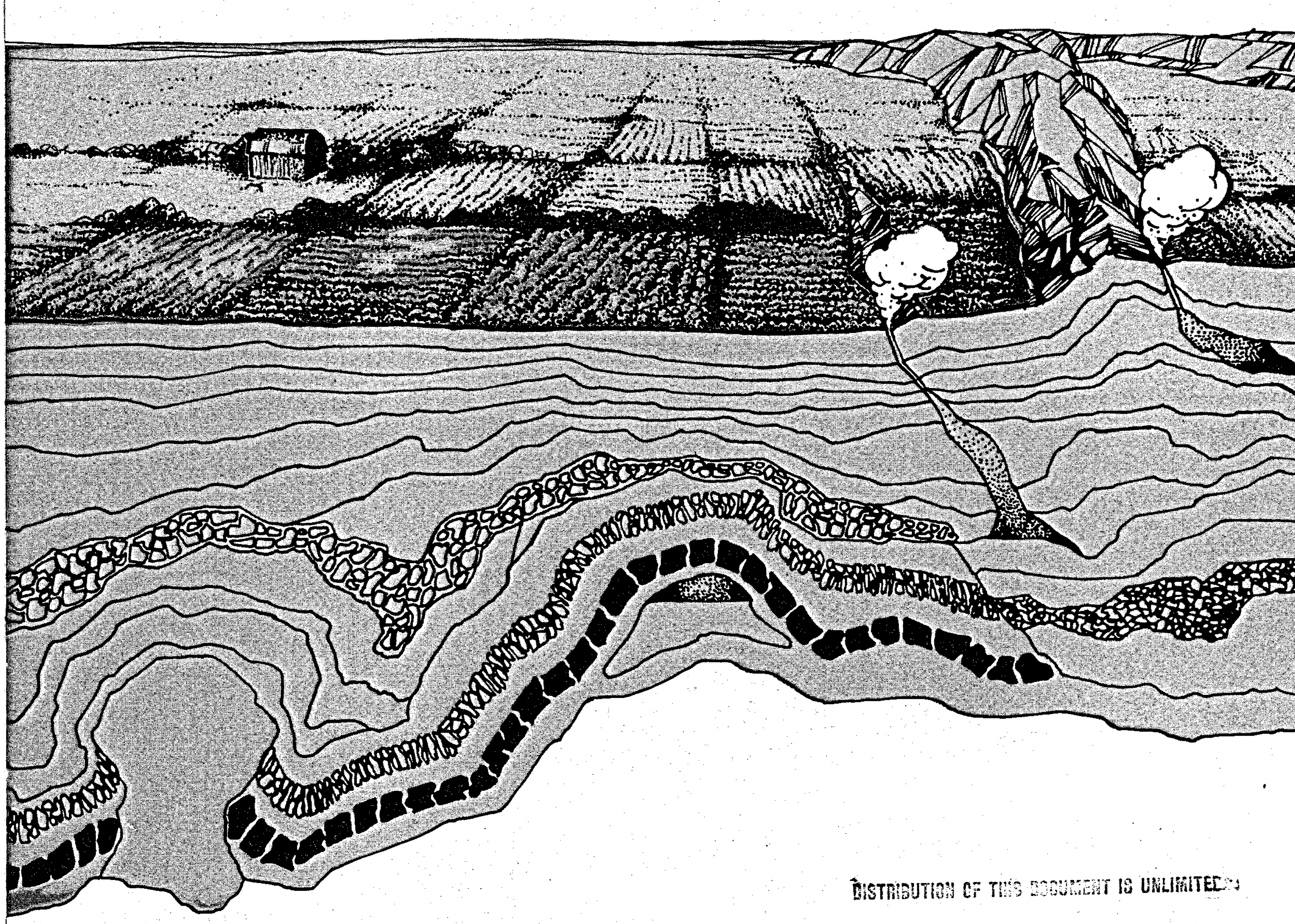
DOE/TIC-11308
U. S. Department of Energy
Assistant Secretary for Environment
Office of Environmental Assessments
Technology Assessments Division
October 1980

An Assessment of Geothermal Development in the Imperial Valley of California

Environment, Health, Socioeconomics and Environmental Control Technology

Executive Summary



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Available from

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes

Printed Copy: $ 6.00
Microfiche Copy: $ 3.50

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Environment, Health, Socioeconomics and Environmental Control Technology

Executive Summary

Prepared by
David W. Layton
Environmental Sciences Division
Lawrence Livermore National Laboratory
Livermore, California 94550
Under Contract No. W-7405-ENG-48

U.S. Department of Energy
Assistant Secretary for Environment
Office of Environmental Assessments
Technology Assessments Division
Washington, D.C. 20545

PREFACE

The Department of Energy (DOE) has projected that geothermal energy resources have the potential of providing 4.0 to 9.0 quads of energy per year by the year 2000, in the form of both direct heat and electric energy generation. Currently, the Geysers Field in Northern California is the only place in the United States where electricity is commercially produced from geothermal resources. Power plants in that resource area use dry-steam supplied from production wells to drive turbine generators. The energy potential of liquid-dominated resources is much larger than the potential of dry-steam resources. California's Imperial Valley, in particular, contains nearly a third of the Nation's identified hot-water resources. Geothermal energy produced from the valley could make an important contribution to California's energy supplies in the next 20 years.

Geothermal energy, similar to other forms of energy utilization, has the potential for developing conflicts between resource utilization, protection of the environment, and maintenance of stable societal conditions. Accordingly, the Assistant Secretary for Environment/DOE initiated the Imperial Valley Environmental Project (IVEP). The IVEP is a regional case study representing a program of surveys, field measurements, and analyses aimed at characterizing existing environmental conditions in the valley and assessing the potential impacts that geothermal development could have on these conditions.

This document is a summary of the final assessment report.

An Assessment of Geothermal Development in the Imperial Valley of California, DOE/EV-0092, July 1980

Volume I. Environment, Health, and Socioeconomics

Volume II. Environmental Control Technology

Although this study centers on the Imperial Valley, California, it is hoped that it will serve as a basis for understanding geothermal impacts from liquid-dominated resources in other regions of the country.

Throughout the document scenarios and views of social/economic and institutional futures are presented. These should be considered as illustrations for exploring impacts of policy strategies, not as projections for a likely future.

Robert P. Blaunstein, Chief
Conservation, Solar & Geothermal
Technologies Branch
Technology Assessments Division
Office of Environment

ACKNOWLEDGMENTS

This document summarizes material written by contributors to Volumes 1 and 2 of the final assessment report. It is appropriate to acknowledge those individuals here: L. Anspaugh, G. Armantrout, N. Crow, D. Ermak, C. Hall, J. Kercher, D. Layton, P. Leitner, C. Molenkamp, W. Morris, Y. Ricker, and F. Stephens.

CONTENTS

ABSTRACT

This report summarizes the important findings of a two-volume report that deals with the potential impacts and environmental controls associated with the operation of geothermal power plants in California's Imperial Valley. The valley contains nearly a third of the nation's total energy potential for identified hot-water resources. Possible impacts of developing those resources include violation of air quality standards if emissions of hydrogen sulfide are not abated, negative ecological effects resulting from increases in the salinity of the Salton Sea, and damage to irrigation systems caused by land subsidence induced by the extraction of geothermal fluids. Other minor impacts concern occupational health and safety, socioeconomics, and hazardous wastes. Analyses of environmental impacts and the control measures for minimizing negative impacts are based primarily on a projected production of 3000 MW of electrical power by the year 2010.

INTRODUCTION

The Imperial Valley of California contains nearly a third of the nation's identified hot-water geothermal resources. The valley, with its 475,000 acres of irrigated lands and warm climate, also represents one of the more important agricultural resources of the United States. Utilization of the valley's geothermal resources to support energy production could be hindered if environmental impacts prove to be unacceptable or if geothermal operations are incompatible with agriculture. To address these concerns, an integrated environmental and socioeconomic assessment of energy production in the valley was prepared. In addition, a study of environmental control technologies that could be used to reduce negative impacts was conducted. These studies, funded by the U.S. Department of Energy, culminated in a two-volume report entitled An Assessment of Geothermal Development in the Imperial Valley of California: Volume I. Environment, Health, and Socioeconomics;[1] Volume II. Environmental Control Technology.[2] This document reviews the major findings of both volumes.

GEOTHERMAL RESOURCES

The geothermal resources of the Imperial Valley are subsurface reservoirs of hot-water comprised of one or more deep aquifers, or water-bearing strata. Figure 1 shows the location of the major geothermal resource areas (KGRAs) and the extent of agricultural lands. Temperatures of the geothermal fluids range from around 350°F to over 500°F; salinities range from under 2000 milligrams per liter (mg/ℓ) to over 250,000 mg/ℓ of total dissolved solids (TDS). The valley's geothermal resources have the potential for producing nearly 7000 MW of electricity for 30 years.[3] To generate electricity, geothermal fluids will be extracted from wells drilled into a reservoir, processed on the surface in either a flashed-steam or binary-fluid power plant, and the spent brine will then be injected back into another part of the reservoir through separate wells.

The valley's identified geothermal resources are significantly larger than those of any individual state in the country, and they amount to over half of California's hot-water resources. The resources with the greatest

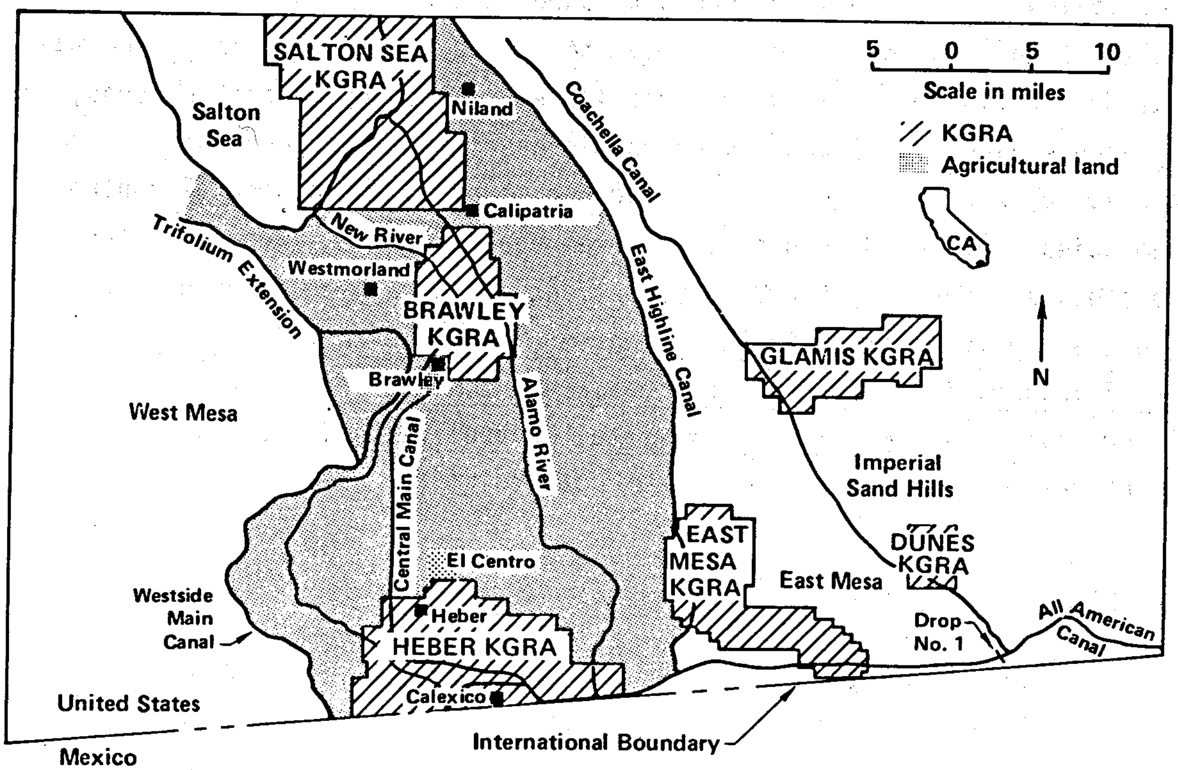

Fig. 1. The Imperial Valley, California, and its known geothermal resource areas (KGRAs). There are about 475,000 acres of farmland in use at the present time, supported by water imported from the Colorado River.

potential for energy production are located at the north end of the valley, near the Salton Sea. However, the geothermal fluids found there are also the most saline, with levels of total dissolved solids around 250,000 mg/ℓ. Technical problems associated with scaling and corrosion of pipelines, wells, and other equipment have hindered exploitation of those resources. Geothermal fluids are less saline in the resource areas near Brawley, Heber, and on East Mesa. Geothermal fluids contain gases that will not condense at atmospheric pressures. Carbon dioxide usually makes up more than 90% of the noncondensable gases. However, hydrogen sulfide is the most important gas from a health perspective because most people can detect its odor at relatively low concentrations (e.g., as low as 0.003 parts per million by volume (ppmv)).

GEOTHERMAL TECHNOLOGIES

The technologies required to produce electrical energy from geothermal resources can be grouped into two categories: (1) the technologies related to geothermal fluid extraction, transmission, and disposal and (2) the technologies involved with the above-ground processing of fluids to actually generate electricity. Geothermal fluids will be extracted from individual wells or from multi-well production islands, consisting of several wells that have been completed by slant drilling. Fluids are transported to a power plant, of either a flashed-steam or binary-fluid design, where the heat energy of the fluids is converted to electrical energy. Figure 2 depicts simplified versions of these two types of power plants. The amount of fluid required for each kilowatt-hour of electricity generated depends primarily on the temperature of the geothermal fluid. More specifically, as the temperature of the fluid rises, the conversion efficiency of a geothermal power cycle increases, thereby reducing the demand for fluid. But for even the hottest resources, fluid requirements are large. For example, a 100-MW power plant using hot water of about 570°F needs approximately 20,000 acre-feet (af) of fluids each year. As the final step

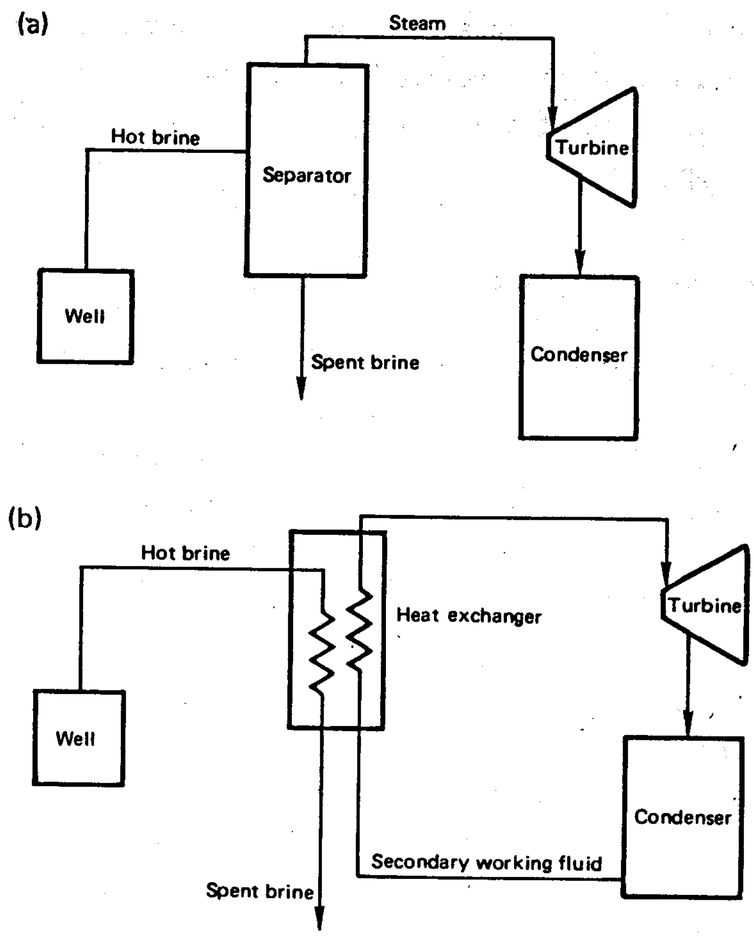

Fig. 2. Simplified conversion cycles for the flashed-steam and confined-flow binary systems: a. single-stage, flashed-steam conversion cycle, b. binary fluid conversion cycle.

in the energy conversion process, the cooled fluids must be disposed of by subsurface injection. This is a crucial part of the conversion cycle. In order for power plants to operate reliably, injection wells must dispose of large quantities of spent fluids for long periods of time.

IMPERIAL VALLEY ENVIRONMENTAL PROJECT

In 1975 the Energy Research and Development Administration (ERDA), the predecessor agency to the U.S. Department of Energy, contracted with the San Diego Gas & Electric Co. to build and operate a geothermal test facility in the Salton Sea area. As part of that contract, ERDA agreed to sponsor a project that was to include a field survey program for the collection of baseline environmental data and an assessment effort for examining the potential impacts of geothermal development in the Imperial Valley. The Environmental Sciences Division of the Lawrence Livermore National Laboratory (LLNL) was given the responsibility of fulfilling the agreement on ERDA's behalf. An integrated project of field measurements and assessment studies, termed the Imperial Valley Environmental Project (IVEP), was initiated by LLNL.

The IVEP included the following elements:

- Air Quality
- Water Quality
- Ecosystem Quality
- Subsidence and Seismicity
- Health Effects
- Socioeconomic Effects
- Integrated Assessment

The study was coordinated with all other major studies relating to environmental and socioeconomic effects in the valley. Efforts were made to achieve a broad participation in the IVEP. LLNL worked closely with a number of universities and various federal, state, and local agencies and other groups to obtain needed information. Good cooperation was received from other agencies, and in some cases their programs were even reoriented to assist with problems specific to geothermal energy production in the Imperial Valley.

After the Department of Energy was established in 1977, the IVEP was continued under the auspices of the Assistant Secretary for Environment. During 1978 major field measurements were completed as planned, and baseline data were entered into a computerized data base. Efforts to study the consequences of large-scale geothermal development in the valley were continued. A closely related activity was a study of environmental control technologies.

Assessments of the cumulative impacts of geothermal development were based primarily on a scenario in which energy production grows at 100 megawatts (MW) per year starting in 1982 and reaches 3000 MW in 2010. The scenario also included a set of plausible sites for power plants located in the valley's geothermal resource areas. The following sections review impacts and environmental controls involving air quality, water resources, liquid and solid wastes, subsidence and seismicity, agriculture, health and safety, fish and wildlife, and socioeconomics.

AIR QUALITY

Noncondensable gases released from flashed-steam geothermal power plants are a potential problem because such releases could degrade the valley's air quality. Emissions of hydrogen sulfide are of particular concern because people can detect this gas at low concentrations. Furthermore, cumulative emissions associated with major geothermal energy production could raise ambient levels of hydrogen sulfide above the California air quality standard of 42 $\mu g/m^3$ for a 1-h average. At The Geysers dry-steam geothermal area in northern California, emissions of hydrogen sulfide have already become the primary environmental issue related to geothermal development.

As part of the IVEP, background air quality and meteorological data were measured at six stations in the Imperial Valley. Ambient levels of hydrogen sulfide, sulfur dioxide, ozone, oxides of nitrogen, carbon dioxide, mercury, and particulates were monitored. Results of the measurements indicate that the California air quality standard for hydrogen sulfide was rarely exceeded. Occasional violations of the standard were probably due to the agricultural use of liquid sulfur fertilizers that released hydrogen sulfide into the atmosphere. Levels of suspended particulates generally exceeded the California 24-hr air quality standard of 100 $\mu g/m^3$. Most ozone concentrations were below the California hourly standard of 100 parts per billion by volume (ppbv); however, some of the daily maximum values violated the standard. In addition, the maximum hourly concentrations of nitrogen oxides periodically exceeded the state standard of 250 ppbv. Other gases were well below established standards. Meteorological measurements indicated that stable atmospheric conditions were much more frequent than unstable conditions. The prevailing winds were from the west, and average wind speeds at the stations were between 4 and 7 miles per hour.

The changes in air quality expected from the production of 3000 MW from geothermal energy were simulated using atmospheric transport models.[1] The primary inputs to the models consisted of the meteorological data obtained from the six monitoring stations, the assumed locations of geothermal facilities producing 3000 MW, and the estimated emission rates of noncondensable gases from these facilities. Unabated emission rates, those that assumed no emission control, were used in order to determine whether air quality standards would be violated and to calculate the degree of control necessary to reduce emissions of any gases whose predicted ambient levels exceeded standards.

SUMMARY OF IMPACTS

- For 3000 MW of development and <u>no abatement of hydrogen sulfide,</u> the California air quality standard would be violated at least 1% of the time over an area of approximately 580 square miles surrounding power plants in the Salton Sea resource area and extending over the power plants in the Brawley area. Figure 3 shows the areas most likely to have violations of the standard.
- The highest predicted hourly concentration of hydrogen sulfide at a site within the Salton Sea resource area (where the greatest number of power plants were sited) was 260 $\mu g/m^3$. To bring that

predicted concentration within standards, emissions of hydrogen sulfide from individual power plants in the Salton Sea and Brawley areas would have to be reduced to 0.7 gram per second (g/s). That level of abatement represents 85% control, assuming unabated emissions of 4.4 g/s from power plants in those two resource areas.

- Simulations of the emissions from a single, 100-MW power plant indicate that the hydrogen sulfide standard is not exceeded beyond a distance of 0.6 mile from the plant when the emission rate is less than 0.8 g/s.
- The predicted levels of sulfur dioxide, carbon dioxide, ammonia, mercury, radon, and benzene were all below applicable standards.

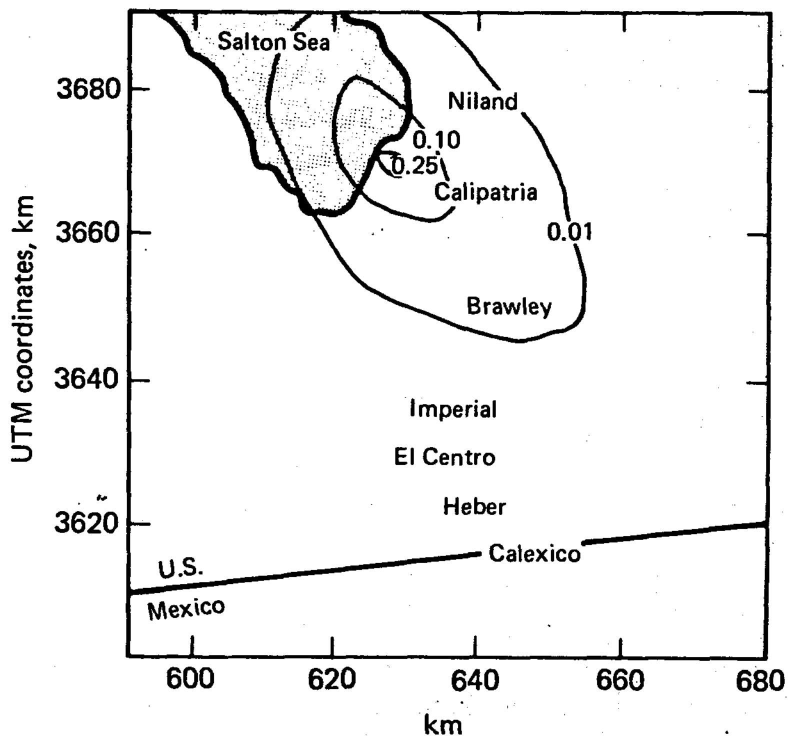

Fig. 3. Isopleths of the estimated frequency with which the California air quality standard would be exceeded near the Salton Sea at a production level of 3000 MW. The 0.25 isopleth (line of equal frequency) indicates where violations would occur one fourth of the time.

CONTROL MEASURES

Table 1 lists several candidate technologies for controlling hydrogen sulfide from geothermal power plants. The technologies involved use different chemical removal processes, and are in various stages of development. None have been commercially applied to geothermal facilities in the Imperial Valley. The technologies are grouped into two general types; those that remove hydrogen sulfide from the noncondensable gas stream and those that remove it from the geothermal fluids. The processes that are applicable to the noncondensable stream are the most developed. Existing data indicate that two of the more promising control technologies of this type (i.e., the Stretford and EIC processes) have potential removal efficiencies above 90%. If those levels can indeed be achieved with Imperial Valley resources, it is improbable that violations of the hydrogen sulfide standard will occur. It should be pointed out that the above controls are meant for flashed-steam facilities. Binary-fluid power plants are not expected to have significant emissions of hydrogen sulfide, and therefore controls are not necessary.

TABLE 1. Comparison of possible systems to control hydrogen sulfide for two process streams related to geothermal electric power development in the Imperial Valley.[4]

Process stream H_2S control system	Potential H_2S removal, %	Geothermal status[a]	Negative factors
NONCONDENSABLE GAS STREAMS			
Stretford	99+[b]	U	None
Brine scrubbing	80 to 90	L	Unknown
EIC copper sulfate	98 to 99	P	Unknown
UOP catalytic oxidation	Unknown	L	Unknown
LIQUID RESOURCE STREAMS			
Dow oxygenation	90 to 100	L	Corrosion
SRI electrolytic oxidation	95	L	Unknown

[a]U—Used currently for geothermal hydrogen sulfide abatement at The Geysers.
L—Laboratory or very small-scale field evaluation.
P—Pilot plant studies being conducted.

[b]Better than 99% applies only to the hydrogen sulfide reaching the Stretford unit. Overall abatement efficiency depends on partitioning of H_2S between the vapor and liquid phases when geothermal fluids are flashed to produce steam.

WATER RESOURCES

Geothermal power production based on hot-water resources is one of the most water-intensive energy technologies known. In addition to the large amounts of hot water necessary for energy conversion, significant amounts of water are necessary for heat rejection. The primary sources of cooling water in the Imperial Valley include irrigation water imported from the Colorado River, agricultural waste waters from irrigated lands, and steam condensate produced from flashed-steam power plants. Despite the presence of multiple water supplies, their use is complicated by problems involving quality, quantity, and the environmental effects of water use. Institutional, legal, and political constraints also influence the availability of the water supplies. Accidental spills of saline geothermal fluids represent an important concern due to the presence of irrigated lands, which will often be adjacent to power plants.

Steam condensate from flashed-steam power plants could supply all, or nearly all, the water requirements of those facilities. No external supplies of cooling water would then be needed. This is significant because the total water requirements of a 100 MW power plant could range from 6000 to above 10,000 af per year, depending primarily on the conversion efficiency of the plant. However, concern over the possible effects of subsidence on the valley's irrigation and drainage systems has resulted in the adoption of a county policy favoring the full injection of withdrawn geothermal fluids.[5] Geothermal developers cannot rely on condensate unless they can show that subsidence would be inconsequential if the condensate is not injected. Other water supply options include irrigation water and agricultural waste water.

In an average year the Imperial Valley has about 475,000 acres of farmland under cultivation. These lands currently require approximately three million af of irrigation water each year from the Colorado River.

Nearly a third of the imported water ends up as waste water in the form of surface runoff, subsurface drainage, and operational losses. Waste waters are discharged to drainage ditches and local rivers, and subsequently to the Salton Sea, California's largest inland water body. It is unlikely that large amounts of irrigation water will be made available to geothermal facilities on a long term basis because this water is already dedicated to irrigated agriculture. Furthermore, a county policy now limits the use of irrigation water to the initial 75 MW of capacity in each geothermal resource area, and then for a maximum of five years.[5] After five years, an alternative source of cooling water will be required.

There is a possibility that in the years ahead surplus irrigation water may become a supplemental source of cooling water, but only if water conservation in agriculture continues to improve. Because of existing constraints associated with steam condensate and irrigation water, waste water from agricultural lands has become an important alternative water supply for geothermal facilities. We estimate that waste waters could sustain almost 7000 MW of geothermal development, even if increased water conservation in irrigation reduces discharges of drain water. Unfortunately, large scale use of this water in geothermal power plants would increase the Salton Sea's salinity and put extra stress on its ecosystem. Based on the assumed rate of energy growth (i.e., 100 MW/yr starting in 1982), salinities in the sea could reach 50,000 mg/ℓ TDS by the year 2000 under average hydrologic conditions.[1] In Fig. 4 we estimate the sea's salinity for three different cases: increased water conservation in agriculture, existing irrigation efficiencies (reference case), and the reference case with geothermal energy development. Each case results in a different quantity of water and salt discharged into the sea.

Other potential sources of cooling water include water from the Salton Sea and ground water on East Mesa. It is doubtful whether these supplies will receive widespread use. For example, the use of Salton Sea water in a cooling tower would create severe corrosion and scaling problems. Ground water may have some use on East Mesa, but the costs of transporting it to other resource areas would probably be prohibitive.

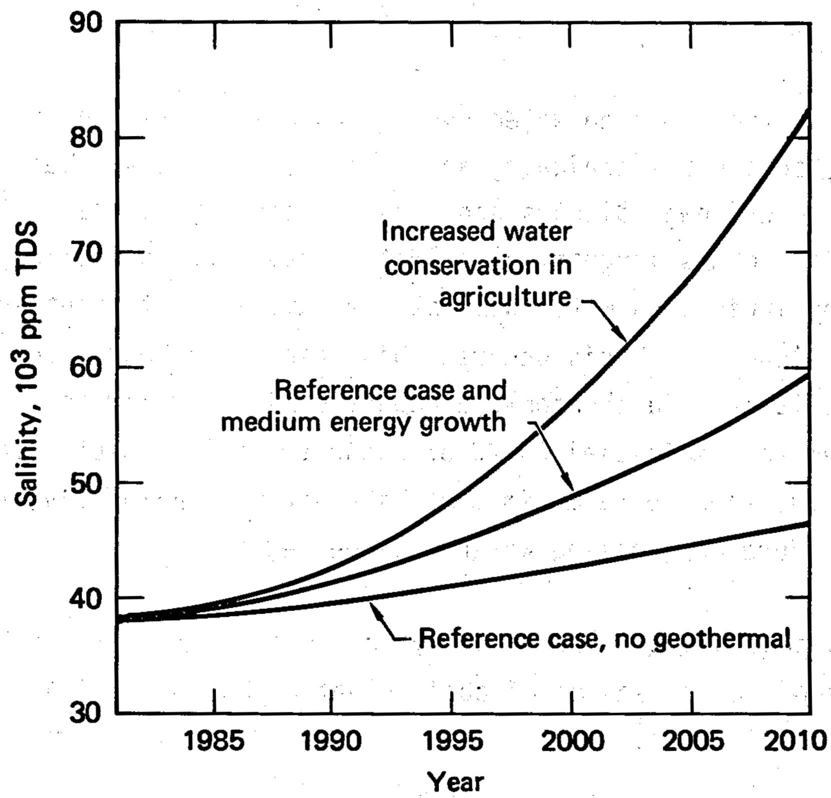

Fig. 4. Salinity of the Salton Sea predicted for three cases: existing irrigation efficiencies (reference case), improved efficiencies (conservation case), and the reference case with growth in geothermal energy generating capacity of 100 MW/year and the extensive use of agricultural waste waters for cooling. Toxic effects on fish reproduction are expected when the concentration of total dissolved solids exceeds 40,000 ppm.

SUMMARY OF IMPACTS

- The primary sources of water that are capable of meeting long-term cooling water requirements of geothermal facilities are steam condensate and agricultural waste waters.
- Irrigation water is presently dedicated to agricultural users and, except for temporary use at demonstration-type geothermal facilities, it is unlikely that this source of water will be available for geothermal development.

- Flashed-steam geothermal facilities will have to rely on external sources of cooling water instead of steam condensate as long as the full injection of withdrawn geothermal fluids is required for the control of land subsidence.
- Agricultural waste waters could support large-scale geothermal development; however, the use of this supply would accelerate increases in the Salton Sea's salinity. Increased water conservation in irrigation would also accelerate such increases.
- Constraints on the use of agricultural waste waters would directly hinder the operation of binary-fluid power plants because such plants must rely on external sources of cooling water.

CONTROL MEASURES

The most appropriate way of reducing impacts on surface waters (e.g., increases in the Salton Sea's salinity) is to use steam condensate as the sole source of cooling water for flashed-steam plants. For this process to be feasible, it must be shown that partial injection (i.e., 80 to 85% of withdrawn fluids are returned to a geothermal reservoir) does not lead to detrimental subsidence. Accordingly, future studies should address the effectiveness of injection as a means of controlling subsidence.

LIQUID AND SOLID WASTES

Liquid and solid wastes will be generated during all phases of geothermal development. The primary liquid wastes will be residual geothermal fluids produced from the operation of power plants; and saline water (termed blowdown) discharged from cooling towers. Solid wastes will be derived from drilling operations, preinjection treatment of geothermal fluids, the removal of scale from pipelines and equipment, the treatment of cooling waters, and the operation of hydrogen sulfide control equipment. Wastes from geothermal energy production in the valley must be disposed of in an environmentally safe manner.

Geothermal power plants will produce large volumes of spent geothermal fluids. A 100-MW power plant will yield between 20,000 and 70,000 af of spent geothermal fluids each year. The lower value would be associated with facilities using the hottest geothermal fluids (over 500°F); the higher value corresponds to facilities using lower temperature fluids (around 350°F). In addition, discharges of blowdown from cooling towers used with 100 MW generating facilities could range from as low as 500 to as high as 2,000 af. Actual amounts depend on evaporation rates from towers and limits on the salinity of water circulating in cooling systems.

As far as solid wastes are concerned, we estimate that approximately 2,200 af of potentially toxic wastes could ultimately be produced with 3000 MW of geothermal development. This total includes 740 af of solids (e.g., drilling muds and cuttings) associated with well drilling, 1,200 af of solids removed from spent brines prior to disposal by subsurface injection, 145 af of solids associated with the removal of scale from geothermal pipelines and equipment, and 97 af of solids (as ammonium sulfate) from the abatement of hydrogen sulfide.[1] Additional solid wastes would be derived from the treatment of cooling waters.

SUMMARY OF IMPACTS

The potential impacts associated with liquid and solid wastes will greatly depend on the methods used to dispose of them. Generally, current regulations should provide satisfactory environmental protection. A possible exception would be spills of geothermal fluids onto irrigated lands or into surface waters. It is difficult to predict the actual consequences of such events.

CONTROL MEASURES

Because liquid and solid waste by-products of geothermal energy production could be toxic to fish and wildlife, as well as to man, those wastes will have to be isolated from the biosphere. The control options for the different wastes are summarized here.

- Subsurface injection is the only feasible method of disposing of spent geothermal fluids, and is therefore a crucial control technology for geothermal facilities. This disposal technology must be able to handle large volumes of fluids for long periods of time. In most cases, spent fluids will have to be treated prior to injection in order to prevent the formation of precipitates that could clog wells.[2]

- Blowdown from cooling towers can be discharged to surface waters if its salinity is below 4,000 mg/ℓ TDS, and does not contain unacceptable levels of toxic substances. For blowdown that is more saline, subsurface injection would probably be preferred. Other disposal options include discharge to surface waters after being treated or discharge to evaporation ponds. However, pretreatment would be expensive, and evaporation ponds would consume too much agricultural land.
- Solid wastes containing toxic substances will have to be placed in special disposal sites (denoted as Class II-I) certified by the State of California. Such sites are now being prepared and should be able to handle the volumes of solid wastes we predicted. In the future, the handling, transportation, disposal, and monitoring of wastes must meet regulations of the Resource Conservation and Recovery Act.
- Recovery of marketable minerals from geothermal wastes is a potential option for waste management. However, further studies on this subject are needed.

SUBSIDENCE AND SEISMICITY

The Imperial Valley exhibits natural subsidence of up to 1.5 inches per year. Figure 5 depicts the vertical movement measured on a series of bench marks running north-south across the valley, for a 5-year period. The extraction and injection of large volumes of geothermal fluids could alter naturally occurring subsidence. For example, the removal of hot water from a geothermal reservoir composed of one or more aquifers could result in compaction of the aquifer(s). Compaction within the reservoir could eventually cause a depression in the land surface, which could hinder the

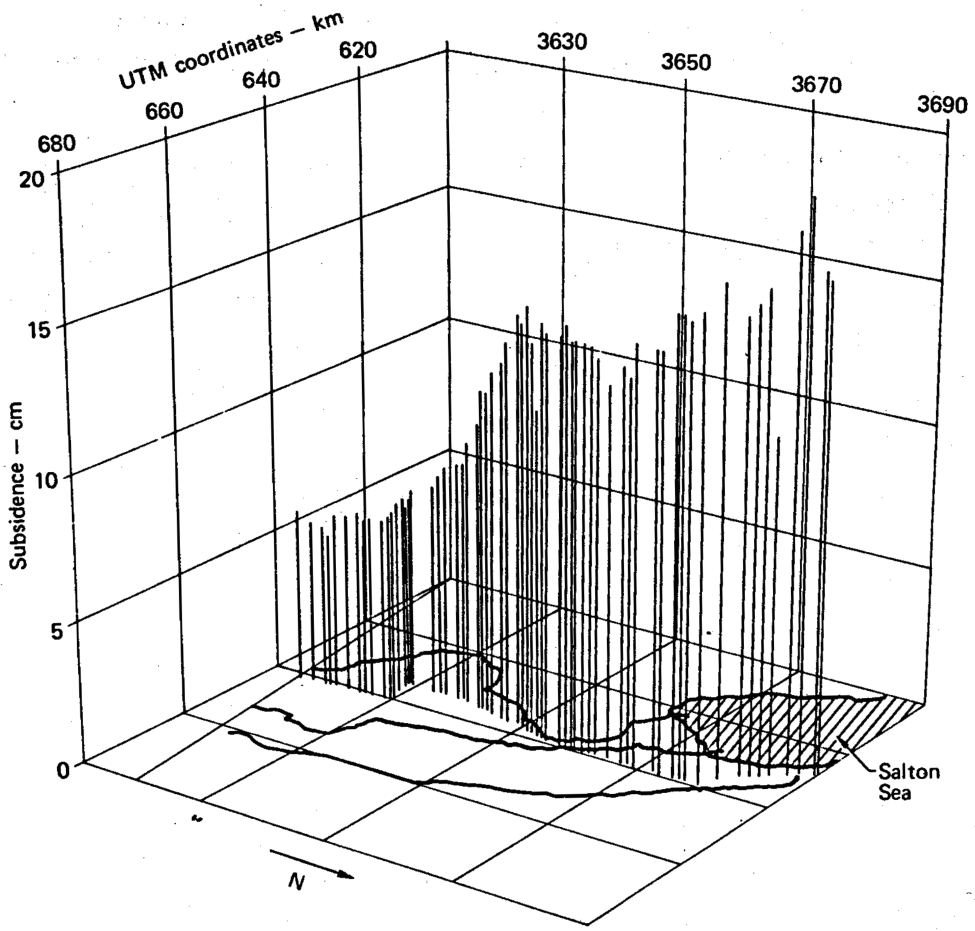

Fig. 5. Natural subsidence for a 5-year period at each of a series of benchmarks that run from north to south in the central part of the Imperial Valley. This profile shows that subsidence gradually increases toward the north end of the valley. The rate of ground settling is about three times higher in the northern part of the valley than in the area near the international border.

irrigation of crops. The possibility of seismic activity induced by the injection of geothermal fluids is also of concern because of incidents in Colorado in which injection caused earthquakes.

To assess the potential impacts of land subsidence due to geothermal operations, we made estimates of how much subsidence might occur above a reference reservoir used to supply hot water to a 50-MW geothermal power plant. In our analysis[1], we estimated upper bounds of subsurface compaction based on the assumption that the porosity and compressibility of sediments were functions of the depth below the surface. As a worst case estimate, we assumed surface subsidence to be 30% of the total compaction within the reservoir. In this case, the estimated subsidence depression altered the natural slope of the land surface enough to potentially affect the irrigation of agricultural lands, which is done mainly by surface irrigation techniques (e.g., furrow irrigation). Changes in slope could hinder the proper application of water to crops. The movement of water in canals and drainage ditches, essential elements of the valley's irrigation system, could also be affected.

There have been concerns that injection of geothermal fluids into a reservoir could induce seismic activity. These concerns stem from separate incidents in Colorado in which injection triggered earthquakes. In those incidents, however, fluids were injected at pressures that caused fracturing of rocks. An injection experiment in Colorado[6] did show that the possibility of induced seismic activity can be lessened by reducing injection pressures below a threshold pressure, which is a function of the physical properties of the fluid/reservoir system. The risk of inducing earthquakes in the Imperial Valley should not be great because injection will be done at low pressures.

SUMMARY OF IMPACTS

- Potential subsidence resulting from long-term extraction of geothermal fluids cannot be ruled out.
- To improve our ability to predict future subsidence and its potential impacts, field data are needed from specific geothermal reservoirs on the behavior of reservoir materials subjected to

pressure changes. Such data could be used to check the accuracy of laboratory measurements of compressibility. Data are also needed on the expansion of sediments above a geothermal reservoir that is compacting due to the extraction of fluids for energy production.

- Agricultural lands in the Imperial Valley could withstand some subsidence, provided that certain minimum slopes be maintained. The application of water to some crops would be difficult, for example, if slopes became lower than .0005.

CONTROL MEASURES

Two sets of measures can be implemented to reduce subsidence-related impacts on agricultural lands.[2] The first set arrests or controls subsidence by maintaining pressure in a geothermal reservoir. Pressures may be controlled by changing the rates of production and injection, and by careful placement of wells. The second set of measures involves the repair of surface damage, modifications of irrigation and drainage systems, and adjustments in irrigation. For example, sprinkler systems could be used instead of furrow irrigation because sprinkler irrigation does not require carefully leveled land.

Even though it is unlikely that subsurface injection will induce seismic activity, it is still important to monitor earthquakes to determine if seismicity changes with geothermal development. If harmful changes in seismicity are detected and appear related to geothermal activities, then injection can be stopped until the exact causes are known.

AGRICULTURE

Because the local economy of Imperial County is based on irrigated agriculture, it is imperative that geothermal development proceed in a way that is compatible with or even complementary to agriculture. In our assessment of the potential impacts on agriculture, we examined the following aspects of geothermal operations: (1) gaseous emissions, (2) land use, (3) accidental spills of geothermal fluids, and (4) emissions of salt drift from cooling towers.

Our assessment of the effects of gaseous emissions on crops was conducted in two phases. In the first phase we carried out a detailed computer simulation of the effects of gaseous emissions from 3000 MW of geothermal development on a target crop, which we chose to be sugar beets. For the second part of the assessment, we used existing data on effects of pollutants to analyze the impacts of emissions on other important crops. Simulation of the response of sugar beets to unabated emissions of hydrogen sulfide and carbon dioxide from 3000 MW of geothermal energy production indicates that growth of beets could be enhanced significantly (greater than 10%) at locations near geothermal facilities.[1] Even with abatement of hydrogen sulfide and lower ambient concentrations of that gas, there would still be a positive but reduced effect on beets. Based on the results of previous crop-fumigation experiments,[7,8] we conclude that yields of alfalfa, cotton, and lettuce will be unaffected by ambient concentrations of hydrogen sulfide assuming abatement. Fumigation studies with honey bees show that the average lifespan of bees would be shortened by continuous exposure to hydrogen sulfide concentrations of .10 ppmv and above.[9] Ambient concentrations of that gas are not expected to reach that level in the valley with geothermal development.

Geothermal power plants and related facilities will remove little land from agricultural production. Our calculations show that at most only about 0.2 percent of the lands normally irrigated would be used by geothermal plants at 3000 MW of development. Negative impacts at specific sites, though, could be caused by accidental releases of geothermal fluids and by emissions of drift (i.e., droplets of saline water entrained in the air exhausted from a cooling tower) from cooling towers. The direct consequence of a spill of geothermal fluids onto a cultivated field will be the destruction of crops, within the bounds of the spill, due to thermal stress. Indirectly, contamination of soil waters beneath lands affected by a spill could have toxic effects on future plantings of crops. Based on the chemical composition of geothermal fluids, the toxic effects of accidental releases would be greatest in the Brawley and Salton Sea resource areas. The impact of cooling tower drift on fields adjacent to cooling towers is difficult to assess because there is only limited information on the toxic effects of drift on crops. We recommend that post-operational studies be implemented to determine if and how crops are affected by drift derived from different types of cooling waters (e.g., agricultural waste waters and steam condensate).

SUMMARY OF IMPACTS

- Geothermal operations will largely be compatible with irrigated agriculture.
- Emissions of hydrogen sulfide are not expected to have a measurable effect on any of the crops grown in the valley.
- Accidental spills of geothermal fluids represent a potential problem; however, there are methods of preventing such releases.
- The effects of cooling tower drift on crops cannot be accurately predicted, and experimental programs should be implemented to study this aspect of geothermal operations.

CONTROL MEASURES

Accidental spills pose the greatest danger to irrigated lands. However, there are some measures that can be taken to prevent or reduce spills. Containment berms can be constructed around production and injection wells and around power plants. Pressure-activated sensors can be used to detect accidental releases so that corrective actions can be taken. If spills do contaminate soils, the affected soils will have to be leached to remove toxic substances. Field studies may be necessary to prove the effectiveness of soil reclamation techniques. Drift eliminators in cooling towers can control emissions of drift to less than 0.001% of the circulating water flow in a cooling system.[2] The use of efficient drift eliminators is particularly important if cooling waters contain boron or elevated levels of TDS.

HEALTH AND SAFETY

Future geothermal operations in the Imperial Valley could result in some health-related risks to the general public as well as to workers in the geothermal industry. Because the production of electricity from hot water resources in the valley will involve flashed-steam and binary-fluid power plants that are relatively new technologies in the United States, it is difficult to accurately predict health and safety effects. However, experience gained at The Geysers dry-steam geothermal resource area does suggest that health related problems could accompany geothermal operations in the valley.

General occupational health and safety concerns include the handling of toxic compounds and hazardous materials as well as job related accidents. At The Geysers, occupational problems have been associated with the maintenance of hydrogen sulfide abatement equipment, which requires hazardous chemicals. Abatement systems will also be installed on geothermal facilities in the valley, and precautionary measures may be necessary to ensure that such systems are operated safely.

Residents of communities near The Geysers have made complaints about hydrogen sulfide odors caused by emissions of that gas from power plants. Geothermal facilities in the valley will also emit hydrogen sulfide, but at much lower rates than do power plants at The Geysers. Nevertheless, with 3000 MW of energy production, control technologies will be necessary to meet the California ambient air quality standard of 0.03 ppm (equal to 42 $\mu g/m^3$) for a 1-hr average. But even if the standard is met, odor problems may still occur because 50% of the population can detect hydrogen sulfide at concentrations between 0.003 to 0.009 ppmv. Our analyses of other gases such as ammonia, mercury, radon, and benzene indicate that they will not pose public health problems. We have identified the transfer of toxic substances to man via the foodchain as a possible health concern that requires further study.

SUMMARY OF IMPACTS

- Emissions of hydrogen sulfide pose the most significant potential problem because the odor of this gas is detectable at concentrations as low as 0.003 ppmv; the present California standard, by comparison, is 0.03 ppmv for a 1-hr average.
- Noncondensable gases including ammonia, mercury, radon, and benzene do not appear to present public health problems.
- Experience at power plants in The Geysers suggests that occupational health and safety problems can occur when workers are exposed to toxic compounds like those involved with hydrogen sulfide abatement systems.
- Noise produced from geothermal facilities is not expected to disturb local residents, provided that facilities are not adjacent to residential areas.

CONTROL MEASURES

The most important measure to reduce potential impacts on public health is to install hydrogen sulfide abatement equipment on power plants. A secondary effect of installing that equipment could be increased incidences of occupational health problems for workers maintaining the equipment, when toxic substances are used in the control systems. Accordingly, industrial hygiene programs should be adopted to limit exposure to hazardous materials.

FISH AND WILDLIFE

Ecologically, the Imperial Valley is a land of contrasts. It contains important aquatic ecosystems such as the Salton Sea's quasi-marine ecosystem and the fresh water ecosystems of the valley's rivers, drains, and canals. In addition, there are terrestrial ecosystems associated with desert areas on either side of agricultural lands, and wetlands along the Salton Sea and the New and Alamo Rivers that serve as important habitats for thousands of migratory birds. Each of these ecosystems will be affected in some way by large scale geothermal development.[1] However, the most significant impact involves changes in the sea's salinity and elevation and the intrusion of geothermal facilities into sensitive habitat areas near the Salton Sea.

SUMMARY OF IMPACTS

- The extensive use of agricultural waste waters for power plant cooling or even for injection to geothermal reservoirs will lower the Salton Sea's elevation and increase its salinity. From an ecological stand point, these changes result in contradictory effects. The sea's elevation has been rising in recent years, inundating wetland habitats. Consumption of waste waters in support of geothermal development could stop the increases in elevation and lessen the impacts to wetlands.
- Increases in salinity, in contrast to increases in the Salton's Sea's elevation, will have an undesirable impact on the reproduction of fish in the sea. Toxic effects on fish reproduction are expected to occur when salinities exceed 40,000 mg/ℓ TDS. With geothermal energy growth of 100 MW/yr starting in 1982 and normal hydrologic conditions, our analyses indicate that salinities would reach toxic levels between 1985 and 1990; without development toxic levels are not likely to appear until the early 1990's (see Fig. 4).
- The most sensitive habitats in the valley are located along the southern end of the Salton Sea, which is in the Salton Sea resource area. As a consequence, geothermal facilities will have to be carefully sited in order to prevent unacceptable disturbances.
- Transmission lines near the Salton Sea could interfere with flights of water birds, particularly along the New and Alamo Rivers.

CONTROL MEASURES

To ensure that geothermal development is compatible with wildlife, it may be necessary to establish buffer zones between habitats and power plants. Transmission lines should be designed and placed in ways that minimize the possibility of collisions.

SOCIOECONOMICS

The economy of Imperial County is dominated by agriculture and associated support services. In 1978 the county's population was approximately 90,000. About half of the population of this border county is Mexican-American. Unemployment has historically been high in the county, and in 1979 it was estimated to be over 25%. Geothermal development could have a range of impacts on the county and its people. For the initial stages of development, impacts are expected to be minor; however, the cumulative impacts resulting from the construction and operation of a number of plants could be significant.[1]

SUMMARY OF IMPACTS

- With large-scale geothermal development, the county's population could increase by as much as 30% over the projected population without development.
- Even though geothermal development will create additional jobs, unemployment in the county is apt to remain high because many of the unemployed may not have the skills necessary for employment in the new industry.
- Geothermal energy production at the 3000 MW level and higher could have significant effects on the economy of Imperial County. The gross output of goods and services, for example, could be increased by a factor of three over normal growth by the year 2020.
- Geothermal power plants will result in more revenues than costs for county government and the school districts. City governments,

however, will not be able to obtain funds derived from property taxes on power plants, because geothermal facilities will not normally be in urban areas. Cities will therefore have to rely on secondary growth tax sources, but such revenues are not expected to compensate for the services that cities will have to provide for the worker population.

CONTROL MEASURES

Geothermal development may not help to reduce the county's high unemployment rate unless job training programs are introduced. Special revenue sources may have to be developed to compensate cities for the service they provide to the increased population.

CONCLUSIONS

The geothermal resources of the Imperial Valley of California have the potential of producing almost 7000 MW of electrical power for 30 years.[3] This represents almost a third of the nation's total identified resources for hot water (greater than 300°F) hydrothermal systems. The valley is also one of the most productive agricultural regions in the United States, with gross revenues amounting to a half billion dollars annually. The ultimate extent to which the valley's geothermal resources are developed will depend in part on the environmental acceptability of geothermal operations and the compatibility of those operations with agriculture. Our assessment of the consequences of geothermal energy production, based on a scenario of 3000 MW of ultimate development, indicates that future geothermal developments will generally be compatible with agriculture. However, mitigation measures may be necessary to prevent impacts associated with land subsidence, the emission of drift from cooling towers, and inadvertent releases of geothermal fluids. The environmental acceptability of geothermal operations will depend heavily on the effectiveness of controls to reduce emissions of hydrogen sulfide.

At the 3000 MW level of geothermal development, emissions of hydrogen sulfide would exceed the California air quality standard of 30 ppbv averaged over 1-h. Therefore, abatement equipment will be necessary. Nevertheless, just meeting the ambient standard may not eliminate odors because most people can smell hydrogen sulfide at concentrations below the standard. The seriousness of future odor problems will largely depend upon reactions of people who are exposed to concentrations of hydrogen sulfide above their personal tolerance levels. It should be pointed out that there are other sources of annoying odors in the valley, notably cattle feed lots and liquid sulfur fertilizers that release hydrogen sulfide upon application. Because of the presence of other odor sources, it is difficult to predict whether odors related to hydrogen sulfide emissions from geothermal facilities will be unacceptable to residents.

Extensive use of agricultural waste waters to support geothermal operations will increase the salinity of the Salton Sea, putting additional stresses on the sea's aquatic ecosystem. The consumption of waste waters would be reduced if steam-condensate could be used as the sole source of cooling water for flashed-steam facilities. But in order for that source of water to be available, partial rather than full injection of withdrawn geothermal fluids will have to be allowed. Currently, the full injection of withdrawn fluids (spent geothermal fluids plus condensate) is required by a county policy[5] designed to control potential subsidence. Until partial injection is shown to be possible without increased subsidence, external sources of water will be required for geothermal power production. Aside from potential impacts of increased salinity on the Salton Sea's aquatic ecosystem, the only other major impacts to fish and wildlife would be associated with habitat alterations and accidental spills of geothermal fluids. However, the careful siting of geothermal facilities can prevent significant impacts on sensitive habitats, particularly in the Salton Sea resource area where wetland habitats support large numbers of migratory birds. Accidental spills can be controlled through the use of containment berms, warning devices, and contingency plans.

Large-scale geothermal energy production is expected to have minor impacts on agriculture. Emissions of noncondensable gases from geothermal power plants generating 3000 MW of electricity will not produce negative impacts on crops or honey bees - even if emissions are unabated. That level of geothermal development will have minor land-use consequences because less than 0.2% of the lands normally irrigated will be needed by geothermal facilities. Negative impacts of a site-specific nature could result from land subsidence, cooling tower drift, or accidental spills of geothermal fluids.

For geothermal development to proceed unhindered in the valley, liquid and solid wastes containing toxic substances will have to be disposed of in ways that do not result in adverse impacts to water quality, fish and wildlife, or human health. The largest volume of waste will be thousands of acre-feet of spent geothermal fluids produced by power plants. The only environmentally safe method of disposing of these fluids is by subsurface injection. Therefore, it will be extremely important that injection wells perform successfully over long periods of time, otherwise the reliability of power plants will be lowered. Solids suspended in residual geothermal fluids will have to be separated to prevent clogging of injection wells. These solids - together with other wastes including solids derived from well drilling, scale removal, and hydrogen sulfide abatement - will be placed in one or more special land disposal sites.

Positive impacts of geothermal energy production on socioeconomic conditions in Imperial County should more than compensate for any negative impacts. For example, direct and indirect employment opportunities are predicted to increase greatly with large-scale development. Moreover, the county's economy will become more diverse, and the gross output of goods and services will rise.

Table 2 summarizes some of the various environmental controls that could be implemented to eliminate or minimize negative environmental impacts.

FUTURE MEASUREMENTS AND STUDIES

Our assessment of environmental, socioeconomic, and human health effects was based on the best available information on conditions in the valley, the chemical composition of geothermal fluids, the technical characteristics of

TABLE 2. Environmental impacts and potential methods of control.

Source of impact	Possible impact(s)	Alternative control measures
A. Emission of hydrogen sulfide	Violation of standards and aversive odors	1. Abatement of hydrogen sulfide 2. Reliance on binary-fluid power plants
B. Withdrawal of river water for cooling	Increases in the Salton Sea's salinity	1. Use steam condensate as the sole source of cooling water 2. Implement salinity control program for the sea
C. Generation of liquid and solid substances	Contamination of ground waters	1. Disposal of wastes to regulated land fills 2. Subsurface injection of spent geothermal fluids
D. Worker exposure to hazardous substances	Occupational health problems	1. Implement proper industrial hygiene programs 2. Install equipment to limit exposure
E. Intrusion into special habitats	Disruption of terrestrial ecosystems	1. Site facilities to avoid ecological impacts 2. Use buffer zones around plants
F. Land subsidence	Disruption of irrigation and drainage systems	1 Alter rates of geothermal fluid extraction and injection 2. Change locations of wells 3. Repair surface damages 4. Implement sprinkler irrigation
G. Cooling tower drift	Foliar damage to crops and trace metal uptake by crops	1. Reduce concentrations of toxic substances in cooling water 2. Install effective drift eliminators 3. Grow tolerant crops near towers 4. Designate buffer zones around towers
H. Accidental spills	Thermal stress to crops and contamination of soil waters	1. Construct berms to contain spills 2. Use pressure activated alarms to warn of inadvertent releases 3. Reclaim affected soils by leaching
I. Injection of spent geothermal fluids	Induced seismicity	1. Monitor seismic activity to detect changes 2. Change injection pressures or stop injection entirely

geothermal energy systems, and the effects of pollutants. As geothermal development proceeds, there will be a need to compare actual impacts with the predicted impacts. Monitoring will be particularly important in studying impacts (e.g., subsidence) that are difficult to quantify because of uncertainties regarding physical processes, and uncertainties about the construction and operation of geothermal power plants and well fields. To verify predicted impacts and to detect other impacts as they occur, post-operational monitoring of the environment and studies of effects will be necessary.

Chemical analyses of geothermal fluids will be needed to determine if the concentrations of different substances vary through time, and thus change the nature of potential environmental impacts. To support future assessments of air quality, periodic measurements of hydrogen sulfide, ammonia, mercury, carbon dioxide, methane, radon, and hydrocarbons should be made. In terms of public health, emissions of benzene will not be a problem; however, additional measurements of this gas in geothermal fluids should be made because only limited data are now available. Additional chemical analyses are needed on steam condensate, particularly for ammonia and boron. Ammonia concentrations need to be quantified because this compound can be toxic to fish. Boron concentrations should be measured to help determine whether additional amounts found in drift from a cooling tower using condensate would damage crops.

Appropriate measurements need to be taken periodically to confirm the validity of baseline measurements of the IVEP and of other organizations. Important measurements are summarized here:

- To update IVEP air quality measurements, the basic requirement will be to monitor hydrogen sulfide concentrations at air quality stations in the Salton Sea, Brawley, Heber, and East Mesa resource areas.

- Water quality monitoring should be done quarterly at selected sampling locations in each of the resource areas. Laboratory analyses of the samples should include: specific conductance, temperature, pH, and concentrations of Na, K, Ca, Mg, Cl, CO_3, HCO_3, SO_4, TDS, B, Cd, Li, Mn, Sr, and Zn.

- The Imperial Valley Subsidence Detection Network should be resurveyed every two years to provide data on changing land surface elevations. Downhole monitoring of compaction in a geothermal reservoir would provide additional data that could be useful in predicting subsidence.

- The existing seismometer network of the U.S. Geological Survey should be maintained. Data on the location and depths of seismic events obtained from these stations will form the basis for comparisons of seismic activity before and after geothermal facilities are installed.

- Remote sensing of each resource area, including large-format aerial photography and multi-spectral photography, should be done annually.

There is also a need to conduct studies dealing with the effect of cooling tower drift on crops. At the present time there are very little data that can be used to quantify potential impacts. Laboratory and/or field studies could be conducted to determine the sensitivity of crops to different doses of saline drift. Other post-operational studies should address land subsidence, health and safety aspects of geothermal operations, accidental spills of geothermal fluids, and the effectiveness of pollution controls.

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