-Commercial</td>
<td>15 MW</td>
<td>400 MW</td>
</tr>
<tr>
<td>Agricultural</td>
<td>1</td>
<td>5500</td>
</tr>
<tr>
<td>Industrial</td>
<td>6</td>
<td>200</td>
</tr>
</tbody>
</table>

\textsuperscript{a}J.H. Howard, Ed., Lawrence Livermore Laboratory, Rept. UCRL-51926 (1975).

\textsuperscript{b}Buffalo (Wyo.) Bulletin, 87 (45), 7 (1977).
Table 2. Total dissolved solids content (TDS) of fluids from several geothermal reservoirs.

<table>
<thead>
<tr>
<th>Location</th>
<th>TDS (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Geysers, Calif.(^a)</td>
<td>28</td>
</tr>
<tr>
<td>Salton Sea, Calif.(^b)</td>
<td>240,000</td>
</tr>
<tr>
<td>Westmorland, Calif.(^b)</td>
<td>37,000</td>
</tr>
<tr>
<td>Brawley, Calif.(^b)</td>
<td>76,000</td>
</tr>
<tr>
<td>Heber, Calif.(^b)</td>
<td>14,000</td>
</tr>
<tr>
<td>East Mesa, Calif.(^b)</td>
<td>7,600</td>
</tr>
<tr>
<td>Cerro Prieto, Calif.(^a)</td>
<td>17,000</td>
</tr>
</tbody>
</table>


Table 3. Measured or calculated unabated discharge of several chemicals to the atmosphere at The Geysers Power Plant, as a result of producing 502 MW(e) of power. The discharge of H₂S is currently being abated to a level much below that indicated.

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Discharge kg/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂S&lt;sup&gt;a&lt;/sup&gt;</td>
<td>21,700</td>
</tr>
<tr>
<td>CO₂&lt;sup&gt;a&lt;/sup&gt;</td>
<td>313,000</td>
</tr>
<tr>
<td>NH₃&lt;sup&gt;a&lt;/sup&gt;</td>
<td>18,500</td>
</tr>
<tr>
<td>CH₄&lt;sup&gt;a&lt;/sup&gt;</td>
<td>18,500</td>
</tr>
<tr>
<td>H₂&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5,380</td>
</tr>
<tr>
<td>N₂&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5,060</td>
</tr>
<tr>
<td>As&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>0.023</td>
</tr>
<tr>
<td>B&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>48.6</td>
</tr>
<tr>
<td>Hg&lt;sup&gt;c&lt;/sup&gt;</td>
<td>~ 0.12</td>
</tr>
<tr>
<td>H₂O&lt;sup&gt;a&lt;/sup&gt;</td>
<td>8 x 10⁷</td>
</tr>
<tr>
<td>²²²Rn&lt;sup&gt;d,e&lt;/sup&gt;</td>
<td>9 x 10⁻⁹</td>
</tr>
</tbody>
</table>

<sup>a</sup>PG & E, Environmental Data Statement. Geysers Unit 13 (1975).

<sup>b</sup>Based on calculated cooling tower drift rates.


<sup>d</sup>L.R. Anspaugh, Lawrence Livermore Laboratory, Rept. (1978).

<sup>e</sup>9 x 10⁻⁹ kg = 1.4 Ci
Table 4. Representative values of ambient air concentration standards for hydrogen sulfide.

<table>
<thead>
<tr>
<th></th>
<th>Long Term&lt;sup&gt;a&lt;/sup&gt;</th>
<th></th>
<th>Short Term&lt;sup&gt;a&lt;/sup&gt;</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>ppmv</td>
<td>Avg. Time</td>
<td>ppmv</td>
<td>Avg. Time</td>
</tr>
<tr>
<td>California</td>
<td></td>
<td></td>
<td>0.030</td>
<td>1 hr</td>
</tr>
<tr>
<td>New Mexico</td>
<td></td>
<td></td>
<td>0.003</td>
<td>30 min</td>
</tr>
<tr>
<td>New York</td>
<td></td>
<td></td>
<td>0.009</td>
<td>30 min</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>0.005</td>
<td>24 hr</td>
<td>0.1</td>
<td>1 hr</td>
</tr>
<tr>
<td>Czechoslovakia</td>
<td>0.005</td>
<td>24 hr</td>
<td>0.005</td>
<td>30 min</td>
</tr>
<tr>
<td>Hungary</td>
<td>0.1</td>
<td>24 hr</td>
<td>0.2</td>
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<td>Protected Areas</td>
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<td>0.005</td>
<td>30 min</td>
</tr>
<tr>
<td>Israel</td>
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<td>0.03</td>
<td>24 hr</td>
<td>0.07</td>
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<td>0.006</td>
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<td>USSR</td>
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<tr>
<td>Yugoslavia</td>
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Table 5. Summary of the evaluation of occupational hazards for geothermal energy.

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<th>Explosive Compounds</th>
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<th>Noise</th>
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aKey: 3 = serious hazard potential, substance above regulatory limit, circles indicate one or more illness reports; 2 = hazard potential, substance near regulatory limit; 1 = minimum hazard potential, substance detectable but below regulatory limit.
FIGURE LEGENDS

Fig. 1  Summary of more recent data concerning the odor detection threshold for hydrogen sulfide. ◇ 16 subjects, Ref. 19; ○ 12 subjects, Ref. 20; × 789 subjects, Ref. 21; ▼ 11 subjects, Ref. 21; ◆ panel of 4 subjects, Ref. 22; ◇ 84 subjects, Ref. 21; △ 114 subjects, Ref. 21; and ● 33 subjects, Ref. 23.

Fig. 2  Number of Doctors' First Reports of Occupational Illness per six-month period for the geothermal industry. Circles are data points for illnesses due to general occupational hazards; squares are data points for illnesses related directly to hazards unique to geothermal energy.
Figure 1
Figure 2

Number of reports